Thermal Analysis of Commercially Available Water Heaters: A Focus on the South African National Standard

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Abstract

The improvement of energy efficiency in the residential sector is one of the simplest ways of making the use of resources more sustainable. One of the strategies used is to look at those household appliances that consume the most power. To minimise emissions and energy consumption, it is imperative to improve the efficiency and the MEPS levels of one of the highest electricity consumers in residential households, namely water heaters. This thesis presents an investigation of the South African standing loss standards of water heaters and tests locally manufactured water heaters to determine heat loss profiles and standing loss values. Using thermal imaging, the main sources of heat loss are identified. Post-test tear down analyses are conducted to determine the distribution of insulation, positioning of elements and unique design modifications done to minimise heat losses. Using variables and data obtained in a practical thermal decay test, equations are derived to predict the expected standing loss values. Thermodynamic simulations are conducted, using inter alia Rayleigh-Bénard Convection principles, to evaluate the effectiveness of water heater orientation and element orientation, element type and water heater mounting position as well as element mounting position. This is done with a view to gain insight on how to optimise design for flow patterns and heat distribution inside the water heater. The simulations showed that the use of CFD software is a powerful tool to assist in the understanding of water heater thermal behaviour of the water body for heat loss analysis purposes. Consequently, suggestions were made for the improvement of the standard to ensure that South Africa remains internationally competitive. Out of the tests and simulations came a different testing methodology, aimed at reducing power consumption and minimising the dependable variables in the standing loss test. The thesis concludes with design recommendations and suggestions for future work.

Abstrakt

Die verbetering van die energie-doeltreffendheid in die residensiële sektor is een van die eenvoudigste maniere om die gebruik van hulpbronne meer volhoubaar te maak. Een van die strategieë wat gebruik is, is om na die huishoudelike toestelle wat die meeste krag verbruik te kyk. Om uitstoot en energieverbruik te verminder, is dit noodsaaklik om die doeltreffendheid en die MEPS vlakke van een van die grootste elektrisiteitsverbruikers in residensiële huishoudings te verbeter, naamlik water verwarmers. Hierdie tesis bied 'n ondersoek van die Suid-Afrikaanse staande verlies standaarde van water verwarmers an en toetse plaaslik vervaardigde water verwarmers om hitteverlies profiele en staande verlies waardes te bepaal. Die gebruik van termiese beelding, is die belangrikste bronne van hitte verlies geïdentifiseer. Post-toets afbreek ontledings word gedoen om die verspreiding van isolasie, posisionering van elemente en enige unieke ontwerp veranderinge gedoen om hitte verliese te verminder bepaal. Die gebruik van veranderlikes en data wat in 'n praktiese termiese verval toets ingesamel is, is vergelykings afgelei om die verwagte verlies staande waardes te voorspel. Termodinamiese simulasies is uitgevoer, met behulp van onder andere Rayleigh-Benard Konveksie beginsels, om die doeltreffendheid van die water verwarmer oriëntasie en element oriëntasie, element tipe en water verwarmer toenemende posisie asook element toenemende posisie te evalueer. Dit word gedoen met die oog op die insig oor hoe om die ontwerp vir vloei patrone en hitte verspreiding binne-in die water verwarmer te optimaliseer. Die simulasies het getoon dat die gebruik van CFD sagteware 'n kragtige instrument is om te help in die begrip van water verwarmer termiese gedrag vir hitte verlies analise. Gevolglik is voorstelle gemaak vir die verbetering van die standaard om te verseker dat Suid-Afrika internasionaal mededingend bly. Uit die toetse en simulasies is 'n ander toets metode geskep, wat gemik is op die vermindering van energieverbruik en die vermindering van die betroubare veranderlikes in die staande verlies toets. Die tesis word afgesluit met ontwerp aanbevelings en voorstelle vir toekomstige werk.

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1 Project Overview

1.1 Introduction

Earth orbits a star that provides the planet with energy in the form of heat and light. On a less significant level, although of importance to humanity, the sun supplies the earth with the energy needed to survive.

Humans exploit that energy by harvesting it from the primary source, the sun, and from secondary sources on earth that have stored the energy in the form of coal, oil and natural gasses, to name a few. With an exponentially expanding population however, the demand for energy inflates in the same fashion. Extraordinary amounts of natural resources are required to support an ever expanding population, yet the resources are limited [1]. The reckless consumption of resources has resulted in a change in climate, both with the weather and in the economy. The weather has changed for the worse, with an increasing occurrence of natural disasters in the form of droughts and hurricanes which result in agricultural setbacks [2]. It is quite evident then that the current rate of consumption of resources is not sustainable and poses a substantial risk to future economies.

In the past, strategies used to manage energy consumption focused on load forecasting. This aided in the planning of building future power stations and advanced purchasing of coal and oil [3]. But the focus has shifted, with the realization that the available resources are limited, to the efficiency of energy generation, transmission, distribution and consumption.

On the power generation side, the need to mitigate the consequences of demand expansion (the demand for clean and viable energy alternatives) is growing. Countries have implemented strategies to minimize the resource use on the planet, but are fast approaching a tipping point where the earth’s climate system reaches a state where pollution content in the atmosphere will be irreversible [4].

Countries have moved from coal, oil and gas energy to alternatives such as wind, hydro and solar energy to supply power. Governments have started giving tax credits and incentives and are offering subsidies to individuals who build renewable energy farms or to those that install infrastructure for private use and in industry, that decrease the load on the electricity suppliers [5] [6].

The transmission of electricity incurs a major cost for energy producers. Large tracts of land have to be bought or rented in order to construct transmission lines and substations. Environmental impact assessments also have to be completed to make sure the impact on the surrounding environment is not too significant. The alternatives to transmission are very limited. Smart grids have the potential to aid in the reduction of energy expenditure. In Europe Smart Grids are defined as *"an electricity network that can intelligently integrate the actions of all users connected to it (generators, consumers and those that do both) in order to efficiently deliver sustainable, economic and secure electricity supplies"* [7]. Innovative products and services are used to monitor and communicate with other elements on the grid to optimize and improve the system as well as reducing the environmental impact of the whole electricity supply system [7].

As mentioned before, focus on the demand side has shifted from load forecasting to a more resource friendly strategy. Demand Side Management (DSM) is a strategy implemented by the major energy producer in South Africa (Eskom) and focuses on reducing the load in all sectors, including the industrial, commercial and residential sectors. One of the strategies used to reduce the load is by creating awareness about energy consumption and offering incentives and rebates to those entities that reduce their energy consumption.

This change in focus was brought about by the power crisis of January 2008, where the power system reserve margins fell from 10% to virtually zero overnight due to a combination of maintenance needs, coal availability and unplanned outages [8]. The consequences of those actions resulted in power losses to industry and residential communities. After the power crisis, the pursuit for more effective strategies was tackled with renewed vigour.

Demand Side Management (DSM) and other strategies implemented by Eskom have been put in place to encourage institutions, industrial entities and individuals to decrease their energy usage through the awareness and management of appliances. The installation of more efficient appliances has been emphasized to assist in curbing the load but very little data has been available to justify the monetary expenditure of switching over to more efficient appliances and using load reducing strategies. Even though they might be more efficient, the appliances and the implementation of such strategies are still costly.

Eskom's DSM policy was drafted to attempt to align itself with the department of Mineral and Energy's (DME) energy efficiency policy and the National Energy Regulator's Energy Efficiency and Demand Side Management policy. The DME's strategy promotes the development of the energy efficiency area [9] while the National energy Regulator ensures the installation of generation capacity to meet the electrical demand growth [10].

The National Energy Regulator's Energy Efficiency and Demand Side Management (EEDSM) policy focuses on making sure the cheapest fuels are used and to, amongst others, provide tariff-based incentives to stimulate entities to become more energy efficient [10]. It stipulates a standard offer that describes an energy efficiency resource standard. The standard offer consists of rebates granted to government-owned buildings as well as residential dwellings, and the amount will relate to the “verified energy savings that have been achieved” [10]. But buildings that don’t adhere to the energy efficiency standard will not benefit from the standard offer. The policy also states that certain key Industrial electricity customers will have to submit a consumption profile and, based on that usage profile, will be assigned a baseline usage. If those customers exceed the baseline usage they will be subject to fines [10].

The DME’s strategy provides a set of objectives outlining the requirements that need to be reached in order to “*contribute to a successful and sustainable national growth and development strategy*” [9]. These include improving energy governance and stimulating economic governance. It is also mentioned that before 1994, the energy industry focused its efforts mainly on the industrial sector and ignored the energy requirements of low income households. This resulted in the infrastructure transporting energy to those households to be underdeveloped when compared to the industrial sector. To assist with the underdeveloped infrastructure, and to minimize the effect of introducing numerous users to the grid, Eskom has implemented a campaign where compact fluorescent lamps, solar water heating and aerated showerheads are slowly being phased in and being promoted through awareness campaigns [11].

Although Eskom’s records reflect that the residential sector consumes 17.8% of the total energy generated in South Africa, the peak demand contribution on the residential side is as high as 35% [12]. In other words, during peak times (7 to 10 in the morning and 6 to 9 at night [13]) the residential sector consumes over 35% of the total energy generated [13]. With the peak demand contribution of the residential sector being so high, greater focus on the residential sector is warranted.

1.2 Project Motivation

The European Commission has published a Green Paper which proposes a strategy to promote energy security. This comes in light of the growing dependence of Europe on external supplies such as oil and gas. According to the paper, in the year 2000 some 50% of the requirements for energy production were imported; a figure that could rise to 70% by 2030 if strategies were not put in place to curb the dependencies [14]. By 2014 the European Council had agreed to implement diversification of energy suppliers as well as better use of regasification for emergency situations. The council had also agreed to negotiate with members of state and companies to gauge compatibility with EU legislation and energy security priorities [15]. Mention is made in the Green Paper about the Kyoto Protocol which talks about reducing emissions with all partners involved in the conference, and is one of the major influences in the drive to increase energy supply as well as reduce energy demand in various sectors. Thus the renewable energy sector has become a priority [14]. One of the strategies discussed in the conference involves labelling appliances in relation to their efficiency standards. Another is to implement the use more efficient lighting systems with a view to reduce energy demand by up to 40% in that category [14]. In addition to the lighting systems, the paper included computers, refrigerators, household TV's and water heaters as being identified as large energy consumers in the residential sector.

A study conducted by Zpryme Smart Grid Insights revealed that the residential appliances that used the most energy, ranked from the highest consuming appliance downwards, were the water heater, clothes dryer, air conditioning and the oven. [16] Lighting wasn't addressed in this instance because the power usage of lighting can vary dramatically from one instance to the next. In addition bulbs do not consume extraordinary amounts of power when compared to, say, a water heater. Please note that these assumptions represent the best available information at the time of the study, but infrastructure and human behaviour change, leading to patterns changing.

In addition, water heaters are costly and poverty rates around the globe are incredibly high. Incentives and projects implemented by energy producers and state owned entities do decrease the load but electricity prices are still on the rise. The most affected by these price hikes are the poor consumers. Poor consumers do not have the means to invest in energy efficiency initiatives and minimise their load on the energy sector. The incentives and energy efficiency projects are only able to reach few of those in need. However, should being energy efficient be cheaper and more accessible to those in need, the adoption rate will also be greater.

Eskom is promoting the replacement of conventional water heaters with solar water heaters and heat pumps to attempt to decrease the load. An additional initiative is a national rollout of water heater insulation blankets. With these initiatives being implemented, Eskom has seen a resulting energy saving of 60GWh per annum [17]. The market has also adjusted to the change in demand in the form of new solar water heater suppliers coming on to the market providing a competitive environment.

Additionally an initiative is in place to manage the residential load by introducing Ripple Control Units into residential households (or relays) to allow for water heaters to be switched off during high demand [18]. This initiative is part of the Integrated Demand Management (IDM) initiative which aims at securing short term energy security through *"coordinating and consolidating the* *various initiatives aimed at optimising energy use and balancing electricity supply and demand"* [18].

In the private sector, a company called Geyserwise is implementing a technology consisting of a controller to allow the resident full control over the intervals the water heater switches off to allow for energy savings during peak load and when not in use [19]. This initiative, as well as the initiative from Eskom to install remote Ripple Control Units, are all intended to wisely and responsibly reduce power consumption.

The amount of energy used by a water heater is very dependent on the demand for hot water and on the ambient temperature. If the water heater is installed externally on a residence then the fluctuations in ambient temperature will have a large influence on the standing losses. If the water heater is placed in an insulated environment and the ambient temperature is low then the heat loss of the water heater will be greater than if the environment is warmer. Defined by the SANS 151 document, which is discussed later in the investigation in full, standing losses per 24 hours are [20]: "*the energy consumed by a full water heater connected to the electrical supply (after steady state conditions have been reached) during any 24 h period when no water is withdrawn."*

The fact that water heating accounts for 30% to 50% of a residential household's energy bill, as quoted in Eskom's Solar Water Heater Program, should indicate that it is necessary to investigate the energy efficiency of water heaters [17] [18].

1.3 Project Overview

1.3.1 Introduction

In this investigation a study was conducted into the standing losses of water heaters as per the SANS 151 documentation. In addition, it also investigated where the heat losses in the water heater occurred by systematically looking at practical experiments as well as simulations of the internal mechanics and heat transfers within the water body contained within the water heater.

National Standards are established for the development, promotion and maintenance of standardisation and quality related to commodities and the rendering of related conformity assessment services [21]. In the South African context, the national standards encompassing the quality, as well as the testing methodology of thermostatically controlled water heaters on the South African Market, are largely based on the SANS (South African National Standard) 151 document.

The SANS 151 Standard covers the testing arrangement of the water heater as well as the location of temperature measuring points inside and around the water heater for the standing loss test. In addition it defines the maximum permissible standing losses for different volumes of water heaters as well as the equations necessary to calculate the standing losses once the standing loss test is complete [20].

This investigation followed the SANS 151 standard in order to gauge the standing losses of water heaters from companies that have the largest market shares. After the practical measurements and investigations were done, a further exploratory study was done by simulating the thermal transients within the body of water as well as the flow induced by heat transfer and convective effects.

Once completed, the data collected is used with a view to improve future test results and to implement a more efficient, repeatable and robust testing methodology.

1.3.2 Research Objectives

The investigation requires research and development into the testing and implementation of the standards as well as the testing methodology involved. To better understand the internal mechanisms inside the water heater, additional investigations pertaining to the thermodynamic behaviour will have to be completed. This is all done to achieve the following:

- Choosing a number of water heaters, representing the current market leaders and test them and collect thermal data with a view to determine the real standing loss values or MEPS levels for each one using the SANS 151 Standard. Then, calculate the real standing losses of water heaters and compare the results to the maximum permissible standing loss value in the SANS 151 document.
- Identify sources of heat losses on and around the body of the water heater keeping in mind the construction of the water heater. These include the insulation, any mounting mechanisms and bolts and pipe connections. This shall be done using IR imaging.
- Investigate the effects of different water heater mounting orientations experimentally.
- Compare international standards for maximum permissible standing losses for water heaters on international markets.
- Explore further the National Standard of South Africa to define the testing arrangement and identify any gaps and omitted data and information regarding the testing arrangement.
- Explore an alternative test methodology with a view to improve the existing test methodology and produce better guidelines and structures for the arrangement and testing of the water heater and any water pipes connected to the aforementioned water heater.

- Investigate the effect of different element types and element positioning on power consumption and heat dissipation. Model the dynamic behaviour of the water mass inside the water heater with a view to better understand the heat distribution. In addition, investigate the effect of the heat distribution on heat losses regarding the hot spots inside the water heater.

The outcomes of these objectives will provide insightful data into the mechanics and thermal behaviour in the water mass. This will assist in exploring any improvements or modifications that could be made to the design of the water heater. Additionally, unlike in previous investigations, this new understanding of the thermal behaviour will grant insight for water heater manufacturers and will assist in future investigations into water heaters.

1.3.3 Key Questions

The key questions that this investigation aims to answer are as follows:

- What water heaters should be tested for this investigation?
- What testing arrangements should be chosen and what pipe arrangement should be attached to the water heater?
- What testing environment would be most suitable for the purposes of this investigation?
- What hardware and software should be used to capture and process the data?
- What standards are to be reviewed for the comparison?
- What software packages should be used for the thermal simulations of the water mass taking into account:
    - Available mesh size
    - Processing power
    - CAD support
    - Availability
    - Cost
- What design improvements can be made after viewing the data collected in the investigation?

1.3.4 Research Tasks

Research tasks are completed with a view to complete the research objectives and answer the key questions as defined earlier in this chapter. Those include the following:

- Choose a number of water heaters that represent the current South African water heater market.
- Construct an assembly to hold the water heater in different orientations for testing.

- During testing collect the necessary data including power usage statistics and thermal images.
- Validate the data and choose correct time intervals for the most reliable results.
- Use the data to develop a new standing loss test methodology.
- Better define the testing arrangement and methodology so that testing and data collection can occur seamlessly and without data corruption for test validity.
- Build and simulate a model of the water heater in ideal conditions.

1.4 Thesis Document Overview

This investigation will explore different models of water heaters and try to identify the leading causes for heat and energy losses within the water heaters in a controlled environment in all possible installation configurations. Once the standing losses are calculated and the consumption profiles are acquired, the results will be used to provide a baseline energy consumption profile usable for DSM initiatives. Thus it is decided to structure the investigation as follows.

Chapter 2 covers the following objectives:

- The history of water heaters
- Comparison of global water heater standards
- Insulation grading in water heaters

Chapter 2 carries out a broad investigation into the history of water heaters as well as the health standards involved in designing, manufacturing and operating the water heaters. Following that, an extensive investigation is conducted on the standards currently in effect firstly in South Africa and secondly in a few of the world's leading economies. Once the standards are presented and scrutinised, comparisons can be made on all the standards and from this investigation a baseline can be established as to what the goals of the investigation entail.

Chapter 2 continues by investigating the means by which the data will be collected. This is done in tiers, first identifying which method is best for determining the temperature and secondly, the method of data capture is analysed with a view to find a robust and reliable system.

The thermodynamic principles used to analyse the thermal transients in Chapter 7 are introduced in Chapter 2. This is done in conjunction with the fluid flow principles and boundary conditions that are encountered in the thermodynamic field.

Chapter 3 focuses on the testing methodologies proposed in the existing standards:

- Exploratory look into different aspects of the test methodologies.
- List of all the measuring equipment used as well as a detailed explanation of the testing and measuring arrangement.
- Explanation of the testing strategy.
- Detailed explanation of the final analysis of collected data as well as extensive practical investigation into water heater manufacturing and shortcomings.

In Chapter 3 the test methodologies in the South African Standards are dissected and analysed with a view to gain an understanding of the test hierarchy. Any shortcomings in the proposed testing methodologies are searched for in order to make comments and recommendations for any future research. Once the methodology has been established, the testing arrangement is derived and perfected for quantifying the standing losses. Different equipment used for data capture will be compared, focusing on reducing the impact of external factors and unreliable measurements. Once the equipment has been identified the correct strategies are established to measure accurate and reliable data.

Chapter 3 closes off by describing the necessary equations to be implemented, to acquire the standing losses for each test and describing the analysis's to be carried out to bring the test of each water heater to a close. This establishes the structure of the investigation as it is represented in Chapter 4.

Chapter 4 does a critical analysis of different water heaters. The specifications, the standing loss test, thermal analyses and a tear down analysis are compared. This is done with a view to analyse water heaters from different manufacturers, in order to gain a better understanding of products currently available on the market. A comparison is done on the measured standing losses of each water heater in all orientations as specified by the manufacturer. To gain a better understanding of the thermal behaviour of each water heater, a tear down analysis is carried out. The tear down analysis is carried out by cutting the water heater through lengthways. This will reveal whether it is properly thermally insulated and identify whether the integrity of the insulation is not compromised. All these results are then brought together at the end of the chapter to compare and criticize with a view to find a baseline of what is currently available in South Africa in terms of water heaters. Once the baseline is established, problem areas are identified to see if there is room for improvement.

Chapter 5 carries out an analysis of the collected data:

- Insulation grading analysis.

- Data manipulation.

Chapter 5 takes the data gathered from the tests in Chapter 4 and critically analyses it, identifying the average insulation effectiveness. The resulting information is used to benchmark the quality of manufactured goods evaluated in the tests in Chapter 4.

Chapter 6 explores a novel testing strategy aimed at reducing the impact of thermodynamic effects in the water heater. The test focuses just on the insulation design and performance. The results of the aforementioned tests are examined and compared to the results in Chapter 4 with a view to identify whether the new test strategy holds some substance.

The test is carried out on a select few, namely those water heaters with the best performance and those with the worst:

- Application of new test methodology on water heaters.
- Comparison and analysis.

Chapter 7 discusses the theoretical thermal behaviour involved with thermal problems. It goes on to discuss the principles involved and the programs available in the market that evaluate the water mass behaviour. After identifying the principles and equations involved with thermal behaviour, simulations are carried out to conclude the investigation on water heater thermal response.

Chapter 8 explores any possible design and manufacture improvements that could be made to the water heaters to improve efficiency and effectiveness of the water heaters. It continues by finalising the investigation by suggesting and summarising recommendations on the design and test procedures.

2 Literature review

2.1 Water Heater History

The history of water heating didn’t start until late in the 1800’s when a decorative painter by the name of Benjamin Waddy Maughan came up with a design that revolutionized water heating [22]. The design consisted of a cylindrical heating chamber where cold water entered the top and worked its way down to the bottom through a series of pipes that were heated by hot gasses rising from the bottom of the chamber. The issue was one of safety though:

‘… at the head of the bath towered a dragonlike copper geyser with a gas meter below for shillings. When lit, the geyser burst into life with a deafening roar and spluttered out much steam and little water.’

If the gas was not turned off after the user was finished then the cylinder would start to emit clouds of steam and eventually fall to molten pieces [23].

From this idea many other safety features were added or new systems were designed to improve on the Maughan geyser. One to mention is Edwin Ruud. He was granted a patent for his geyser in 1890. The design consisted of a tank of water that was heated by a gas valve that would be lit by a pilot flame that would regulate the temperature of the water via an expansion valve [24].

Since the 1890’s water heater technology has made leaps and bounds. More recently though, new issues started to arise. One of those was that the energy consumption of the water heaters started to rise to levels that contributed negatively to the environment.

2.1.1 Introduction of Energy Efficiency Standards

Production and improvements of water heaters continued until the oil crisis in the 1970s where the first advances were made to regulate energy demand via the building sector [25]. Limitations and standards were initiated such as the A-G rating for water heaters in prEN 15332; 2006 [26] and the European Commission’s Energy Efficiency Classes [23] which is represented in Figure 2-1. The figure represents the identification of the class of a water heater by matching the volume of the water heater to the measured standing losses of the water heater in question (i.e. it represents the maximum permissible standing losses for a certain volume of a water heater in order for it to fit in a certain class). Once the class of the water heater is obtained a label is used to assist consumers in the purchase of the product. Additional classes do exist for water heaters that operate with renewable energy sources but are classified in other standards.

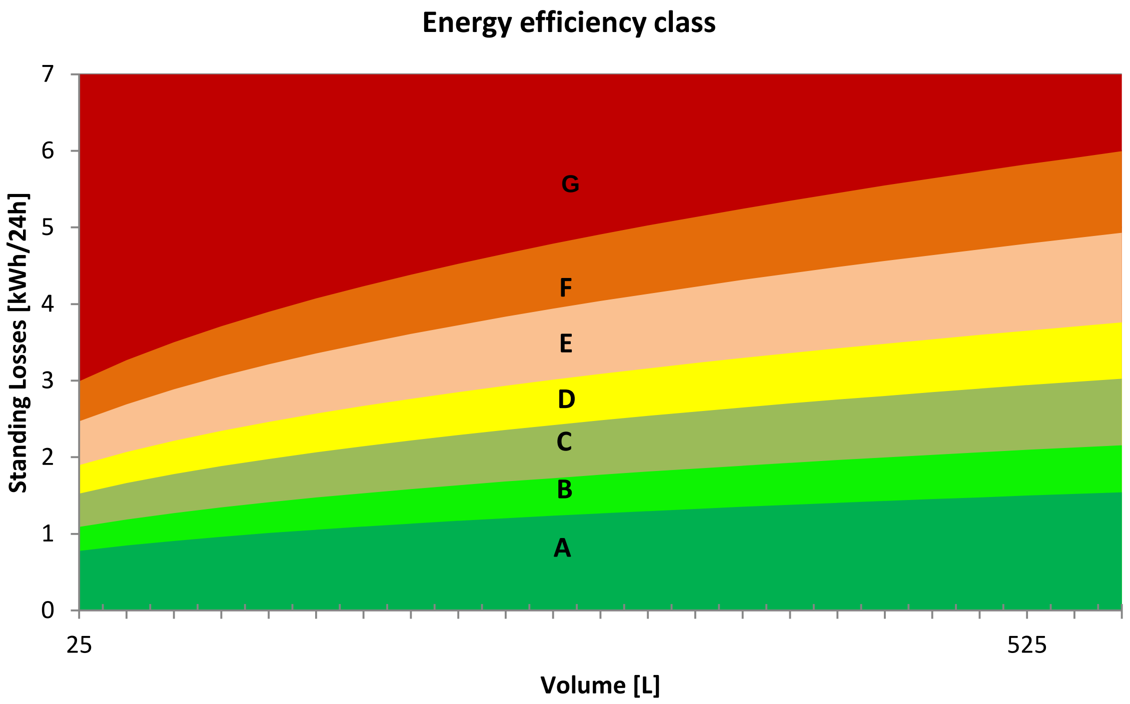


Figure 2-1: Energy efficiency classes (A-G) of hot water sorage tanks.

The ratings are arranged from best to worst, with A representing the most efficient and G representing the least efficient water heaters. More efficiency classes do exist but are reserved for solar water heaters and extend into the A+ rating scheme where an addition operator (+) is added to the label A [23].

The classification used by the European Commission is used as a basis to compare the maximum permissible standing losses for different countries and from this, to infer the efforts and strategies implemented by those countries to curb residential energy consumption and CO_2 emissions associated with electric storage water heaters. This is done with a view to compare the strategies and the legislation of other countries to the South African framework.

The European Committee Equipment Manufacturers (CECED) proposed a commitment to curb energy losses or standing losses in the electric storage water heater industry. As of the year 2000 a phase-out of less efficient water heaters would commence, additional data would be made available and a reduction in consumption of products would be attempted [27].

The CECED also set the standard for the maximum permissible standing losses for imported water heaters. Horizontally mounted water heaters, which run on the pressure of the cold water supply from the regional water provider, have to adhere to the following set objectives:

$$Standing\ Losses\left[\frac{kWh}{24h}\right]=(0.939+0.0104)(\mathrm{V}) \qquad 2.1.1$$

where V denotes the volume of the water heater in litres.

Similarly for vertically mounted water heaters:

$$Standing\ Losses\left[\frac{kWh}{24h}\right]=(0.224+0.0663)\left(V^{\frac{2}{3}}\right). \qquad 2.1.2$$

If the European Commission’s A–G rating objectives are overlaid with the manufacturers proposed commitment, it can be seen that the manufacturer’s commitment focuses on efficiency for smaller volumes of water heaters. But as the volume increases the focus on efficiency becomes more relaxed. In the context of the horizontally mounted water heaters, the focus on energy efficiency comes to be relaxed as the volume of the water heaters increases when compared to the European Commission’s A-G rating as indicated in Figure 2-2.

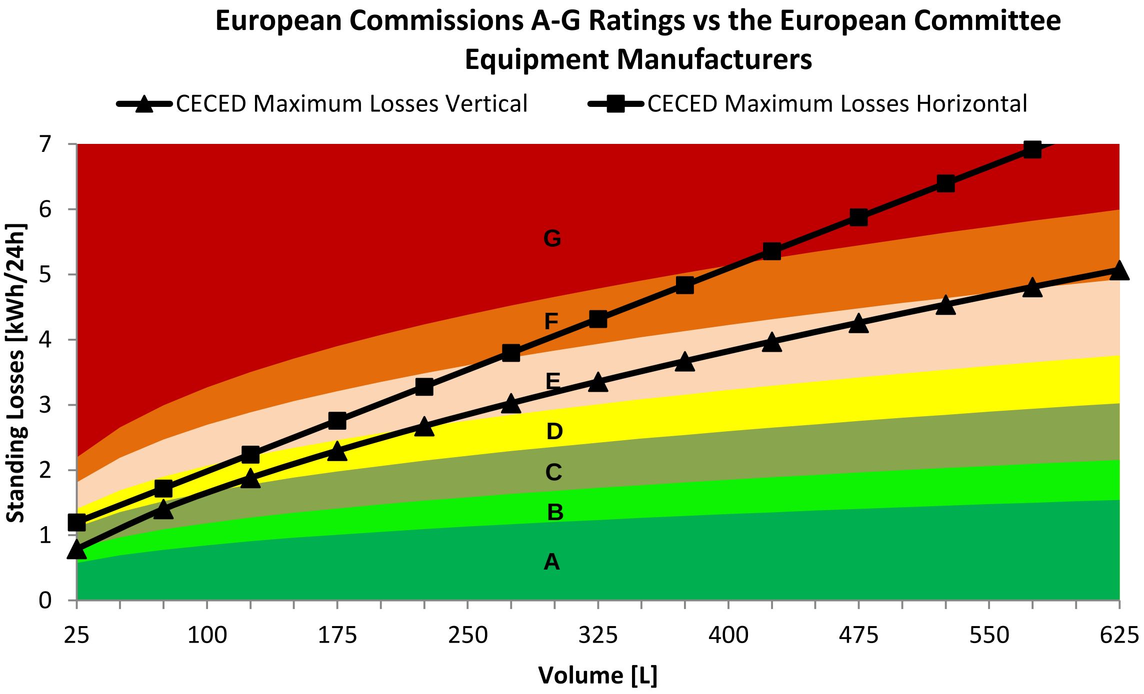


Figure 2-2: European Commission’s A-G rating vs the European Committee of Manufacturer’s importing standards.

This gives rise to the regulations on water heaters being imported into the EU not being stringent enough to curb energy losses.

It is important to note that the controller temperatures used in the study were classified as being 45 Kelvin above ambient temperature (65°C) as classified by EN 60379 [28] but some countries deviate, as is explained later in the chapter. The tolerances measured during the testing must not exceed 15% of the set point temperature. Should the measured value exceed 15% of the declared measured temperature then an additional process must be followed. This process consists of randomly selecting 3 water heaters from the same manufacturer. The average temperature measurement over all 3 selected products must not exceed 10% of the rated value [27].

2.1.2 Health Standards

The standing losses of water heaters are large due to the continuous high storage temperature (usually between 60°C and 80°C [27]). For health reasons, the water temperature is elevated to above 60°C and not at a lower, yet functional storage temperature (45°C for example). This leads to larger standing losses and higher CO_2 emissions. One of the concerns in the EU there is the fear of pathogens transmitted through water such as cholera, typhus and Legionella's disease. The latter is caused by the Legionella bacteria which seems to be the greatest concern [29].

The EU Committee has endorsed an official document published by the European Working Group on Legionella Infections (EWGLI), called European Guidelines for Control and Prevention of Travel Associated Legionnaires' Disease [30]. It provides information on Legionnaires' disease and describes procedures put in place to report and respond to cases associated with Legionnaires' disease in the travel industry [30]. Some countries in the EU have not yet adopted the legislation. Only countries where a breakout of the disease has occurred have taken action to prevent further cases of a breakout of the infection. Outside of the EU however, the concern seems to be less. In the US, no regulations could be found concerning minimum storage temperature although guidelines were stated by the US government as will be discussed later in the chapter [27].

Additional measures such as anodes are installed into water heaters to prevent corrosions inside the water heater. This not only ensures safe water, free of rust, but also increases the lifetime of the water heater [31] [32] [33]. Corrosion is accelerated by higher temperatures and acidity in the water. Different anode metals are used in the industry to mitigate the effects of these actors. Chief among those are aluminium and magnesium. Some manufacturers include zinc in the aluminium rod to reduce the smell of sulphur in the water coming out of the water heater [31] [32] [33].

Anodes are made by wrapping magnesium or aluminium around a steel core wire. These are then screwed into the top or side of the water heater. Some water heaters with larger volumes or longer lifetime warranties will have two sacrificial anodes installed to further help reduce corrosion. The electrochemical process of corrosion begins as soon as water is introduced into the water heater. The metal that is more reactive will corrode first, leaving the other metal intact [31].

2.2 Global National Standards for Water Heater

This section investigates the legislation and existing voluntary measures in place concerning water heaters around the globe. The section will first explore the South African Standards associated with the standing losses and the tests involved with measuring the standing losses and will move on to review the testing standards in other countries including Australia, the US, Australia and New Zealand.

It is imperative to point out that in order to comprehensively compare the maximum allowable standing loss profiles globally, the test procedures have to be akin to one another. Notwithstanding the fact that not all of them will align perfectly, the comparison will still be conducted with a view to determine the superiority or inferiority of the respective test strategies.

2.2.1 South Africa

The South African National Standard (SANS) 151 stipulates a set of tests in order to determine the standing losses of a water heater over a 24 hour period. The testing methodology is discussed in detail later in the text in chapter 3.4.

To compare the South African Standard to others, the testing methodology needs to be explored. It stipulates the following testing hierarchy:

- With probes placed in the water heater, at the hot and cold water pipes, as well as the controller unit, and an additional probe to measure the ambient temperature, temperature readings are taken over a testing period of 48 hours. Data collection only starts after the water heater has been allowed to stabilize at a controller temperature of 65 °C. The mean ambient temperature is kept as close to 20 °C as possible. For the duration of the test no water is drawn from the water heater in order to retain the mean internal temperature.
- The 20 °C is then later used in the standing loss equation to calculate the difference between the controller temperature and ambient, namely the 45 °C or 45 K [20]:

$$Q_{pr} = \frac{45\,(E_1)}{2\,(65 - \theta_{amb})} \qquad 2.2.1$$

Where Q_{pr} denotes the standing losses in kilowatt-hours per 24 hours [kWh/24hr], E_1 denotes the total energy consumption of the water heater in the 48 hour period [kWh] and θ_{amb} denotes the mean ambient temperature over the course of the test in degrees Celsius [°C].

Once the standing losses of a water heater are calculated the result is compared to the maximum permissible standing losses shown in Table I: Maximum permissible standing losses for South Africa .

Table I: Maximum permissible standing losses for South Africa [20].

Maximum allowable standing loss [kWh/24h]			
Nominal capacity of water container [L]	**Open outlet type water heater**	**Cistern type water heater**	**Closed type water heater**
≤15	0.86	1.08	0,86
25	1.30	1.62	1,30
50	1.62	2.16	1,62
75	1.84	2.48	1,84
100	2.16	2.81	2,16
125	2.38	3.02	2,38
150	2.59	3.24	2,59
175	2.78	3.44	2,78
200	3.02	3.67	3,02
225		3.89	3,24
250		4.10	3,46
275		4.28	3,68
300		4.45	3,89
350		4.78	4,32
400			4,75
450			5,18

2.2.2 Australia

In the Australian context the rules and regulations are covered in the Australian and New Zealand Standard AS/NZS 4692.2. Any water heaters manufactured or imported into Australia have had to comply with Minimum Energy Performance Standards (MEPS) set out in AS 1056 Part 1 [34].

The testing procedure for determining the standing losses is defined in Part 1 of the AS1056 [35]:

- With an ambient temperature kept at a nominal 20 °C and the water heater temperature at 75 °C the test is run over a number of complete controller cycles. The recorded data is then normalized to represent a standing loss per 24 hours. From the testing the following equation was deduced to represent the standing losses:

$$MEPS\ (maximum\ daily\ heat\ loss) = (0.255)(V^{0.4032}) \qquad 2.2.2$$

where V denotes the volume of the water heater and MEPS is measured in kWh/day [34].

The maximum permissible standing losses for the Commonwealth of Australia were originally resolved in the AS 1056.1 – Amendment 3 and can be seen in Table II.

Allowances are made for extra elements (0.2 kWh/day), any extra release valves attached to the water heater (also 2 kWh/day) [34] as well as a feed tank (0.3kWh/day).

Because the water heaters in Australia are run at a higher temperature than elsewhere, with a temperature difference of 55 K, the standing losses may appear higher and cannot be viably compared to the other tests, notwithstanding the fact that the standard is more inflexible.

2.2.3 New Zealand

The Australian and New Zealand policies on water heaters are fundamentally the same apart from New Zealand being more stringent on the standing losses.

The testing procedure is stipulated in the standard NZS4606 for mains pressure electric storage water heaters [36]. The strategy is as follows:

- Test the water heater under static conditions where all inlets and outlets are plugged with corks and insulated with 25mm of fibreglass [37], thus no water is drawn off for the duration of the test and all possible heat loss is minimized as much as possible.
- The test is run for 24 hours.

The equation used to identify the standing losses of a water heater are as follows [36]:

$$MEPS\ = (0.0048)(V + 0.72)\ [kWh] \qquad 2.2.3$$

where $MEPS$ is the maximum allowable standing loss value and V denotes the volume of the water heater.

This equation is only valid for water heaters with a volume greater than that of 90 litres. For water heaters with a volume smaller than 90 litres another equation is used [38]:

$$MEPS = (0.0084)(V + 0.40)\ [kWh] \tag{2.2.4}$$

The results of these equations can also be seen in Table II. Comparing the Australian and New Zealand maximum allowable standing losses it is seen that New Zealand is more stringent.

Table II: Maximum heat loss for electric storage water heaters(unvented tanks), Australia: October 2005 [38].

Maximum allowable standing loss [kWh/24h]		
Volume [L]	**Australia**	**New Zealand**
<25	0.98	0.61
25	0.98	0.61
31.5	1.05	0.66
40	1.12	0.74
50	1.19	0.82
63	1.33	0.93
80	1.47	1.07
100	1.61	1.20
125	1.75	1.32
160	1.96	1.49
200	2.17	1.68
250	2.38	1.92
315	2.66	2.23
400	2.87	2.64
500	3.15	3.12
630	3.43	3.74

It is important to note that no water is drawn out of the water heater for the duration of the tests for both the Australian and New Zealand Standing loss tests.

If the values are compared to the South African maximum permissable standing losses it is seen that South Africa is quite lenient compared to the MEPS levels of Australia and New Zealand as can be seen in Figure 2-3. The graph shows a comparison between the South African MEPS levels and the Australian and New Zealand MEPS levels.

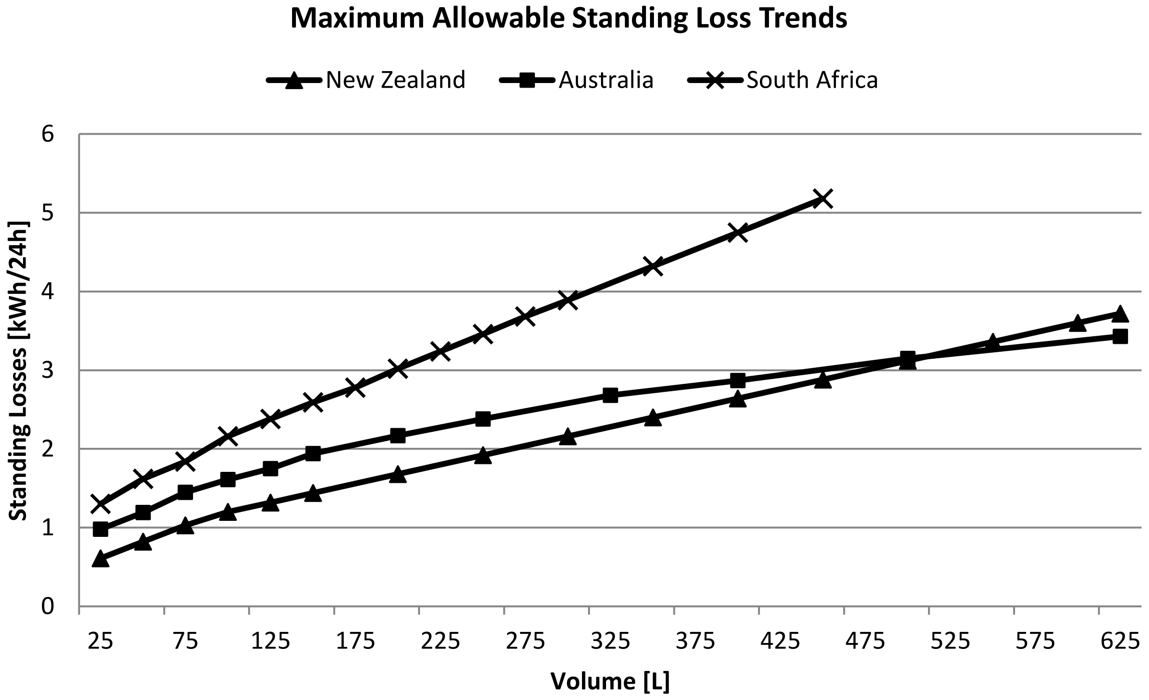


Figure 2-3: Comparison between Australia MEPS, New Zealand MEPS and South African MEPS.

For the evaluation of the following countries the description of the tests and the formulae used will be presented first. Towards the end of the chapter a graphical representation will be presented reflecting the MEPS levels for each country.

2.2.4 France

In France, with the average annual temperature being quite low, water heating systems are put in place to keep residential households warm. This skews the standing loss measurements due to hot water being circulated through the household continuously resulting in significant heat loss. The French do however differentiate between the different sub-systems.

For the electric storage water heaters, 65 °C is used as the controller temperature in conjunction with the rest of the EU, but the test includes a flow rate to take into account the heated pipes used for space heating. A separate chapter covers the pure standing loss calculation.

The storage losses for electric storage water heaters is calculated using the following sets of equations:

- For horizontally mounted water heaters with a volume smaller than 75 litres:

$$C_r = (0.1474 + 0.0719)\left(V^{\frac{2}{3}}\right) \tag{2.2.5}$$

where C_r denotes the standing losses per day measured in kWh/day and V denotes the volume of the water heater measured in litres.

- For horizontal water heaters with a volume greater than 75 litres:

$$C_r = (0.939 + 0.0104)(V). \tag{2.2.6}$$

- Lastly, for vertically mounted water heaters with a volume greater than 75 litres:

$$\mathrm{C_r} = (0.224 + 0.0663)\left(\mathrm{V}^{\frac{2}{3}}\right). \tag{2.2.7}$$

French residences also use gas fired storage water heaters as well as solar hot water tanks where a solar contribution is subtracted from the total power used. This report merely looks at the water heater system itself. Therefore no solar contribution is taken into account.

The maximum permissible standing losses of the French water heaters are not as good as those of the Australian and New Zealand strategies for larger volumes of water. That said, the French do use water heating as a means to heat households due to the climate being colder than that in Australia and New Zealand.

2.2.5 Canada

The Canadian test methodology is covered in the CAN/CSA-C191-M90 [39]. Keeping the temperature difference between ambient and the inside of the water heater at 44 °C the test is conducted over a period of 24 hours. The standing losses are then matched to the static storage capacity and verified against the maximum permissible standing losses. Similarly to the United States testing procedure, which is covered next, the test incorporates a draw off of hot water from the water heater. The standing losses are then estimated using the recorded data from the remaining 24 hours [37].

The calculations used to identify the standing losses are separated into two categories, namely for water heaters with a top inlet or with a bottom inlet for the cold water. This paper focuses on water heaters with a bottom inlet for both vertical and horizontal orientations. In addition the water draw off during the test makes any comparison void for all intents and purposes. But even though there is a draw off something interesting can be observed.

The equations for calculating the MEPS are separated into a further two categories where water heaters with a capacity greater than 270 litres have a separate specification. For water heaters with a volume smaller than 270 litres:

$$\mathrm{MEPS} = (40 + 0.20)(\mathrm{V}) \qquad 2.2.8$$

where MEPS is the energy factor measured in watt-hours.

For water heaters with a capacity greater than 270 litres but smaller than 454 litres [39]:

$$\mathrm{MEPS} = (0.472)(\mathrm{V} - 33.5). \qquad 2.2.9$$

To then convert from the energy factor to the maximum permissible standing losses, the energy factor is multiplied by a scalar to achieve the kilowatt hour value used per day.

2.2.6 United States

Canada adopted a similar test to the test methodology specified in the United States Federal Regulations, namely the CFR430 Subpart B Appendix E, which focuses on the residential sector. One of the differences here though is that the Federal Regulation also covers instantaneous water heaters [37] [40].

In the United States the most widely used appliances for water heating are the electric resistance storage water heaters as well as natural gas water heating [27]. The major focus of the regulation is on water heaters that have the following characteristics:

- The resistive element must be rated at 12 kilowatts or less.
- The internal temperature of the water heater must not exceed 82 °C.
- The volume of the water heater must be in the range of 76 to 450 litres [37].

The test methodology is very different in comparison to the standing loss test in the SANS 151 document. It consists of periodic tapping off of water from the water heater over the first 6 hours after which the water heater is left to recover and as with the Canadian procedure, the standing losses are calculated from the data recorded from the remaining 24 hour testing period.

From the available data in the International review of MEPS for water heaters the following standing losses are available in Table III.

Table III: United States MEPS levels as of 2004 [37].

USA MEPS levels	
Tank volume [L]	**Standing heat loss [kWh/day]**
100	1.233
150	1.593
200	1.968
250	2.358
300	2.763
350	3.186
400	3.626

The standing losses are calculated by first finding an energy factor for a water heater. In 2004 the equations changed slightly to improve the energy efficiency of water heaters in the United States. For water heaters below 210 litres (55 gallons) the equation has changed only slightly compared to the equation used since 1991 [40]:

$$EF = 0.96 - 0.0003V \text{ [gallons]} \qquad 2.2.10$$

For water heaters with a volume greater than 210 litres (55 gallons):

$$EF = 2.057 - 0.00113V \text{ [gallons]} \qquad 2.2.11$$

The energy factor is effectively a representation of the energy efficiency of a water heater. As the volume of the water heater increases, the energy efficiency decreases due to the heat losses becoming greater.

Figure 2-4 shows the MEPS levels of the United States and Canada as well as the MEPS levels of South Africa.

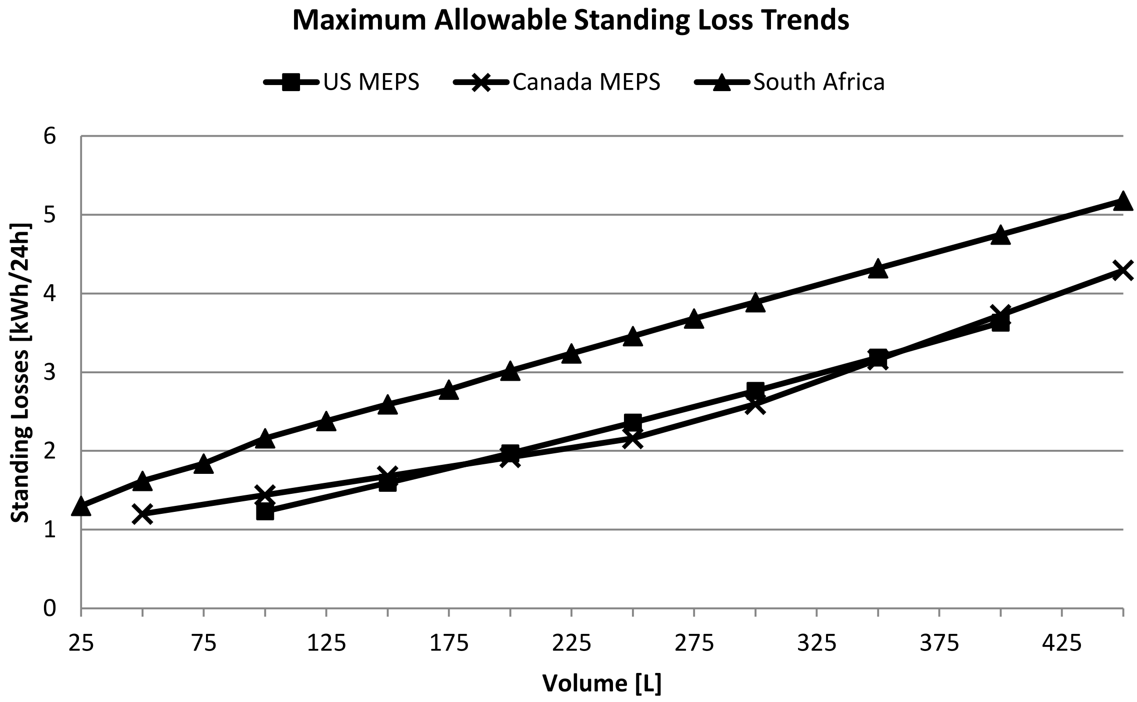


Figure 2-4: Canada MEPS compared to United States MEPS and South Africa.

Looking at the two graphs in Figure 2-4 comparatively, it can be seen that the US and Canada have very similar profiles. The tests are also quite similar with Canada looking at aligning their test procedure with the US test procedure. However if a comparison is made of those two to the MEPS of South Africa, it can be seen that South Africa is still quite indifferent about the low standards when it comes to the legislation put in place to minimize waste energy. This result is more worrying due to the US and Canadian standing loss tests also incurring a draw off of water. Theoretically the energy usage should then be higher due to the introduction of colder water into the water mass. Thus allowances should be made for increased energy usage. Notwithstanding that, the standards of the United States and Canada are still stricter than those of the South African Government.

2.2.7 Other Countries

Countries with generally colder climates such as Germany and the United Kingdom take the space heating into account in their methodology and calculations of the standing losses, as with France. It is therefore challenging to extrapolate a formula that only calculates the standing losses for the electric storage water heaters due to the fact that they are constantly being used. A large portion of the population of those countries use instantaneous water heaters, gas, electric or otherwise which do not incur any standing losses as there is no body of water in storage.

In Austria the responsibility for energy efficiency and performance has been divided at a regional level. The investigation done by Van Holsteijn en Kemna [27] did multiple studies on the existing legislation but couldn't find any transcripts regarding the maximum permissible standing losses for electric storage water heaters.

As with France, German households implement in-house water heating systems. But they have their own efficiency policies in place, e.g. DIN 4701-10; 2003 [41], which covers the efficiency of electric storage water heaters relative to floor space and is also used in the 'Energieeinsparverordnung', the Energy Saving Regulation. A correction is additionally included to correct for the solar load contribution or correction [27].

The Swedish Government hasn't focused much on water heaters in their efforts to promote the Nordic Swan Eco-label since gas, oil fired and electric storage water heaters are not common in the country. The populace derives its heat from heat pump water heaters as well as district heating.

2.2.8 Overall Comparison

From the study on the MEPS levels of the different developed countries in regions across the world it is evident that the South African legislation in place to regulate the energy consumption of water heaters is inefficient and ineffective when compared to the other MEPS levels. Figure 2-5 displays the maximum permissible standing losses per 24 hours in terms of the volumes of water heaters covered in the studies completed thus far.

A general trend can be seen where most of the developed countries are grouped towards the bottom of the spectrum. A clear outlier can be seen trending above all the others. This represents the South African MEPS levels currently in place in the legislation.

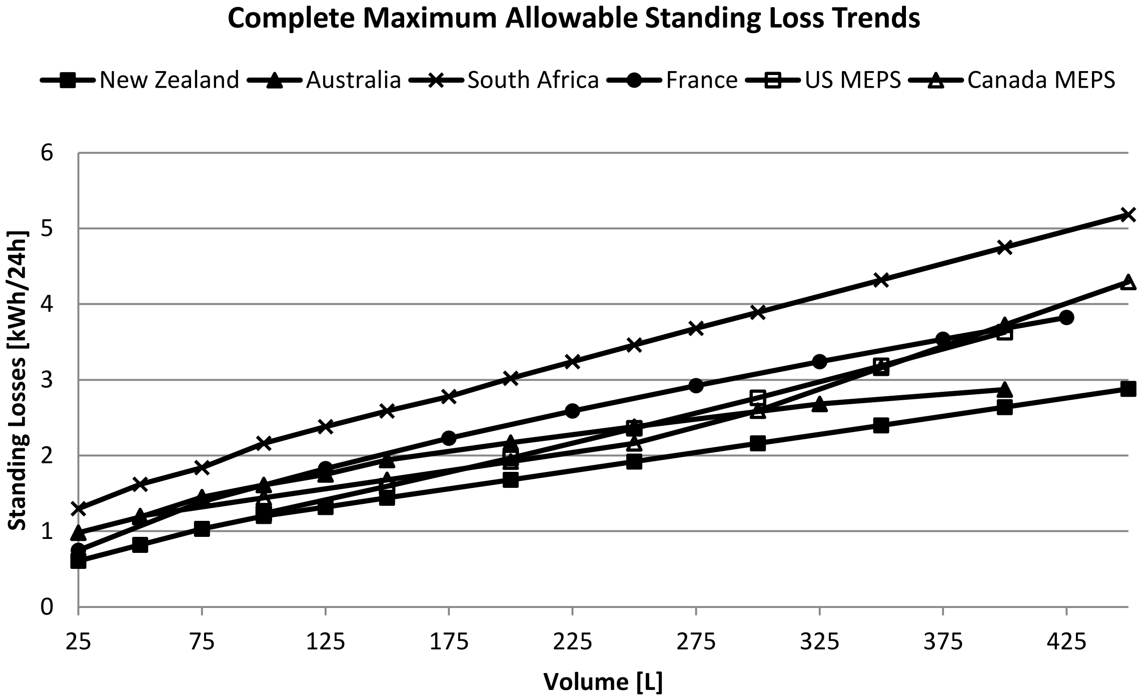


Figure 2-5: Overall comparison of the MEPS levels of all the above mentioned countries.

This result indicates that the legislation in South Africa must be addressed and rewritten to conform to international standards. This will open up the market to imports and exports of water heaters to other global markets that are otherwise closed. It would also grant South Africa greater market stability and a greater customer base [42] as well as relieving some of the load on the economy's power sector.

If all the evaluated MEPS levels are assimilated on the suggested CECED A-G rating, a general idea is formed as to how far the country has developed in terms of the existing legislation and waste consciousness.

For the most part the standards in place insure that for lower volumes the MEPS level is within the A – C range, all apart from South Africa. As the volume increases the allowances become more lax. With a greater volume the issue of a greater surface area of water is encountered and better insulation methods need to be put in place.

It is evident that the results in Figure 2-6 show that South African legislation is behind when compared to other countries in the study. When compared to the CECED MEPS levels for vertically mounted water heaters it is seen that most countries are above the CECED importing standard for lower volumes but this improves as the volume increases. All improve with the exception of South Africa.

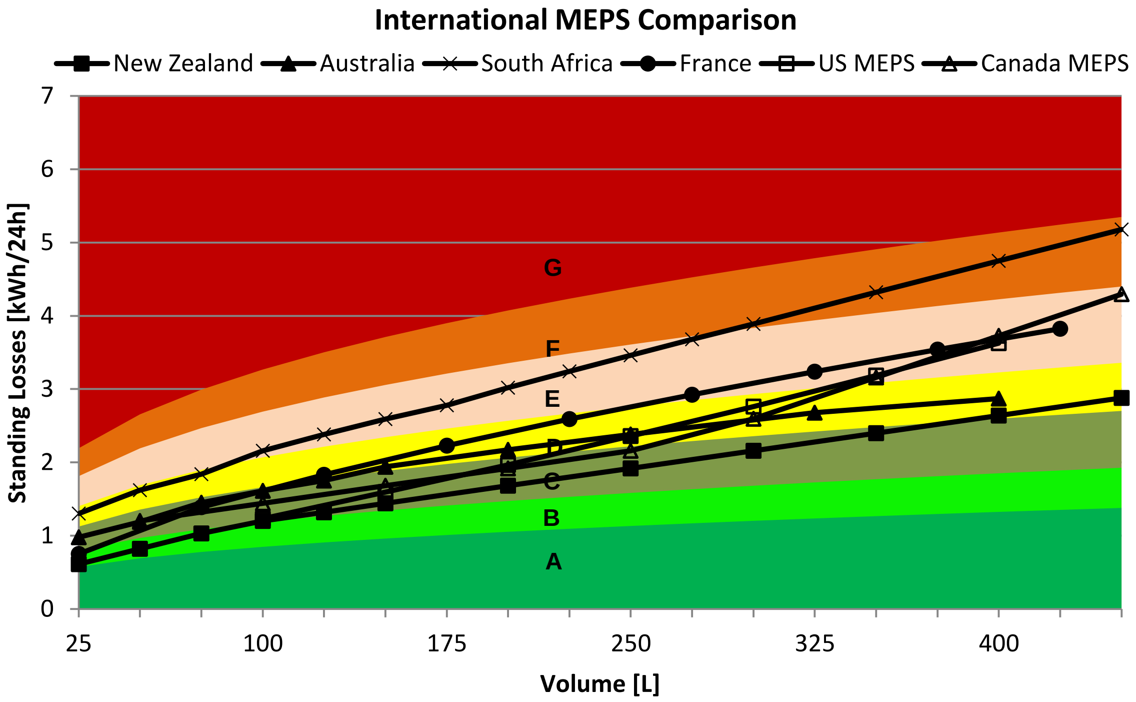


Figure 2-6: International MEPS comparison compared with the suggested european commission's A-G rating.

The importing standards of the CECED seem to be realistic and achievable by most countries. This gives rise to the following question: Does a water heater produced in South Africa conform to the South African Standard and if so, is it possible to look to overseas markets to improve the industries global market share and bring foreign investment into South Africa?

2.3 Measurement Technologies

The standards discussed above all require temperature to be monitored. The hardware needed to achieve this must be accurate in order to avoid data loss and false data collection. The range of temperature sensing equipment on the market is extensive, and calls for a study to be done on materials and sensing methods used. The main contenders are thermocouples, thermometers and Resistance Temperature Detectors (RTDs).

2.3.1 Temperature Sensing Technology

Thermometers rely on the expansion of gas or mercury to measure temperature differences in relation to ambient temperature. Either that or using a combination of two metals that expand at different gradients using the expansion coefficients of the metals.

Thermocouples use two different materials to produce a voltage that can be used to determine the temperature. A higher temperature results in a higher voltage output and is usually measured in millivolts. Thermocouples are used for different purposes and have additional measures and redundancies built in to minimize error. These consist of compensation wires and or duplicate wires. One of the more commonly used thermocouples is the Pt100 consisting of platinum with a resistance of 100 Ohms at 0 °C. The platinum is mechanically and electrically stable in relation to time. The output voltage is more linear than other metals [43] [44]. Thermocouples are used more widely due to their reliable nature and because of cost savings.

RTDs operate by using different materials that achieve different resistances at temperatures within its operating range, higher resistance at higher temperatures and lower resistance at lower temperatures. This change in electrical resistance enables the user to measure temperature. Although these are more accurate, stable and linear than the thermocouples they have a more limited range, cost substantially more and do not boast the same sensitivity as their counterparts [43] [44].

For the purposes of this investigation accurate data will be needed but cost is a limiting factor. The thermocouples seem to offer a balanced package with regards to price, accuracy and stability.

2.3.2 Data Capturing Mechanisms

The most limiting factors when choosing a data capturing method are cost and availability. Secondary to that come stability and reliability. On the South African market the product range is limited to but a few.

Sefram, based in France, is one of the suppliers of data loggers. Their products are usually hand-held devices and only support 4 channel modules such as thermocouples with compensation wires and duplicate wires. This allows for high accuracy and substantially more reliable data capture. The devices are however limited to recording data on an internal hard drive and come at high prices [45] [46] [47].

Pico Tech is based in the UK and supplies analysers, oscilloscopes and data loggers. One such product is the 4 channel temperature data logger PT-104 that communicates over an Ethernet cable. These modules can be daisy-chained up to 20 modules to a single PC. It supports 2, 3 and 4 wire sensors guaranteeing flexibility. The price for a single module is quite reasonable but the limiting factor is that only a single thermocouple can be attached to one module. The costs involved in purchasing multiple modules exceeds the budget [48] [49].

One of the more established firms on the global market is National Instruments (NI). They have a leading market share in most engineering related projects. Additionally the cost of their products is competitive. The products on their site are flexible, are able to support 2, 3 and 4 wire sensors and have built in noise rejection. The modules are robust and can withstand vibration, as well as low and high temperatures. A single module can either support 4 or 8 channels and therefore is the more reasonable option. However, to support the module, a chassis is needed, and that causes an additional cost. The 4 channel module costs the equivalent of a single channel pico Tech module, thus making the NI module more attractive.

In addition, the chassis that the NI module requires has docking ports for multiple modules thus allowing for a scalable project. Should any additional probes be needed, they can be added at will. The available chassis include one with an Ethernet port an one with a USB port. Due to the nature of the network, it being very unreliable, the USB chassis will be chosen. It will be connected to a laptop in the test chamber and record the temperature data to its drive.

2.3.3 Data Capturing Software and Modules

The software used to capture the data from the module itself will be a Labview Virtual Instrument (VI), should the NI module be chosen. It can export the captured data to an excel spread sheet where it can be analysed and manipulated to show the results needed for this investigation. Other analysis tools include those built into MathWorks MATLAB, a powerful software capable of processing and analysing large amounts of data. Most modules are compatible with Microsoft Excel. Any additional data analysis can be completed through extracting the data from excel. The data that is extracted can then be used to calculate the standing losses of the water heater.

In the event of data loss during the test, the procedure would have to start again.

2.4 Water Heater Insulation Grading

Another method of determining the standing losses of a water heater is to use the R-value or thermal resistance to calculate the standing losses.

The R-value is a value that signifies the heat insulation property of a material. If the temperature differential is divided by the R-value, the results will represent the rate of heat transfer per unit area of insulation [50]. The higher the R-value is the more the unit or material is able to insulate. The lower the R-value, the more heat is lost.

Most manufacturers of water heaters do not disclose the R-value for their respective water heaters. This may be due to a poor manufacturing process or uncertainty due to impurities or contaminations in the insulation. Instead they prefer just to release the energy efficiency of the water heater through methods such as energy labels [51].

The first law of thermodynamics states that energy cannot be created or destroyed; it can only be transformed from one form to another [52]. Thus the energy conversions in a water heater must proceed with a certain hierarchy:

> Energy is introduced to the water in the form of electric current flowing through a resistive element. The water absorbs that energy from the element in the form of heat. If the water heater were perfectly insulated there would be no heat loss. Hot water would be drawn off and all the energy from the element would be transferred to the user at the other end of the system (even then the user would only receive all the energy if the conduit for the water were perfectly insulated). Unfortunately this is an imperfect world and this is where the second law of thermodynamics comes into play.

The second law of thermodynamics states [52]:

“In a natural thermodynamic process, there is an increase in the sum of the entropies of the participating systems.”

In layman’s terms, with regards to water heaters, the second law requires that the heat must flow from the direction of the higher temperature to lower temperature [50]. Thus the heat will flow through any heat conductive materials to a region of lower temperature. In the case of the water, the heated water will transfer its energy to the colder water. The insulation around the water heater is another conduit and may have a large influence on the heat losses due to impurities in the insulation, or flaws in the manufacturing process. This leads to uncertainty in the industry with regards to test results, and larger losses and waste energy.

Nevertheless there is a temperature differential over the insulation of the water heater. The equations used to determine the standing losses need the following information:

- The R-value of the insulation.
- As an approximation, the surface area of the inside of the water heater. This is chosen to simplify the equation and to limit the number of dependant variables.
- The temperature difference between the ambient temperature and the temperature inside of the water heater.

The temperature difference can be measured. For theoretical purposes an internal temperature of 65 °C is used. For the ambient temperature 20 °C is used.

The surface area of the insulation inside the water heater is simple arithmetic. The volume of the water heater and the height of the cylinder are known. From this the diameter can be deduced.

As the majority of manufacturers do not disclose the R-value of their products, it can instead be reverse engineered from the measured standing losses. The R-value gives a good indication of the quality of the insulation of the water heater. The lower the R-value is, the lower the quality of the insulation.

Using the second law of thermodynamics, it can be deduced that the heat transfer is inversely proportional to the temperature gradient over a certain surface area through which the heat is transferred. The seventh edition of Principles of Heat Transfer describes this principle using the following sets of equations [50]:

$$q_k \propto (A)\left(\frac{dT}{dx}\right) \qquad 2.4.1$$

where q_k denotes the heat transferred by conduction [W], A denotes the surface area that the heat transfer occurs across $[m^2]$ and $\frac{dT}{dx}$ denotes the temperature gradient across the material [K].

Another way of writing this is by including the thermal conductivity of a material k in [50]:

$$q_k = (-\mathrm{k}A)\left(\frac{dT}{dx}\right) \text{ [W/m K]} \qquad 2.4.2$$

Multiplying both sides by dx, dividing both sides by A and then integrating from one side of the medium where the hot temperature is to the other side of the medium where the cold temperature is leads to the following equation [50]:

$$\frac{q_k}{\mathrm{A}}\int_0^L dx = -\int_{T_{hot}}^{T_{cold}} k\, dT \qquad 2.4.3$$

$$q_k = \frac{\mathrm{Ak}}{\mathrm{L}}(T_{hot} - T_{cold}) = \frac{\Delta T}{L/Ak} \qquad 2.4.4$$

The term L/Ak is equivalent to the thermal resistance R of the medium:

$$R = \frac{L}{Ak} \qquad 2.4.5$$

As q_k is measured in watts the standing losses can be attained by multiplying the heat transferred by 24 hours. The result is a kWh value.

In industry the R-value referred to earlier represents the thermal resistance per unit of area. Thus it only takes the thickness of the insulation medium and the average thermal conductance k into account [50]:

$$Standing\ Loss = \frac{A\ (\Delta T)}{R}. \tag{2.4.6}$$

This equation is quite versatile and can be used to calculate the standing losses for various water heaters of different volumes.

As mentioned before, the issue comes in though that the R-values are not readily handed out by the manufacturers. Thus the above equations can be used to attain the R-value for selected water heaters if the standing losses are already calculated.

Some water heater manufacturers displace the water tank slightly lower within the outer barrel and then fill the gap with insulation. This gives rise to the insulation not having a uniform thickness in the vertical plane.

The calculations will only yield an average R-value for the water heater:

$$R = \frac{A\ (\Delta T)}{Standing\ Loss}. \tag{2.4.7}$$

Equation 2.4.7 shows that the R-value is inversely proportional to the standing losses. Higher standing losses give rise to a smaller R-value. This concurs with the earlier statement that a larger R-value will give rise to lower standing losses.

2.5 Thermodynamic principles in fluid flows

If the insulation is ignored and the issue is looked at from an ideal point of view then a better understanding of the thermal behaviour inside the water mass is needed. This understanding is needed in order to gauge where the heat losses occur and how best to mitigate them. An understanding of the following principles is required:

Reynolds Number (Re): The Reynolds number is a dimensionless quantity used to predict similar flow patterns in various fluid flow problems when flowing past a body or duct [53]. With regards to this investigation the Reynolds number is used to classify different flow regimes within water such as laminar and turbulent flow.

- Laminar flow occurs at a low Reynolds number and characterises a smooth, constant fluid motion throughout the body of water.
- Turbulent flow occurs at higher Reynolds numbers where inertial forces play a large role in the fluid. Typically in such a situation, instabilities occur, leading to eddies and vortices. This shouldn’t apply to this investigation but changes to the simulation geometrics could lead to different flows with eddies and vortices.

Prandtl Number (Pr): The Prandtl number is a dimensionless unit describing the relationship between momentum diffusivity or kinematic viscosity and thermal diffusivity. It is used in heat transfer problems and forced convection calculations, and in the case of the investigation will be used in the analysis of the simulations.

Peclet Number (Pe): The Peclet number describes the transport phenomenon in a continuum and is described as the ratio of the rate of advection (the conserved property by a fluid due to its bulk motion) of a given quantity to the rate of diffusion of the same quantity driven by the appropriate gradient. In thermal fluids it is equivalent to the product of the Reynolds number and the Prandtl number.

Grashoff Number (Gr): The Grashoff number approximates the relationship between the buoyancy of a fluid to the viscosity of that same fluid and is often used in the study of natural convection. In the case of this investigation it will be used to analyse the natural convection inside the water heater while the element is on.

Nusselt Number (Nu): In investigations involving fluids the Nusselt number describes the conductive to convective heat transfer normal to the boundary. A Nusselt number close to one, describes slow or laminar flow, whereas a larger Nusselt number is more descriptive of turbulent flow [54]. With regard to this investigation the Nusselt number close to the boundary of the water heater would be closer to one, whereas the Nusselt number closer to the element would be much larger.

Biot Number (Bi): The Biot number is likewise a dimensionless number or ratio determining the heat transfer resistances inside and on the surface of a body. A higher Biot number implies that the heat conduction is much slower and takes time whereas a smaller Biot Number indicates good heat conduction [55].

Rayleigh Number (Ra): The Rayleigh number refers to a dimensionless number that is associated with buoyancy driven flow, also known as free or natural convection. Each fluid has a critical value. If the Rayleigh number is below the critical value then heat conduction takes place whereas if the value is above then convection occurs [54].

The Rayleigh number is used in calculating Rayleigh-Bénard Convection and is defined as the following [54]:

$$R_{a_x} = \frac{g\beta}{\upsilon\alpha}(T_s - T_\infty)x^3 = Gr_x Pr \qquad 2.5.1$$

where R_{a_x} denotes the Rayleigh number, g denotes acceleration due to gravity, β denotes the thermal expansion coefficient, υ denotes the kinematic viscosity, α denotes the thermal diffusivity, T_s denotes the surface temperature, T_∞ denotes the temperature of the fluid far from the surface and x denotes the characteristic length of distance from the leading edge

Another simpler form of calculating the Rayleigh number is by multiplying the Grashof number Gr with the Prandtl number Pr [54]. The number is used in some software packages and is calculated with each iteration for each element in the mesh.

The above numbers are used in some of the following principles and equations:

Navier-Stokes Equations: The Navier-Stokes Equations describe the flow of viscous fluid substances by applying Newtons second law of fluid motion. The equations make use of the diffusing viscous term and the pressure terms to describe the stress in the fluid.

Rayleigh-Bénard Convection: Rayleigh-Bénard Convection is the more researched phenomena and describes a natural type of convection or instability that occurs in a horizontal layer of fluid heated form below where regular patterns form, known as Bénard cells. This is due to differences in density in hot and cold water and the resulting movement in the body of water [56].

The Rayleigh-Bénard instability takes into account the varying densities in the mass, as well as the force of gravity. Due to the use of these two aspects in the fluid, it also takes into account the varying viscosity of the water and the damping forces involved with the movement in the water mass. The balance of the two forces discussed above give rise to the Rayleigh Number as is discussed earlier in this section.

And for boundary Conditions used in the investigation of convective effect in the water heater:

Dirichlet Boundary Condition: A Dirichlet Boundary Condition specifies, in a partial differential equation, the values that the solution needs to take along a boundary. It is also known as a fixed boundary condition (i.e. the values do not change). In the investigation it is used to specify zero velocity and pressure on certain elements in the matrix of elements used in the mesh.

Neumann Boundary Condition: The Neumann Boundary Conditions are used to describe second order boundary conditions that describe principles such as heat flux and dissipation of power. In the case of the investigation it will be used to impose a heat flux on the boundaries to signify the losses through the isolating materials on the water heater should the ideal case not be sufficient in shedding light on the thermal behaviours inside the water heater.

The above principles are all used to describe the thermal response inside the water heater during operation. As the simulations of the water heater give a general idea of what occurs inside the water heater, the principles can be applied to the results in order to achieve a greater knowledge of what occurs behind the aluminium and foam.

Other phenomena include, but aren't limited to the following:

Rayleigh–Taylor Instability: Rayleigh–Taylor Instabilities occur when different density fluids interface with one another and the lighter fluid pushes the heavier fluid. Examples of this are, when water is suspended above oil in the gravity of the earth, or mushroom clouds seen in volcanic eruptions and nuclear explosions. [57] This applies to the investigation as follows: when less dense warm water rises from the element it will push on the more dense colder water creating a different pattern in the flow of the water heater. Should this be encountered though, it can be easily identified.

Oberbeck-Boussinesq Approximation: The Boussinesq approximation is used in the buoyancy driven flow field. It can be used in instances where the density differences ΔP in the fluid are small enough to be neglected, except when multiplied by g, the acceleration due to gravity [58]. It simplifies the mathematics involved in convection calculations and helps minimise the time and memory used in the simulations, if used by the program. In water heaters, the temperature differences are quite substantial when not at steady state and thus this approximation would not hold in start-up conditions. However once the water heater has stabilised the approximation can be used.

2.6 CFD Software for Dynamic Simulations

Multiple Software packages that are capable of simulating Computational Fluid Dynamic (CFD) problems are available on the market. These include open source programs as well as expensive software packages. Any advantages and disadvantages are explored in this section with a view to identify the program best suited to carry out the simulations. For the purposes of this investigation a model would have to be built using a combination of heat transfer principles and fluid flow analysis.

OpenFoam: OpenFoam is a Linux driven open source CFD software package developed by OpenCFD Ltd. and encompasses a large variety of tools allowing it to solve complex engineering problems from chemical reactions to electromagnetic simulations as well as heat transfer simulations [59].

For the purposes of this investigation OpenFoam offers graphical solutions in two dimensions but does offer planar views and solutions to 3 dimensional spaces as well as pointwise graphical feedback. As it is also Linux based the author would've had to learn how to use a new operating system before being able to completely use the software to its full potential.

ANSYS Fluent: ANSYS fluent is easily able to model flow, turbulence, heat transfer and reactions for industrial purposes from combustion to bubble columns. The software has a costly licence but comes with thorough support and software packages [60]. The modelling is simple but the learning curve involved in getting to know the software is steep.

At the time of the study, the university owned licences for the student version of ANSYS fluent. This limited the available mesh size so that only rudimentary models could be simulated.

Rhinoceros 5: Rhinoceros is a CAD program used to model the water heater and build the mesh. It can create, edit, analyse and render, animate and translate surfaces, surfaces and solids [61]. It was used to generate the mesh structure for ANSYS and other programs offering support for third party CAD models to be imported for further analysis.

ELMER: ELMER, just like OpenFoam, is an open source program that has the ability to model fluid dynamics, structural mechanics, electromagnetics and heat transfer amongst others. It is compact and easy to use but for this investigation a combined model of thermal behaviour and fluid flow is needed. ELMER does not offer support for combined models so this software is not used.

MathWorks MATLAB: MathWorks MATLAB is a high level language and interactive environment used to explore and visualise ideas in fields that do image processing, signal processing and control systems [62]. Once the equations for the different convection principles are identified, simplified and adjusted to fit the water heater model, they can be programmed into MathWorks MATLAB and from there a visual graphic can be displayed showing the behaviour of the fluid inside the water heater. This program includes an animation feature, thus the simulation can be viewed as calculations are made.

Energy 2D: Energy 2D is an interactive visual metaphysics simulation program that models all three mechanisms of heat transfer: conduction, convection and radiation. Because it is very compact, it runs very smoothly on most computers [63]. The simplicity is more aimed at exploratory investigations into fluid dynamics and hasn't got the built in features of some of the larger programs needed to do this investigation. In addition, pointwise investigations inside any model aren't available.

Another concern is that because Energy 2D is only capable of modelling 2D models any simulation model would have to be symmetrical around its centre making this program unsuitable with regards to this investigation.

COMSOL Multiphysics: COMSOL Multiphysics is a general-purpose software platform, based on advanced numerical methods, for modelling and simulating physics-based problems. It incorporates tools that competently handle problems in fields such as electrical, mechanical, chemical and fluid flow domains. Because it can integrate the heat transfer principles with fluid flow principles this software package is best suited for this investigation. [64] COMSOL makes use of the Bussinesq approximation as well as the Navier-Stokes Equations.

The package also allows for CAD models to be built with ease making Rhino 3D obsolete for this program. Thus no alternative model needs to be imported.

The programs above are some of the more commonly used software packages on the market used by industry and academics alike. Another program that is used is EZ Solver but it has no graphical outputs. The results could be exported to MathWorks MATLAB but that would defeat the purpose of using the latter.

2.7 Summary

This chapter covered the history of water heaters and the evolution of the designs that lead to the current design of electric storage water heaters. It also explained why the water temperature inside the water heaters is set at a higher temperature, namely to minimise the effects of any residual bacteria found in the water that could be harmful upon consumption.

Once water heaters were explained, this chapter had a look at the current standards in place to limit the energy usage in residential water heaters. It explored the legislation in place that describes the testing strategies used, as well as the MEPS levels dictated by each country throughout the global market. It established an understanding of the global standing loss levels and compared them with the South African MEPS levels. Upon further inspection the South African MEPS levels were found to be poor when compared with other developed countries.

Other temperature data capturing mechanisms were explored. One was chosen over the others due to the support structure in place in South Africa as well as its accuracy and cost, which were found to be very competitive.

One of the aims of the paper is to grade water heaters on their standing losses over 24 hours. One of the largest contributing factors to mitigate those standing losses is the insulation which was also explored in this chapter. A method is established to attempt to grade the water heaters. This is done to calculate the heat loss through the insulation based on the standing losses, the total surface area and the differential in temperature.

To understand how the heat is distributed in the water heaters, an understanding of fluid flow theory is needed. This information will be used to analyse the simulation output from the program chosen in the last part of this chapter.

3 Testing Methodology for Standing Losses

3.1 Overview

The previous chapter compared international MEPS levels and standards but didn't give the insight needed to complete the SANS 151 test methodology. This chapter covers the test procedure used in the standing heat loss analysis, as well as the specifics involved with the testing arrangement and surrounding locational logistics in section 3.2. It also discusses the measuring arrangement used to record the data in section 3.3, followed up by a step by step description of how the data is analysed as discussed in section 3.5.

Section 3.6 covers the heat loss analysis to identify the problem areas associated with each water heater. How to finish off a tear down analysis is described in section 3.7 in order to better grasp the internal mechanisms of the water heaters.

3.2 Test Arrangement

The testing methods for the water heater analysis are stipulated in the SANS 151 Standard. It specifies the conditions of the testing area, the water supply and the orientation of the water heater.

3.2.1 Atmospheric Conditions

The testing area must be organised according to the following criteria:

The air temperature of the test room is controlled at (20 ± 3) °C. Air circulation in the test room is sufficient to ensure reasonably uniform temperature distribution, but causes no direct draught on the water heater under test. The water heater is so placed or shielded that it is not affected by radiation to or from cooling or heating equipment or outside windows [20].

The chamber supplied by the University of Stellenbosch is an environmental chamber used by the university to test insulators in misty conditions. The square room's floor space is 36m² and is built with a double brick wall which provides good insulation from the exterior. The only variables in the room that might impact the ambient temperature are a circular cavity in the wall 30cm in diameter opening to the outside, where the water pipes will be fed in, a 3m x 1.5m glass panel to an observation room and the wooden doors that open to the outside. The observation room is temperature controlled, thus the effect of the observation room can be minimized. The double doors to the chamber enter from the outside so care will have to be taken not to leave the doors open for too long when changing the arrangement and monitoring the tests. The doors consist of wood which is not very heat conductive.

The circular cavity will be insulated with polystyrene sheets. This will not be as effective as the brick wall but it is a good substitute. The cavity cannot be plugged with anything permanent as the room is also used for other purposes.

Another concern is the drain hole that is fed out of the room, but as the chamber shall be kept closed at all times and there will be no circulation of air, the effect of the drain hole should be minimal.

In order to facilitate accurate ambient temperature measurements and compensate for air circulation, a variable speed fan will be used to equalize the temperature throughout the room.

A portable oil filled heater will be used to regulate the temperature in the room so that the tests will comply with the SANS 151 document.

3.2.2 Water Supply

The water is supplied by the municipality. The conditions for the water supply are stipulated as follows:

The cold water temperature θ C for the tests is (20 ± 3) °C and the water is supplied from a source that gives a steady pressure head. The pressure is adjustable to the values appropriate for the different water heaters. The feed pipe has a controlling stopcock capable of adjustment to give, at the outlet of the water heater [20].

The municipality water supply has a pressure greater than that of the rating of the water heater which is sufficient if the test is done with a pressure regulator. The water heaters tested are rated for two different pressures, namely 400 kPa and 600 kPa. The aforementioned pressure regulators are used to adjust the pressure to "*the values appropriate for the different water heaters,*" preventing any damage from occurring [20].

The inlet pipe for the water heater is fed from a water pipe on the outside of the room. The room does not have a water source itself. The pipe has a stopcock built in so that when the arrangement of the test is changed, the water flow can be halted so that the room won't flood. However, the water heater will not have a hot water pipe attached to the hot water outlet so that no heat losses will occur due to heat transfers in the pipe.

3.2.3 Water Heater orientation

In order to get the right measurements for the inlet pipes, the orientation of the water heater is considered. According to SANS 151 document, the orientation of water heaters intended for a wall or floor mounting must adhere to the following:

A water heater intended for wall mounting is mounted on a panel situated at least 150 mm from any structural wall. It is so positioned that there is a clear space of at least 250 mm above and below the water heater and at least 700 mm at the sides and front. A water heater intended for floor mounting is mounted on the floor or on any stand supplied with it. A false floor may be used to facilitate measurements [20].

To mount the water heater horizontally, it is affixed to a wooden board that is fastened to a stand that conforms to the above requirements. This assists in the acquisition of measurements as it is elevated to the height of the measuring equipment. For the wall mounting of the water heater, a frame is used. The feet of the water heater are fastened to two crossbeams that are secured to two L- shaped struts on either side that are in turn bolted to the stand. Care must be taken to insure that the water heater is placed at the specified distances from structural walls and that the clearance spaces are all up to Standard as defined in the SANS 151 document.

3.2.4 Piping

In order to minimise the heat losses of the piping to the water heater the following guidelines are used. The pipes feeding the cold water to the water heater are copper pipes up to a point one meter away from the water heater. Attached to the copper pipe is a pressure control valve to insure the water pressure to the water heater does not exceed specifications.

The pipe following the pressure control valve is a polycop (PVC) pipe of a length greater than one meter. To feed the polycop pipe to the water heater cold water inlet, a brass fitting is used. On the hot water side of the water heater a brass pipe cap will be attached to minimize the losses incurred if there were a pipe.

The normal installation of a water heater involves the installation of vacuum breakers on both the cold water and the hot water side of the water heater. The purpose of vacuum breakers is to prevent water from being drawn back into the cold water supply should the pressure there drop or the supply be turned off [65]. The test is done without a hot water pipe so that when the water expands when heated, the pressure in the water heater will exceed that of the cold water supply. Thus the expanding hot water in the water heater will have no pipe to go through and eventually the water heater will rupture or burst. Therefore the test configuration will forgo the vacuum breakers and leave the cold water supply pipe open to compensate for the expansion of the water in the water heater.

The brass pipe caps and pipe joints incur heat losses as a result of the hot water circulating around the water heater and going into the pipes. Thermal insulation is used to minimize the energy lost through heat conduction and dissipation through the brass joints. The insulation over the joints is secured with packing tape to insure all exposed heat conducting surfaces are adequately insulated.

The SANS 10254 document indicates on multiple occasions that the standard installation of a water heaters involves a drip tray to catch any "*leakage from the storage water heater and its ancillary components*" that could cause harm or damage to the property or area around the water heater [20]. Because the chamber has a chemical resistive floor any leakage or discharge from the water heater and its auxiliary components won't damage any property around the water heater. The only concern is the measuring equipment that is placed adjacent to the testing arrangement. The blow-off valves are directed away from the measuring equipment to minimise their exposure to any water.

3.3 Measuring Arrangement

3.3.1 Efficiency test Requirements and Recommendations

In order to choose the right testing equipment it is important to define what is to be tested. The SANS 151 document lays out the guidelines for the testing. For the temperature measurement over a period of 48 hours, the ambient temperature in the vicinity of the water heater is continuously recorded, as well as the temperature inside the water heater, at the hot water outlet and cold water inlet. The guidelines also state the assumption that the controller temperature used in equation 3.5.1 is 65,0 °C. For better results, a thermocouple is placed near the controller thermocouple to measure what temperature the temperature controller is observing.

Once the test is underway and the water heater has stabilised, the SANS 151 document states, to *"use the kilowatt-hour meter at the next cut-out of the thermostat to determine the energy consumption* E_1 *in kilowatt-hours over the next minimum 48 h.*" [20] The average ambient temperature of the 48 hour period where the energy consumption is measured, is to be used in equation 2.2.1 to then calculate the standing losses of the water heater in that interval.

3.3.2 Instrumentation

The apparatus recommended by the SANS 151 document are as follows:

- Thermocouples,
- Thermocouple Recorder,
- Kilowatt-hour meter,
- Temperature Controller,

- Calibrated flow-rate meter and
- Chronometer

The thermocouple recorder is used to record and store the temperatures measured by the thermocouples. As the thermocouple recorder is connected to a computer with a clock that is synced to the kilowatt-hour meter, a chronometer is not necessary in this test.

The ambient temperature as well as the water heater temperatures are all measured with PT100 Resistance Temperature Detectors (RTD) that are connected to a Thermocouple recorder. The thermocouple recorder used in this test is the National Instruments (NI) 9217 module. The NI module is in turn is installed in a NI cDAQ-9184 chassis. The NI chassis is a 4-Slot Ethernet NI CompactDAQ Chassis and is connected via an Ethernet channel to the Labview software on a Computer. In the Labview Software a Virtual Instrument (VI) is used to record the samples on the Computer in binary format.

The only way measurements of the water temperature in the cold water inlet and hot water outlet pipes of the water heater can be taken is, if the piping and joints are altered to allow for holes through which the thermocouples can be inserted into the water heater. An alternative option is to attach thermocouples to the copper pipes at the inlet pipe but this does not reflect the inside temperature of the water heater and is very vulnerable to ambient temperature. Holes are drilled through the side of the brass joints closest to the water inlet and outlet fittings of the water heater and a ¼ copper pipe in inserted into the hole. The copper pipe is secured by brazing the pipe to the joint. The thermocouple is fed through the pipe and glued to the end of the pipe with two-component glue. This allows for accurate measurements of the water temperature inside the water heater.

The water heaters come shipped with a standard temperature controller. Not enough information about the stock controller is given. Therefore a custom temperature controller is used in order to insure the controller temperature is kept within the range specified in the SANS 151 document i.e. a water temperature of 65 °C ± 1.5 °C. This modification in turn allows for a more controllable input to the water heater and allows for easier monitoring during the testing.

The custom controller used in the test is an RKC Instrument INC. CB100 Digital controller. The controller was used in the on/off control type configuration. Other control methods are available but when tested the overshoot of the controller was out of range of the rated temperatures of the water heater. Should these control settings be used the water heater might explode.

The temperature was acquired using a PT100 RTD inserted into a casing meant to house the temperature gauge of the standard water heater temperature controller. Heat paste is used to ensure proper heat conduction to the thermocouples. The element of the water heater is connected to the temperature controller via a FOTEK Solid State Relay SSR–25AA. No custom element is used since the element design for each water heater differs.

A calibrated flow rate meter is not used in this instance because the water heater is connected as a dead-end system (a blockage is fastened to the hot water side of the water heater). The only flow inside the water heater, and through the pipes, occurs when the water expands when it is heated.

An accurate measurement of the power used by the water heater is achieved using an AMSO PowerTrack Energy Analyser and verifier. The average power consumption is measured over consecutive 30 second intervals.

Table IV: Equipment used in the investigation.

Summary of Equipment		
Temperature measurement equipment		
Thermocouple recorder	National Instruments cDAQ-9184 4-Slot Ethernet CompactDAQ	4-Slot Ethernet
	National Instruments 9217 module	4-Channel 3-4 wire analog RTD input 30s sampling without averaging
Thermocouples	Pt100 Resistance Temperature Detectors	3-wire 100Ω Platinum Resistance Temperature Detector
Temperature control equipment		
Temperature controller	RKC Instruments CB100 Digital Controller	On/Off Control. 0.5V peak control band. Continuous Sampling.
	Pt100 Resistance Temperature Detectors	3-wire 100Ω Platinum Resistance Temperature Detector
Power measurement equipment		
Kilowatt-hour meter	AMSO PowerTrack Energy Analyser and Verifier	30s sampling rate with averaging

A block diagram of the testing arrangement is shown in Figure 3-1. It shows the entire arrangement as well as the temperature control feedback loop, where the power to the element is controlled via the custom temperature controller that receives its input from the thermocouple placed inside the thermostat sleeve.

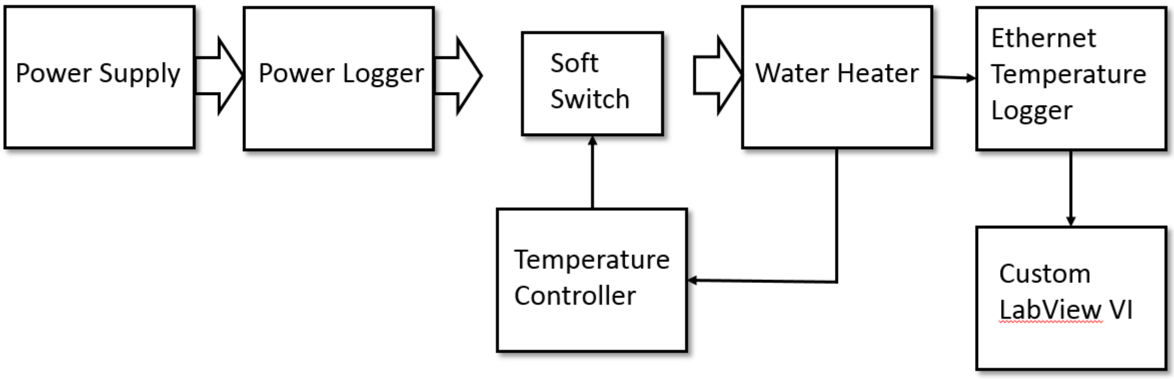


Figure 3-1: Block diagram of testing arrangement

3.4 Testing Strategy

Guidelines for the standing loss test of a water heater are set in the SANS 151 document. They cover a range of water heaters including solar water heaters including those that are not fitted with immersed heating elements. The guidelines are as follows:

"*Fill the water heater with cold water and then operate it with the temperature controller at the maximum rated voltage input of its heating element for a period of not less than 24 h. Thereafter, after the next thermostat cut-out, without withdrawal of water, use the kilowatt-hour meter to determine the energy consumption E 1 in kilowatt-hours over the next minimum 48 h, and determine the mean ambient temperature θ amb in degrees Celsius* " and "*Take the controlled water temperature to be 65,0 °C*" [20].

The test is done following these guidelines with a few minor alterations that will become evident in the summary of the test hierarchy to follow.

- Once the water heater has arrives the preparation work begins:
    - All water heater pipes are cleared.
    - The thermocouple and contacts of the element are modified to incorporate the custom temperature controller.
    - Heat paste is lathered on the inside of the water heater thermocouple pocket.
    - Thread tape is wound around the inlet and outlet pipes of the water heater (only if the pipes are male). If the inlet and outlet are female then the thread tape is wound around the straight couplers thread.
- The water heater is mounted on the testing structure and fitted with pipes:
    - The feet of the water heater are bolted to a wooden board that is in turn fixed to a frame intended to lift the water heater off the floor and assist with measuring.

  - If the test means to investigate the vertical standing losses the water heater is mounted on a steel frame and erected on the frame.
  - The pressure release valves and the modified elbows / stops are attached to the relevant pipes. The Hot water pipe cap is only tightened to the water heater after the water heater has been allowed to fill.
  - A plastic pipe is coupled with the inlet of the water heater in such a way as to allow water to come up to the elbow and then into the water heater. This generates a heat-well that doesn't allow hot water to flow back into the cold water pipe and minimizes heat losses..
  - A pressure control valve is adjoined to the plastic pipe. The pressure control valve is rated at the same pressure of the water heater to prevent bursting or rupturing of the water heater.
  - The cold water supply is then coupled with the pressure control valve via a stopcock.
- The stopcock is opened and water is allowed to flow into the water heater:
  - Once the water heater is full the stopcock is closed and the hot water pipe cap is tightened.
  - Any leaks found are dealt with as soon as they occur. Should a leak prove too challenging to repair or plug the water heater is drained and alternative sealing methods are explored.
  - Once the hot water pipe cap is fastened the stopcock is once again opened and the pressure is allowed to stabilize.
  - If any more leaks are found they are immediately dealt with.
  - Additional sensors are attached to the pipes, as close to the water heater inlet and outlet as possible, to have a fall-back temperature should the inside probes fail.
- All peripheral brass connectors and pipes are insulated with foam to reduce heat losses.
- The temperature logging program is prepped and activated:
  - The NI CompactDAQ is placed alongside the water heater and is connected to a laptop via an Ethernet cable.
  - The laptop is placed outside the testing room to ensure that monitoring of the temperatures does not influence the ambient temperatures inside the room.
  - The VI on the laptop is operated through Labview. Once the logging program is activated the values recorded on the thermocouples are saved to a binary file on the laptop. The laptop is connected to a power outlet to prevent any loss of data.
- The element of the water heater is switched on via the custom controller.
- Once the water heater controller temperature as well as the hot water and cold water temperatures have all stabilized, the 48 hour test window commences.

- The ambient temperature is monitored throughout the test to ensure it stays within specifications.
- Once the test is complete the water heater is switched off and left to cool down.
- Once the water heater water is cool the water heater is drained and dismantled:
    - The insulation is removed,
    - The pipes are disconnected,
    - Once the water has drained the rest of the fittings are removed.
- Thus begins the preparation work for the next test.

Once the temperature and power data has been collected the process can advance to the point where the standing losses can be calculated.

In order to better understand the above process it might be better to simplify it to just a few steps that represent the whole. Figure 3-2 depicts the test hierarchy as per the list above omitting a few of the more trivial processes.

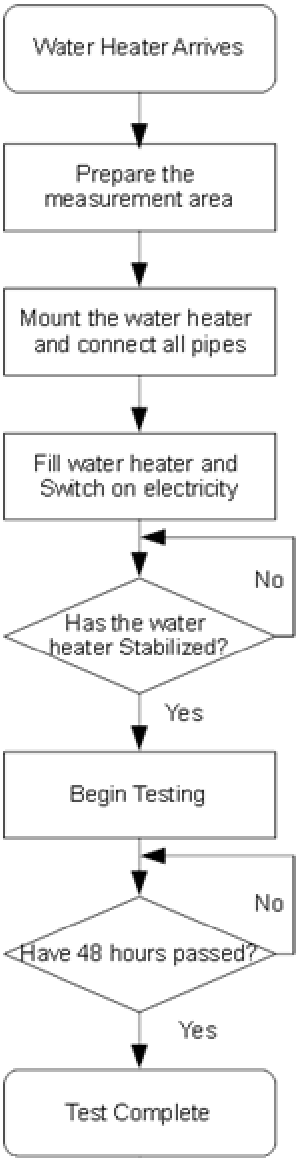


Figure 3-2: Standing loss test hierarchy.

3.5 Calculations

In order to calculate the standing losses the collected data is analysed to verify that it is within the requirements of the SANS 151 document. The standing losses for a water heater are calculated using the measured ambient temperature over the 48 hour period as well as the total power used within the 48 hour period. The equations given in the SANS 151 document on page 26 makes the assumption that the average water heater controller temperature is 65 °C. The equation used to calculate the standing losses is given in equation 2.2.1.

$$Q_{pr} = \frac{45 \times E_1}{2 \times (65 - \theta_{amb})} \qquad 3.5.1$$

The total energy consumption is calculated by summing the average power measurements obtained from the PowerTrack Energy Analyser and Verifier. Once the power and temperature data is obtained the 48 hour window is determined and the start and end times identified for both the temperature and the power. The total power used is calculated by tallying up the power used from all the 30 second segments measured:

$$E_1 = \sum_{i=0}^{N} E_i \tag{3.5.2}$$

where E_i denotes the average power used by the water heater in the i^{th} 30 second segment [kWh] and *N* denotes the total number of readings within the 48 hour standing losses test.

The mean ambient temperature is calculated by tallying up the measured temperature values and dividing the sum by the number of records obtained in the test interval:

$$\theta_{amb} = \frac{1}{N}\sum_{i=0}^{N} \theta_{amb\ i} \tag{3.5.3}$$

where θ_{amb_i} denotes the i^{th} reading of the ambient temperature [°C].

Once the total power and average ambient temperature have been acquired the total standing losses can be calculated using equation 3.5.1. The result will yield the standing losses of the water heater over a 24 hour period.

The tests are done with water heaters that all have a capacity of 150 litres. Thus according to table 3 in the SANS 151 document the maximum standing losses for a water heater with a volume of 150 litres is 2.59 kWh per 24h. Once the standing losses are calculated the achieved value is compared with the value in Table 2 (Table 3 in SANS 151).

If the calculated standing losses of a water heater are below the rated value then it is recorded and results are checked and finalized. If the standing losses are above the rated value then the measurements are rechecked. If that yields no improvement then the sensors are recalibrated to account for any deviations in the measurements. The measurements are then adjusted to match the calibration. If that does not improve the figures the test is redone to collect a new set of data and the standing losses are recalculated. If the same outcome is reached then the results are recorded and reported.

3.6 Water heater Heat Loss Analysis

While the test is in progress and has stabilised the heat loss areas on the water heater can be identified using an Infra-red camera. This helps in deducing more effective methods of insulating a water heater and drawing conclusions on whether or not a water heater’s insulation is effective.

For most water heaters there are areas that will have a greater heat loss than others. The insulation is compromised around the element for example so the heat losses there can be greater. The outlet pipe is another source for heat loss and so are the feet of the water heater. If the feet are secured to the internal barrel for support, the heat transfer from the internal barrel to the feet will be accelerated through those support structures.

Questioned is another common design choice; if the internal barrel is displaced towards the bottom of the water heater before the insulation is inserted, will the heat losses be greater at the bottom of the water heater?

An additional question is how the feet of the water heater support the weight of the water heater and does that influence the heat conductance and in turn the heat losses through the feet?

3.7 Tear Down Analysis

In order to help facilitate the investigation, the water heaters will be cut apart in the vertical plane through the hot water outlet pipe. From this the water heaters insulation thickness is scrutinised and the support structure for the feet is investigated. The conduit from the tank to the hot and cold water pipes is included in the investigation due to the heat losses through the pipes also contributing to higher standing losses.

All this is explored and heat loss points are pointed out in a later chapter, as well as the investigation into the internal construction of the water heater. Deductions will be made based on the findings from the investigation.

The following chapter initiates the practical side of the investigation, exploring a sample of water heaters available on the South African market. Each sub-chapter introduces the water heater by giving all the specification and continues with the test procedure as described in this chapter. Once that is concluded, an analysis of the data is completed on all possible orientations of the water heater after which it is split in half to complete the analysis of each water heater in a thorough manner.

4 Standing Loss Test

4.1 Overview

The literature study gave valuable insight into the MEPS levels from different countries. Chapter 3 then further explored the standing loss test methodology of South Africa with a view to gain competence in testing water heaters in a controlled environment. This chapter focuses on using the knowledge gained to test water heaters from market leaders in the water heating industry. Each of the water heaters will be tested following the SANS 151 methodology and a complete breakdown will be done on the insulation and thermal losses of each water heater. Some initiative is taken to make the SANS 151 test more reliable and repeatable.

This chapter covers the entirety of the data collected for the duration of the test. In addition, it completes the standing loss investigation with a further look into the heat loss profile of each water heater. Each water heater is looked at separately. A discussion about the specifications of the water heater is followed by the results of the standing loss test, after which a look into the thermal behaviour of the water heater is made via thermal images taken during the test. After the thermal analysis is done, the insulation of the water heater is looked at. The insulation thickness is analysed after the water heater is cut in half in the tear down analysis.

The standing loss test is done according to the SANS 151 document as discussed in Chapter 3. To summarize, the water heater is connected to the relevant piping and filled to the brim with municipal water. Once the water heater is filled, the element is switched on after which a waiting period of roughly 24 hours needs to pass in order to allow the water heater to stabilize at the control temperature. After an on-cycle of the element, the 48 hour test commences. During this time the relevant temperatures and the power usage of the element are recorded. In addition, thermal images are taken of the water heater for further analysis. Once complete, the data is analysed and the standing losses are calculated.

After the standing losses are calculated, the thermal analysis commences. In order to better understand the mechanics of the water heater an investigation into the heat loss of the water heaters is carried out. Thermal images of the water heater are captured in a hope to identify the problem areas where heat loss may occur in greater quantities

The thermal images are taken with a Fluke heat gun with manual focus. The strategy for the investigation is to identify the major hot spots where heat loss may occur. These include the pipe connections and the element plate or panel. The feet of the water heater are also taken into account due to fact that water heaters are designed to have supports inserted into the insulation to support the weight of the water barrel on the feet once filled, without compromising the insulation.

Once the thermal investigation is complete, the water heater is cut in half via the vertical longitudinal axis and the thickness of the insulation is determined. This allows for a more thorough investigation to be completed.

The evaluation order of the tests is described in Table V. In order for the test to be completed, the water heaters are allowed to stabilise first. Then after a 24 hour settling period the thermal images are taken. Initially a shot of the complete water heater is taken and then analysed. Once the problem areas are identified, they are investigated further to better understand and interpret how the heat escapes. If the area is troublesome or avoidable, then additional measures are taken to assist in insulating the water heater. In the thermal investigation, all the pictures will be presented for each water heater first and then discussed.

Table V: Water heaters tested.

Manufacturer	**Water heater ID**	**Model**	**Orientation**
A	A	600 kPa 150l Slimline	Vertical
			Horizontal
	B	600 kPa 150l Fat Boy	Vertical
			Horizontal
B	C	400 kPa Combi Slim	Vertical
			Horizontal
C	D	400 kPa Standard	Horizontal
D	E	400 kPa Standard	Horizontal
	F	400 kPa Delux	Horizontal

The majority of the water heaters come with an Ingress Protection (IP) rating. The IP is a rating that establishes the protection of an electrical device from external influences mainly focusing on solids and liquids [66]. The IP rating is followed by two digits that denote the characteristics of the product in the following manner. The number following the IP acronym denotes the protection of a device from ingress of solid objects. If the number is higher, then the protection is better, with the highest number being 6 which is total protection against dust [66].

The second number represents protection against liquids with a range of 0 to 9 with zero being no protection (sometimes replaced with an X) and 9 being protected from total water immersion and water jets from multiple directions [66].

4.2 Water Heater A

The first two water heaters (A and B) are produced by the same manufacturer with the leading market share in the South African Industry of electric storage water heaters [67]. With a leading market share the expectation is for the water heaters to be the leaders in standing losses and insulation grading.

4.2.1 Specifications

Each water heater comes with a plaque explaining the specifications of the water heater as well as the fact that it passed the testing phase in the factory. From the plaque the water heater operating voltage and pressure can be determined as well as a few other pieces of information.

The Pressure and the orientation are the only variables important to the testing. The power will be supplied by the municipality as well as the water. Pressure regulators are put in line with the water heater to avoid damage or rupturing of the water tank.

Table VI: Water heater A specifications.

Volts	Volume	Power	Pressure	Orientations	Code	IP
230V/50Hz	150l	3kW	600kPa	Horizontal Vertical	02-S-5	X4

4.2.2 Standing Loss Test

The standing loss test is conducted as per the regulations in the SANS 151 Document as discussed in Chapter 3. The water heater is connected to all the pipes and testing equipment and then left to run for 48 hours after it has reached a stabilised state. The results for the measured and calibrated Temperatures can be seen in Table VII

Table VII: Water heater A temperature averages and standing loss results.

	Vertical orientation			Horizontal orientation		
Measured entity [°C]	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
Ambient temperature	16.3	15.1	17.1	18.2	17.4	18.5
Control temperature	64.9	64.2	65.2	65.2	64.5	66.7
Cold water temperature	63.8	62.8	64.2	56.9	55.9	57.8
Hot water temperature	72.4	71.5	72.7	77.2	76.5	78.2
Standing losses [kWh]			2.34			2.33

Reviewing the recorded data, it is evident that the controller temperature is within the required range as per the SANS 151 standard. The ambient temperature however is outside of the range in the context of the vertical orientation. Nonetheless the data is usable. In the context of the vertical orientation, the cold water side is very close to the temperature of the controller due to the probe being very close and in the same heat plane as the controller probe (a heat plane is to all intents and purposes the level at which the heat is the same in a certain environment) as can be seen in Figure 4-1. The hot water temperature is substantially higher than that of the controller. This is due to heat from the element and inside the water barrel rising to the top of the water heater continuously, i.e. convection.

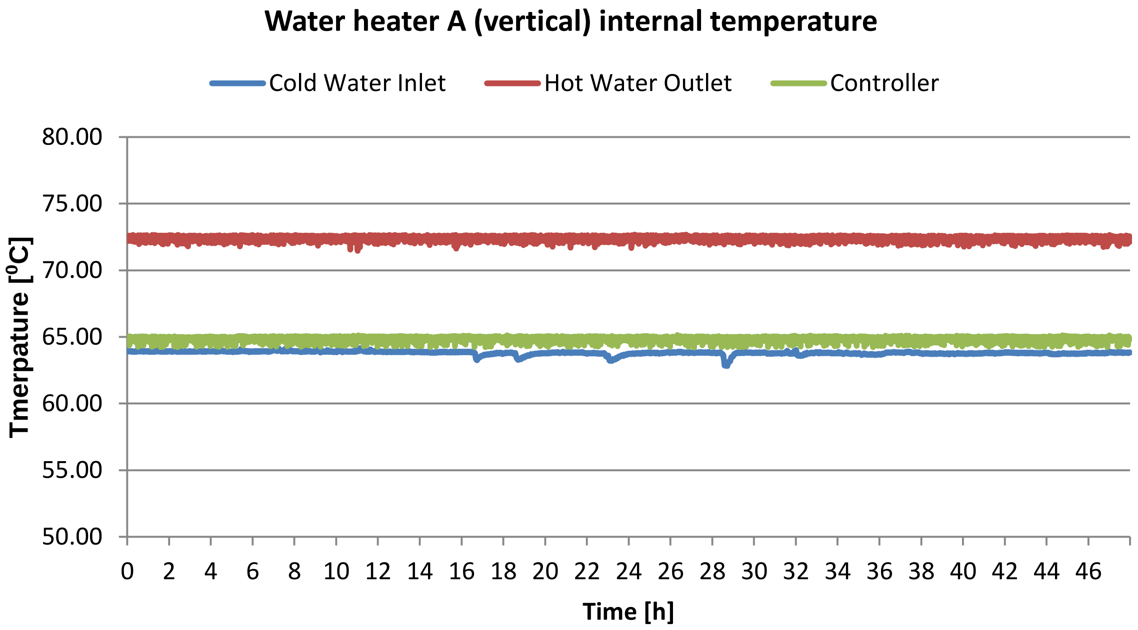


Figure 4-1: Water heater A (vertical) internal water temperature comparison.

The convection in the horizontally mounted water heater is evident. The hot water probe is at the top of the water heater. The controller temperature probe is fairly central and the cold water probe is towards the bottom. The effects of the convection in the water heater can be seen in Figure 4-2.

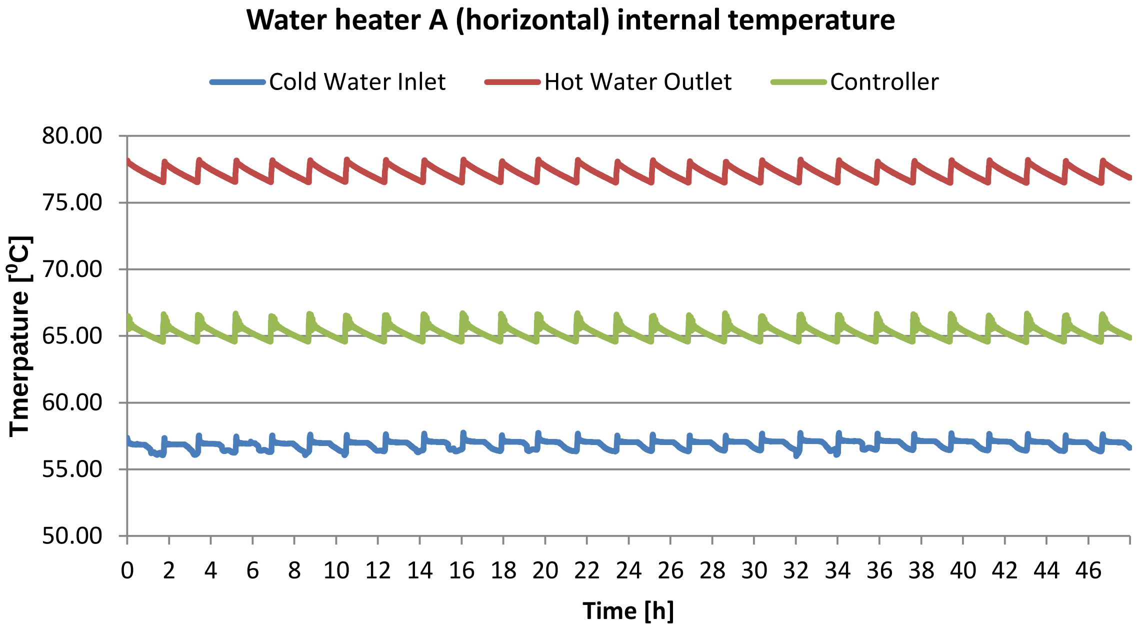


Figure 4-2: Water heater A (horizontal) internal temperatures.

However the standing losses seem to be close to the MEPS levels. Reviewing Table I it is noted that the maximum standing losses for a 150l water heater is 2.59 kWh/24h. Comparing the calculated value of 2.3 kWh/day for both the horizontal and vertical orientation is not very satisfying. If any consideration is given to try to expand into market overseas, it will result in disappointment due to the standing losses being too high.

To summarise, the results of the test Figure 4-3 and Figure 4-4 show the calibrated and ambient temperature as well as the power usage profile on a separate y-axis. In the context of Figure 4-3 it seems that the controller temperature goes through many cycles resulting in untrustworthy recorded data. However the controller power usage, measured on a separate system, reveals that the fast oscillating nature is indeed a true measurement. The ambient temperature is short of 20 °C and falls away as the test progresses. Measures are taken for future tests to avoid this error. The low ambient temperature results in a slightly higher standing loss value. In the SANS 151 a value of 20 °C is used in the calculation of the standing losses. If however the actual mean recorded ambient temperature is used in place of the suggested value the answer differs minimally. For the vertically mounted water heater the standard calculation yields a result of 2.33 kWh/day but if the mean ambient temperature is used a standing loss of 2.34 kWh/day is achieved. In Figure 4-4 there is a much more desirable outcome with a regular visual power and temperature cycle as well as a practical ambient temperature.

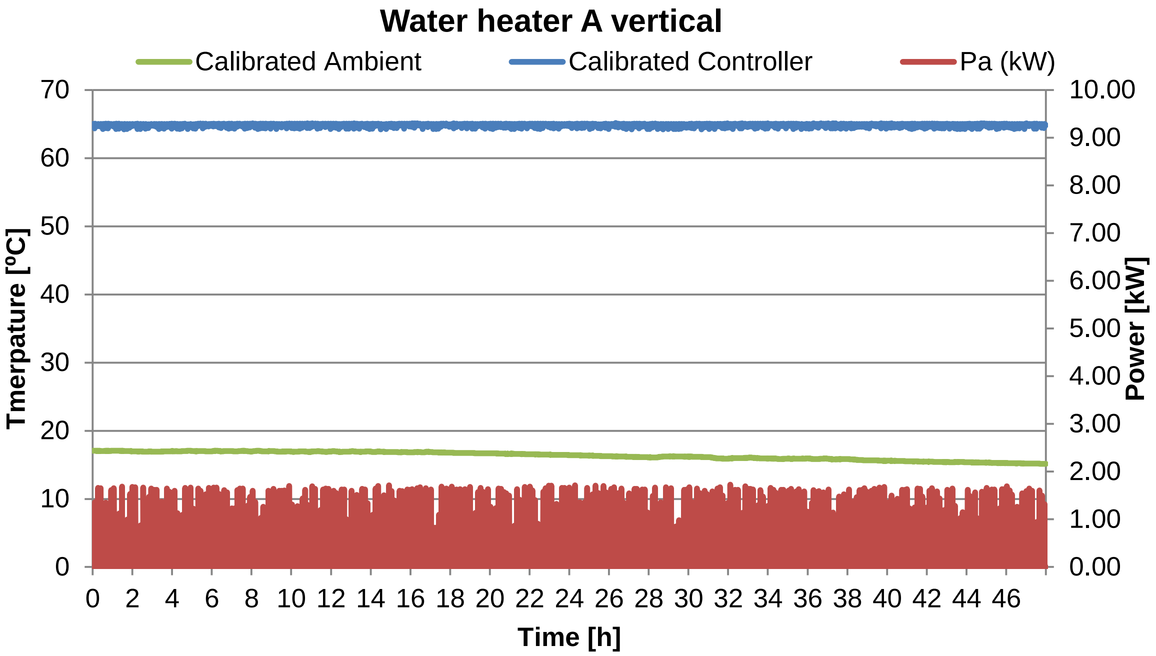


Figure 4-3: Water heater A (vertical); temperatures and power usage profiles.

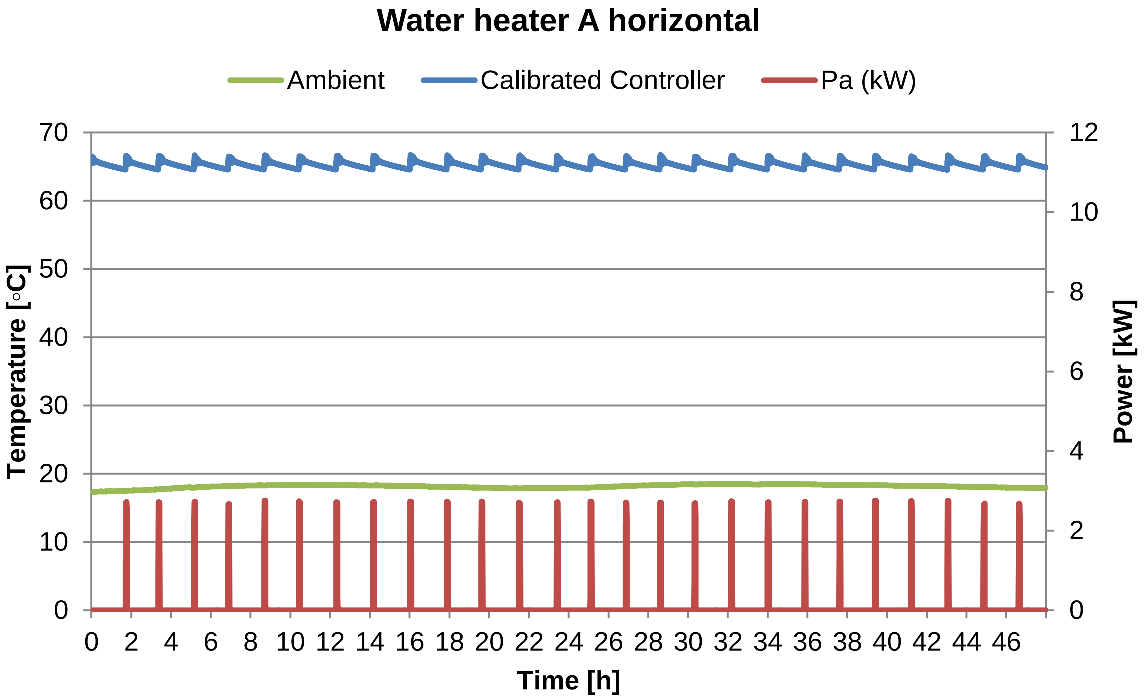


Figure 4-4: Water heater A (horizontal); temperature and power usage profiles.

4.2.3 Vertical Thermal Analysis

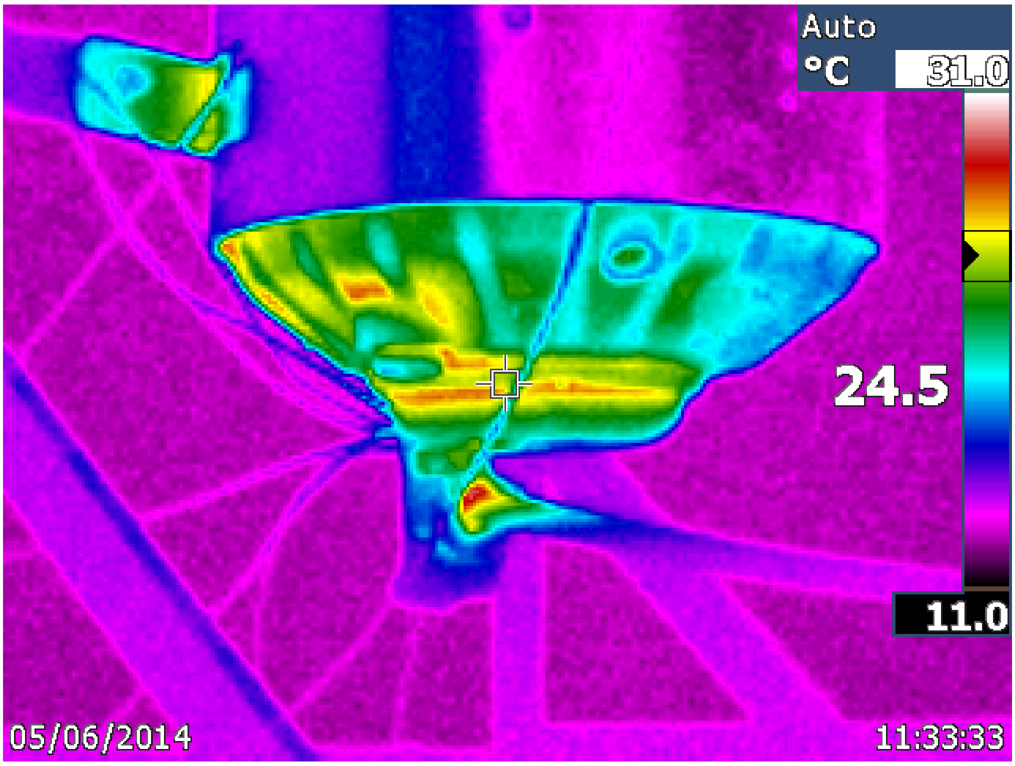


Figure 4-5: Water heater A (vertical), thermal image of the inlet faceplate.

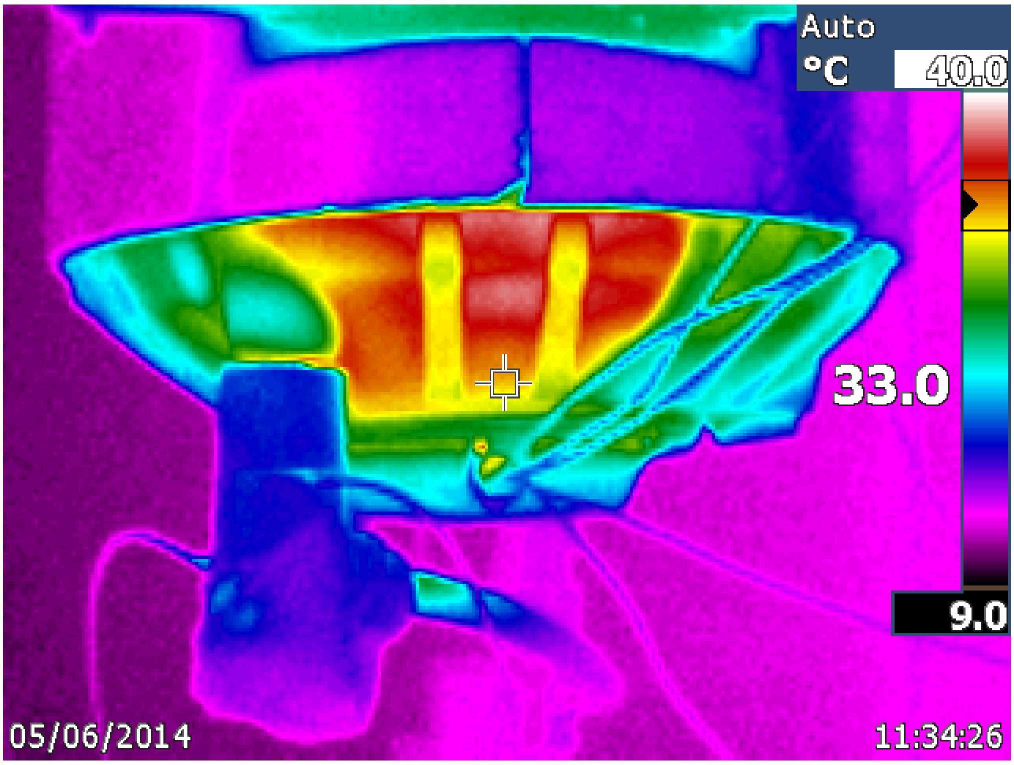


Figure 4-6: Water heater A (vertical), thermal image of the inlet faceplate.

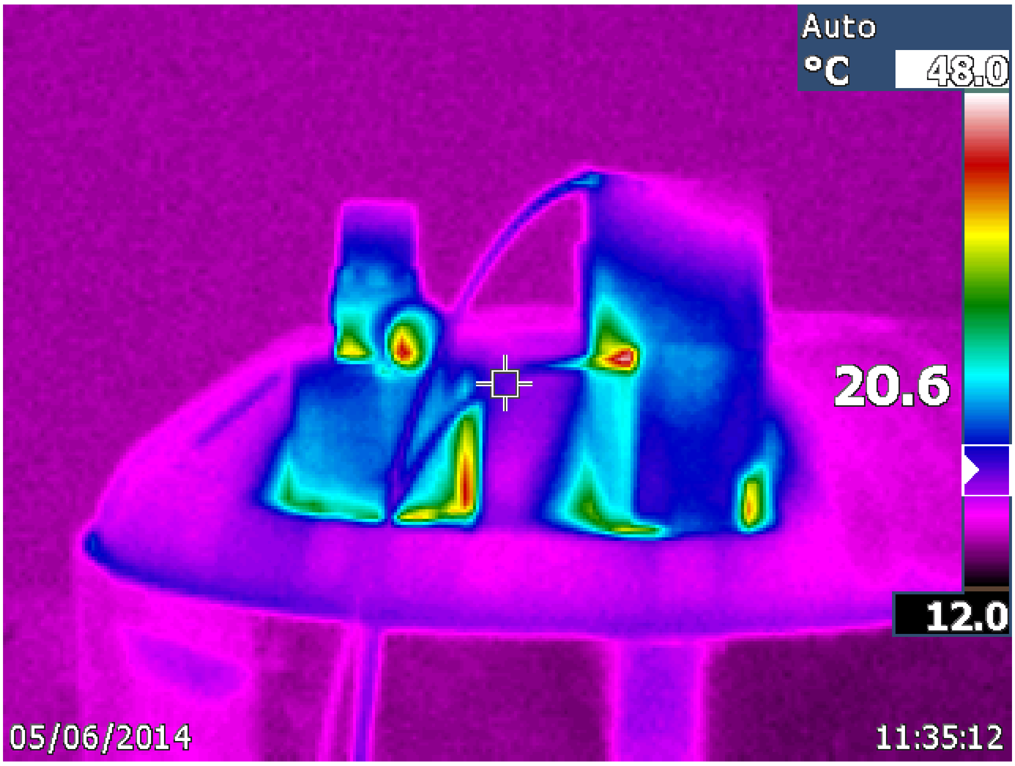


Figure 4-7: Water heater A (vertical), thermal image of the outlet and expansion valve.

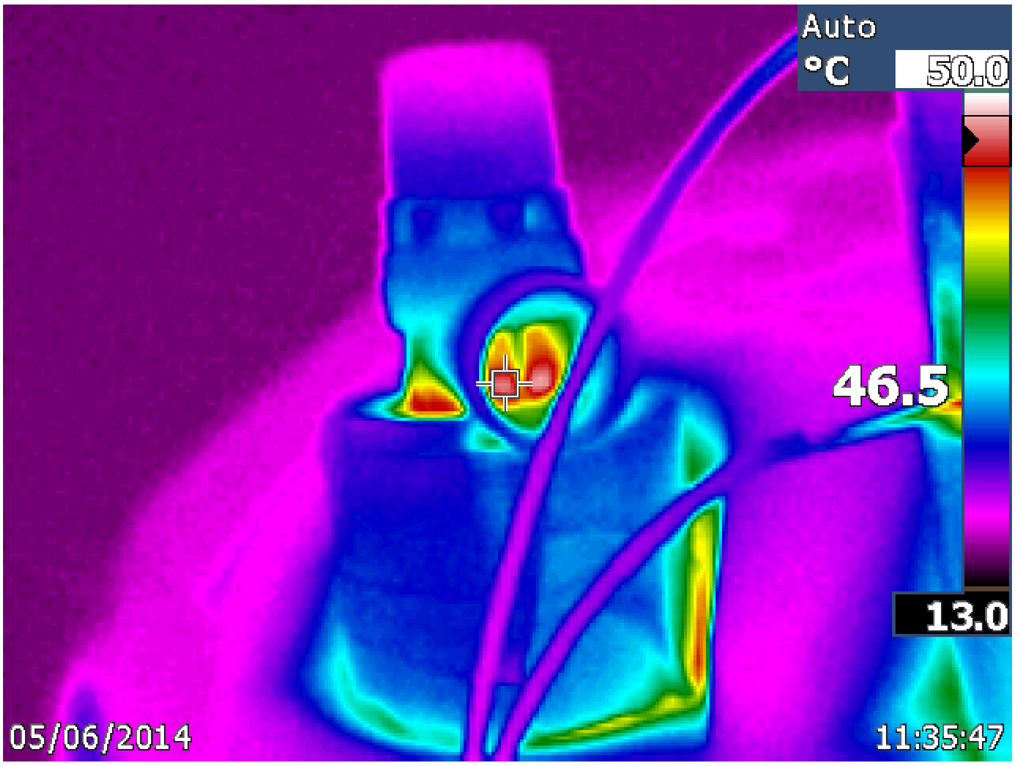


Figure 4-8: Water heater A (vertical), thermal image of the expansion valve.

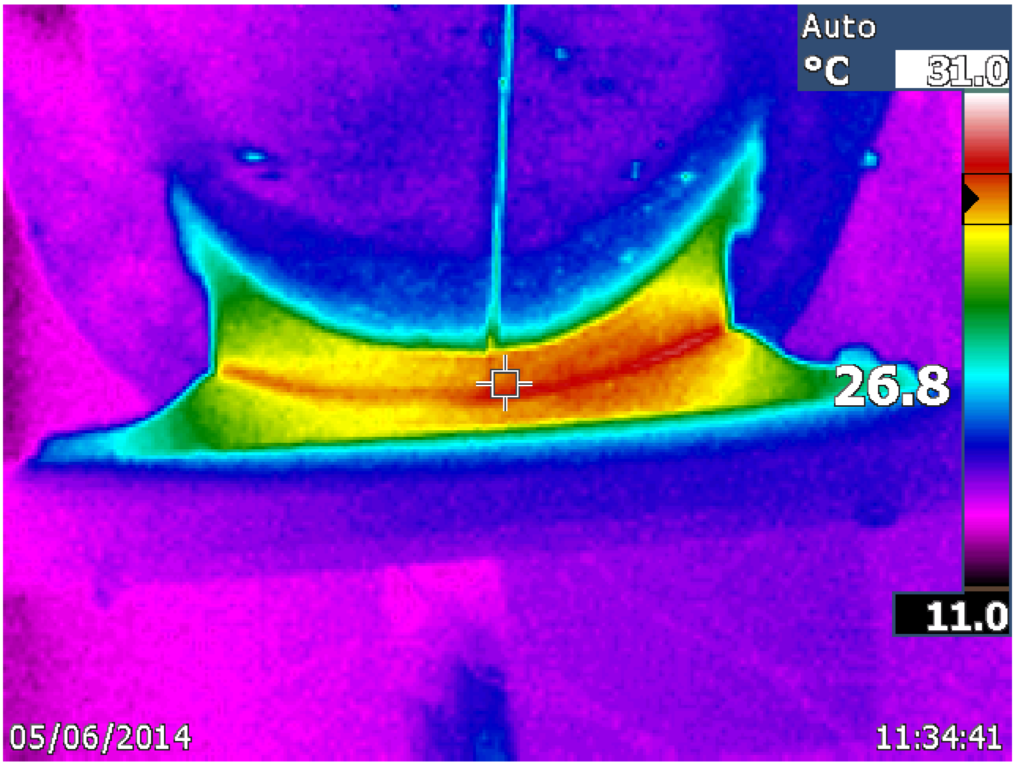


Figure 4-9: Water heater A (vertical), thermal image of the feet.

The water heater consists of an aluminium shell with the sides covered with plastic faceplates. The aluminium shell reflects any light thus it is impossible to view the temperature of the shell. The feet and faceplates give a good indication of the temperature. Figure 4-5 gives insight into the apparent temperature losses around the inlet pipe and element plate. More is revealed in Figure 4-6 where the temperature of the plastic faceplate is as high as 40 °C. It also reveals that the feet incur some losses. Figure 4-9 also sheds some light into this. With the temperature of the feet being 20 °C above the suggested ambient temperature significant heat loss will be experienced here as well.

Figure 4-7 and Figure 4-8 show the thermal images of the outlet pipe stop and the expansion valve. Although they are well insulated they do experience some heat losses. The expansion valve outlet cannot be covered or insulated. The only method of trying to minimise the heat loss there would be to work on the internal mechanics of the water heater.

4.2.4 Horizontal Thermal Analysis

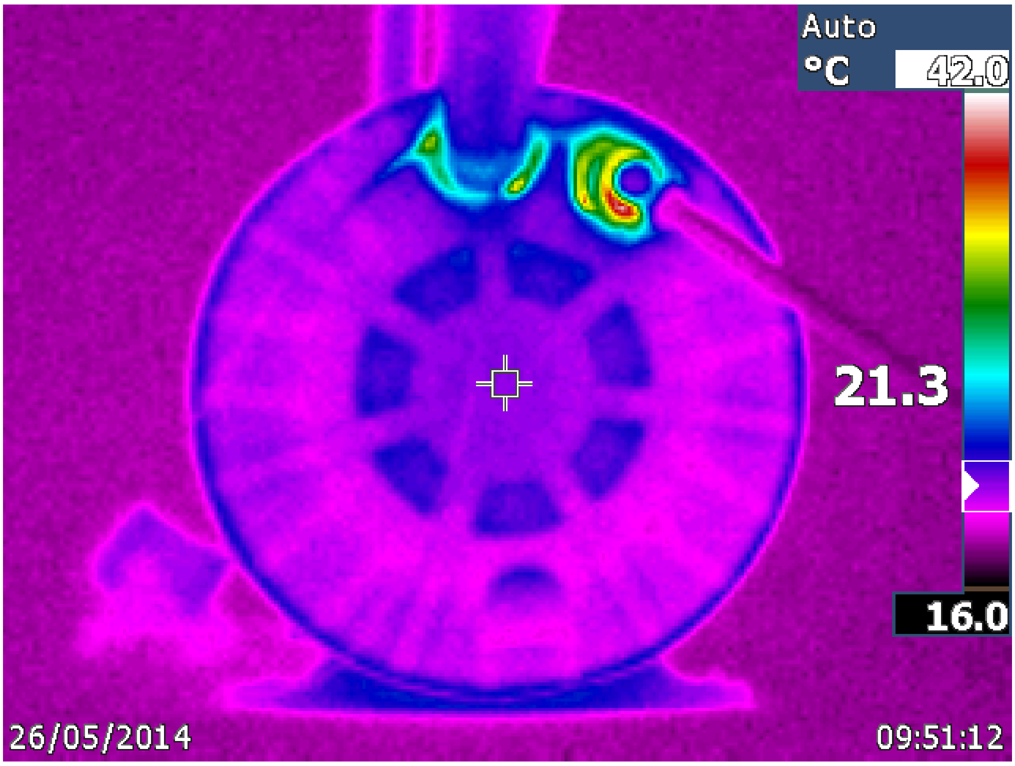


Figure 4-10: Water heater A (horizontal), thermal image of the outlet.

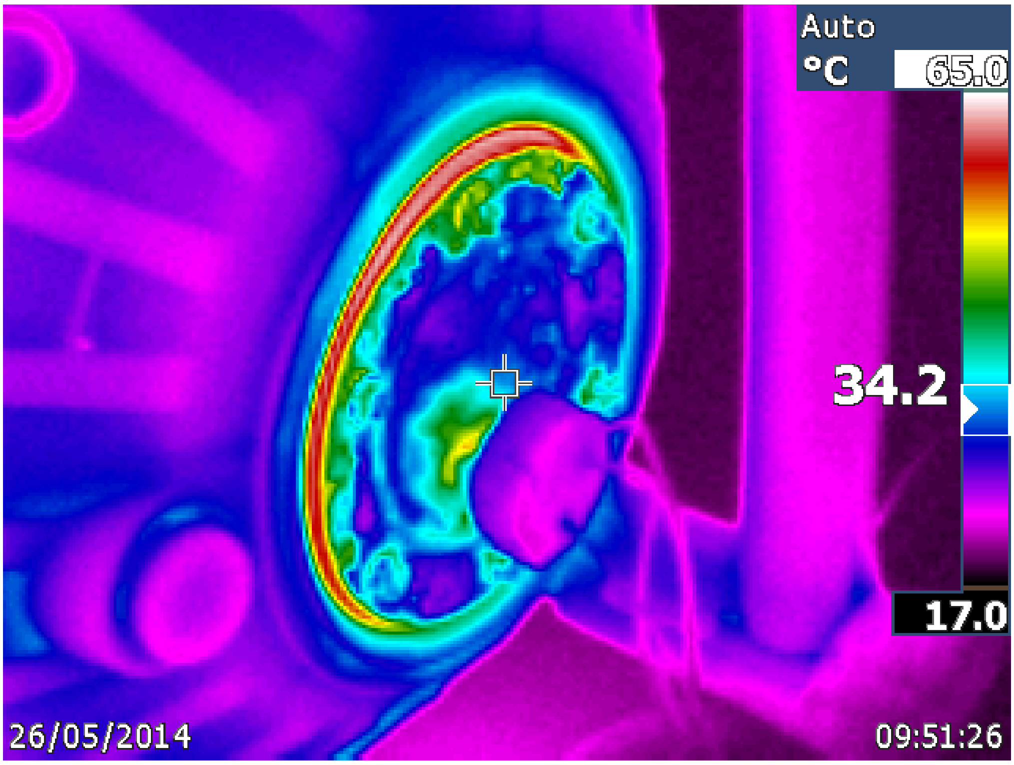


Figure 4-11: Water heater A (horizontal), thermal image of the element mounting plate.

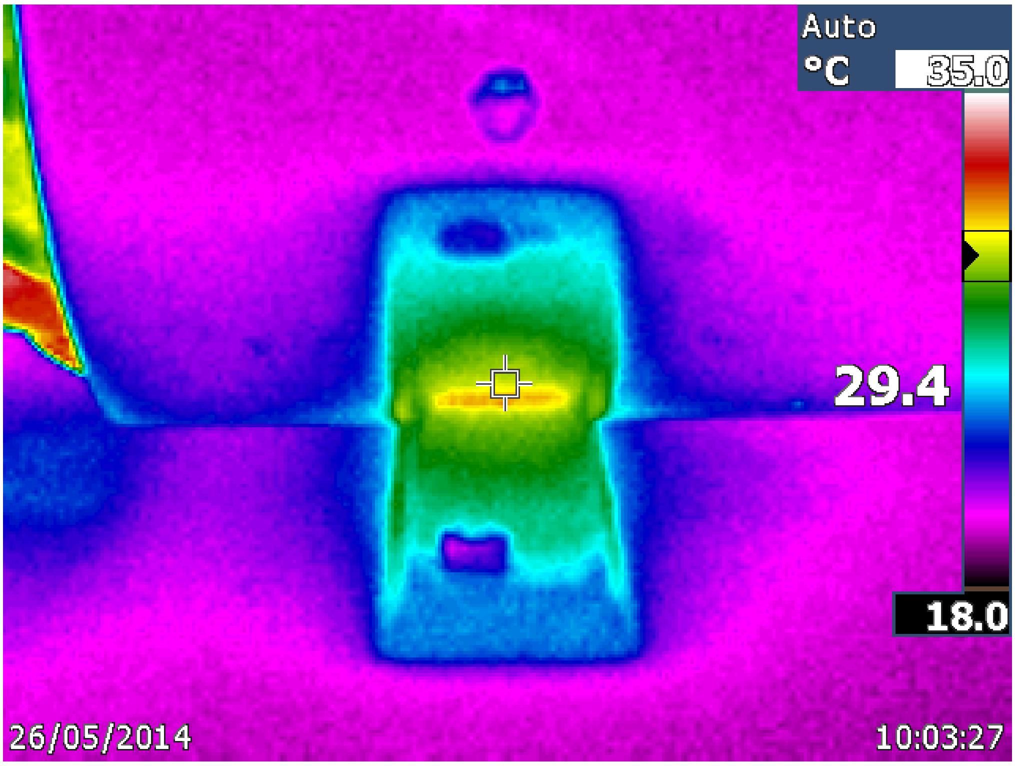


Figure 4-12: Water heater A (horizontal), thermal image of the feet.

In the vertical position it is the inlet side faceplate that achieves a very high temperature. The hot spot is however below the element if the water heater is positioned horizontally. Thus the temperature is lower but only by 5 °C.

The outlet side faceplate does not incur any rise in temperature except for around the outlet pipe as well as the expansion valve as can be seen in Figure 4-10. This temperature is also lower when compared to the same area when mounted in vertical position.

The feet are still problem areas, having decreased by only 1.5 °C from the change in orientation, as can be seen in Figure 4-12.

Figure 4-11 is a picture of the element insert when connected to the water heater. It gives better insight as to how the area around the element reacts to the element. In the figure it is evident that parts of the insert achieve the same temperature as the element. This indicates a very high low temperature gradient through the material (The material conducts heat very well). Very high temperatures are exposed to the surrounding environment which means much greater heat loss in the area localised around the element.

4.2.5 Tear Down Analysis

The heat loss analysis revealed some very interesting results or flaws that warranted a more in-depth investigation. To gain a better understanding of the heat losses, the water heater is cut in half through the longitudinal vertical plane as can be seen in Figure 4-13 and Figure

4-14. In the context of Figure 4-13 on the left, there can be seen a hole where a spiral heating element in inserted. The steel rod is sacrificial anode that is “often inserted into the tank to protect any exposed steel from corroding and causing the tank to leak.” [68]

The pipe on the top right of the figure is the hot water outlet pipe. The inside of the pipe is insulated with a plastic fitting to minimise the heat losses. The same plastic fitting is found on the cold water inlet pipe with an additional fitting to prevent the entering cold water from immediately switching on the element as seen in Figure 4-14.

The thickness of the foam is measured at the top and bottom of the water heater once it has been cut open. The water heater is designed to be mounted horizontally so that the collection of hot water occurs at the point where the insulation is the thickest.

Table VIII: Water heater A insulation thickness.

Water heater insulation	**Thickness [mm]**
Bottom	5
Top	35

As the insulation foam approaches the hole for the element, the thickness tapers off. Once the element is attached, there is nothing preventing the heat from escaping through the element faceplate apart from a thin plastic cover. Another point of interest is the large void or hole in the insulation on the bottom of the water heater towards the element side. This oversight can lead to massive unwanted heat losses.

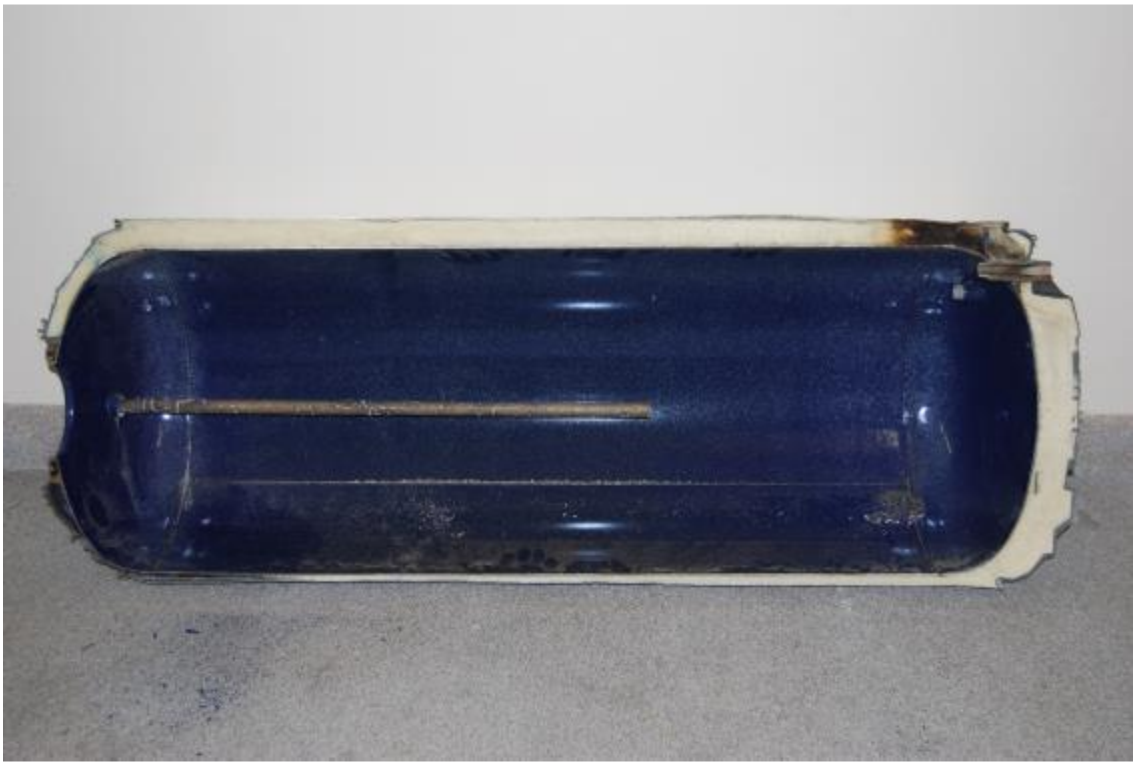


Figure 4-13: Water heater A tear down side 1.

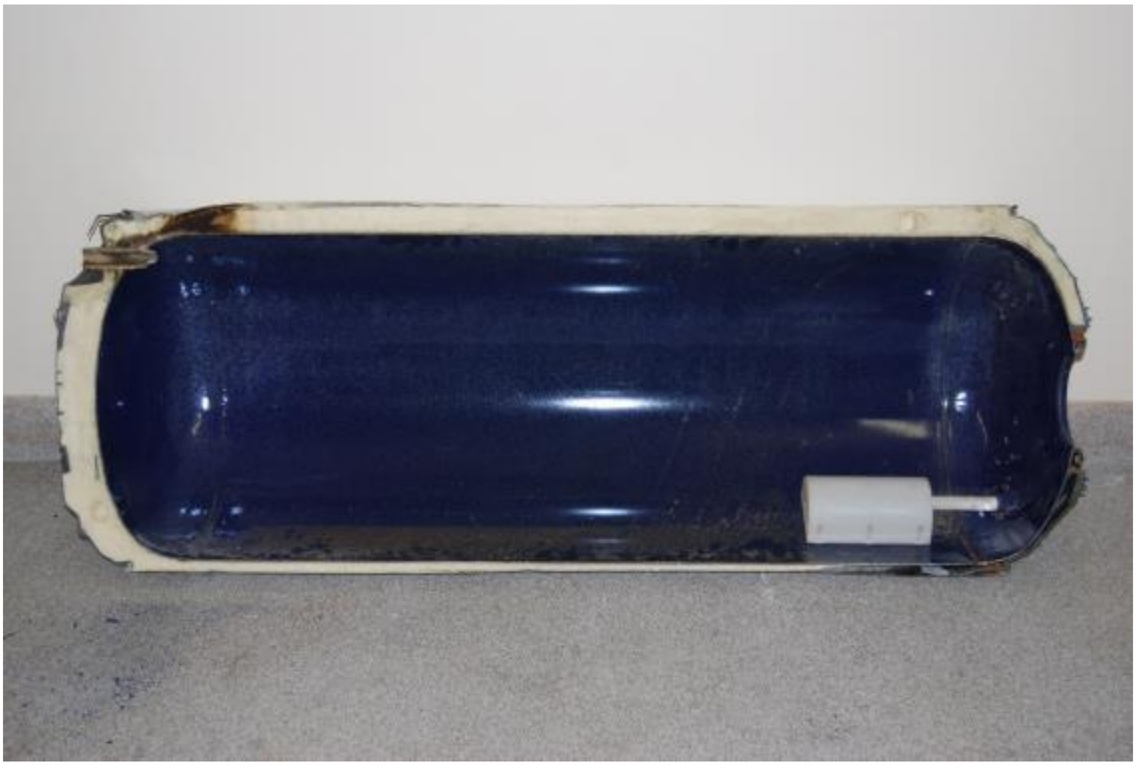


Figure 4-14: Water heater A tear down side 2.

4.3 Water Heater B

As mentioned before, Water heater A and B are made by the same manufacturer. The Fat boy has a larger diameter. This allows for a thicker insulation and better heat storage capacity.

4.3.1 Specifications

Few variations in the specifications exist between the Slimline model and the Fat boy model. The only major difference as mentioned before is the diameter of the cylinder. It was seen that the standing losses are influenced by the design as well as the varying insulation thickness.

Table IX:Water heater B specifications.

Volts	Volume	Power	Pressure	Orientations	Code	IP
230V/50Hz	150l	3kW	600kPa	Horizontal Vertical	05-S-5	X4

4.3.2 Standing Loss Test

The standing loss test is done in accordance with the SANS 151 testing methodology. The results of the test are shown in Table X.

Table X: Water heater B standing loss test results.

	Vertical orientation			Horizontal orientation		
Measured entity [°C]	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
Ambient temperature	20.4	17.8	21.4	20.3	18.9	21.2
Control temperature	64.5	64.3	67.1	64.7	64.3	65.7
Cold water temperature	62.7	42.0	64.6	55.2	54.4	56.4
Hot water temperature	71.8	70.0	72.6	75.2	74.8	75.8
Standing losses [kWh]			2.26			1.91

The standing losses shown in Table X are calculated using the measured mean ambient temperature instead of the suggested 20 °C in the SANS 151 document. The difference is marginal due to the mean ambient temperature being fairly close to the suggested mean. If the suggested value is used then the standing losses for the vertically and horizontally mounted water heaters would be 2.24 and 1.90 kWh/day respectively.

Compared to the Slimline model the results are an improvement. A significant difference 0.4 kWh/day can be seen in the standing losses of the horizontal tests.

As with the Slimline model mounted vertically the cold water temperature is fairly similar to the controller temperature. In this instance the difference is larger. This might be due to the surface area inside the water heater being larger allowing for greater variation. The cold water inlet is also further away from the controller probe.

Further investigating into the vertical orientation results reveals that the cold water temperature experiences a large dip. Looking at Figure 4-15 it is seen that the dip is only a momentary one and doesn't affect the results at all. The fast variations in the controller temperature are seen again, and are very similar to the results from the Slimline model. Once again the results in Figure 4-17 indicate that the measurements are in fact true. On a similar note, the results from the Horizontal tests yield similar results to those of the Slimline in the context of the on-off cycles being more evident than in the Vertically mounted water heater as can be seen in Figure 4-16 and Figure 4-18.

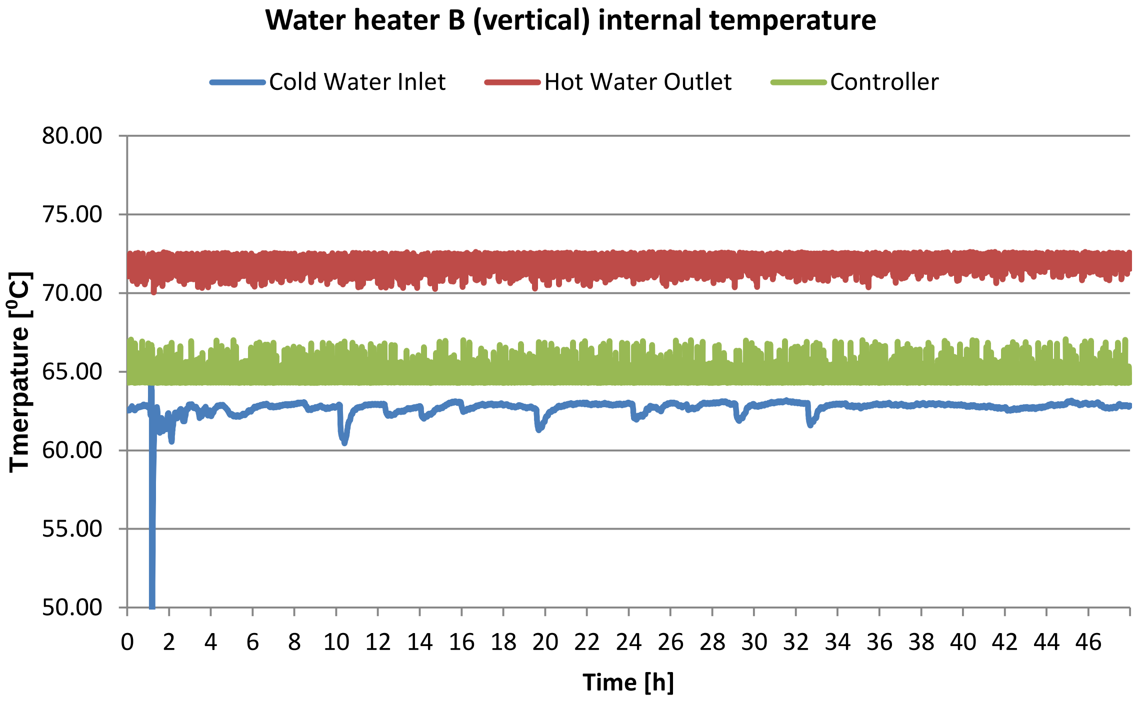


Figure 4-15: Water heater B (vertical) internal temperatures.

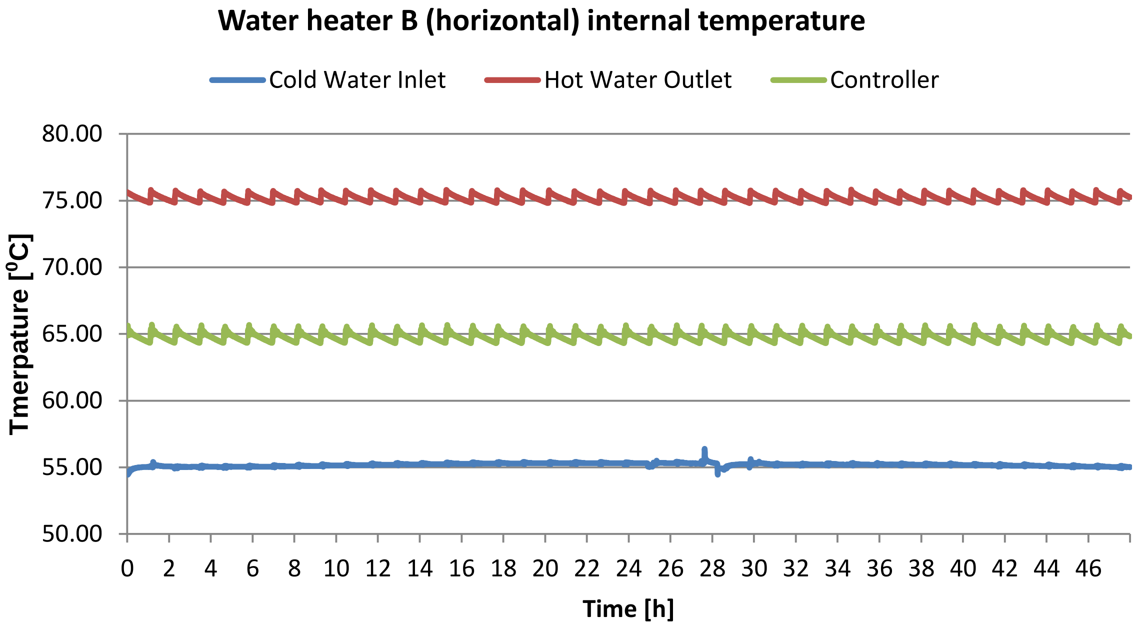


Figure 4-16: Water heater B (horizontal) internal temperatures.

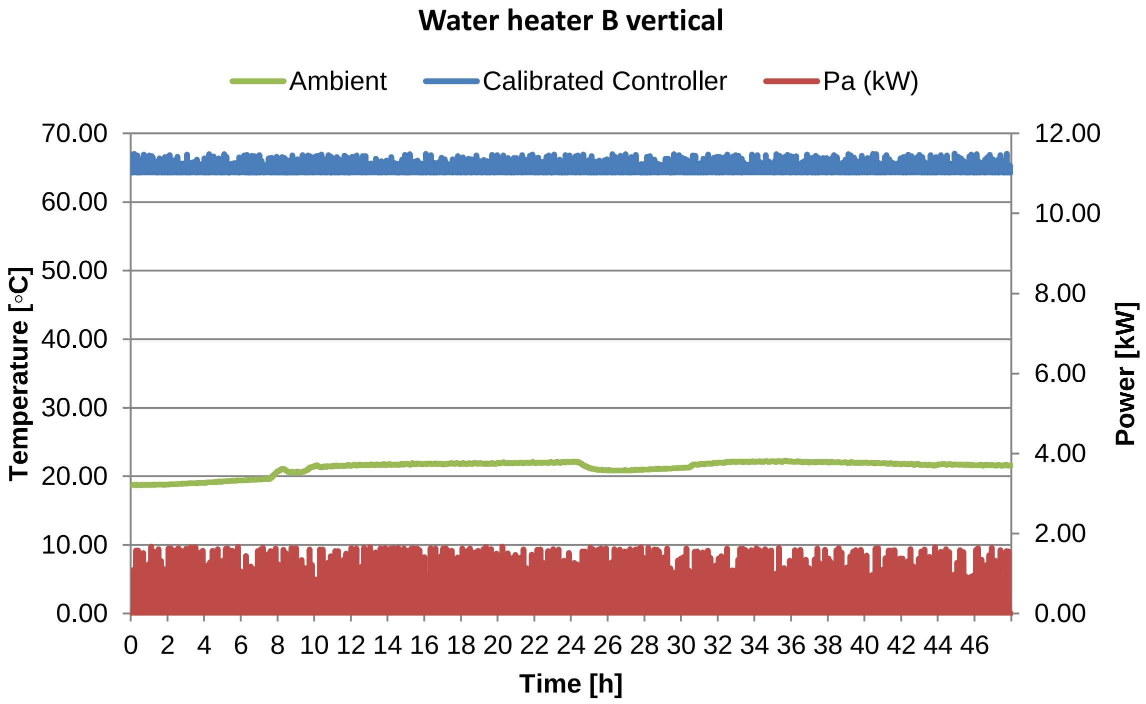


Figure 4-17: Water heater B (vertical) temperature and power usage profiles.

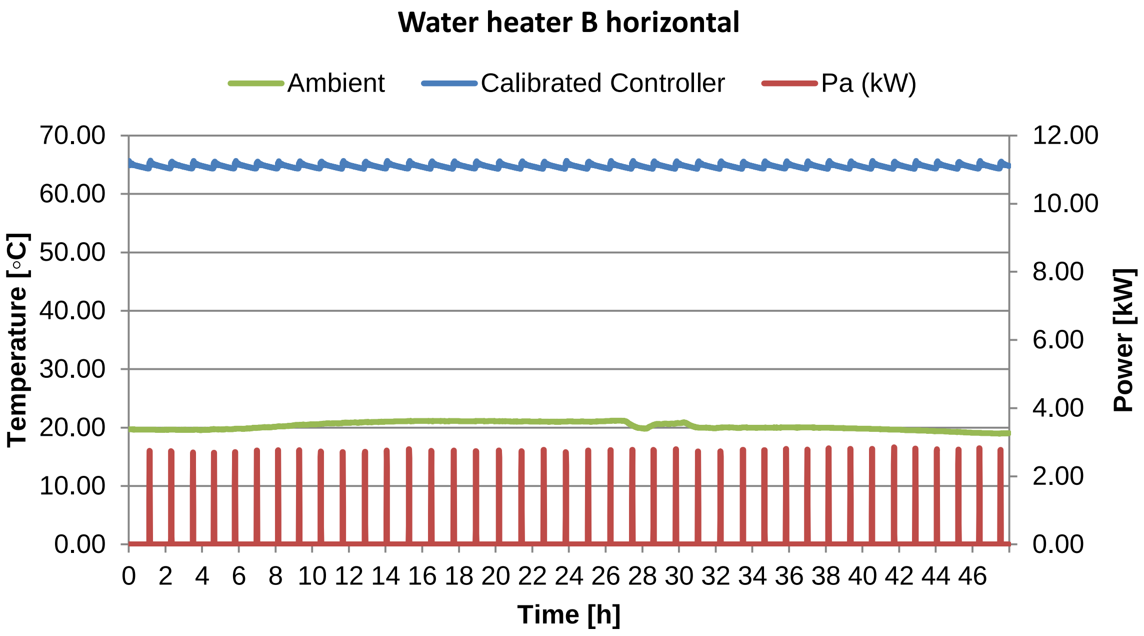


Figure 4-18: Water heater B (horizontal) temperature and power usage profiles.

4.3.3 Vertical Thermal Analysis

Figure 4-19: Water heater B (vertical), thermal image of the water heater.

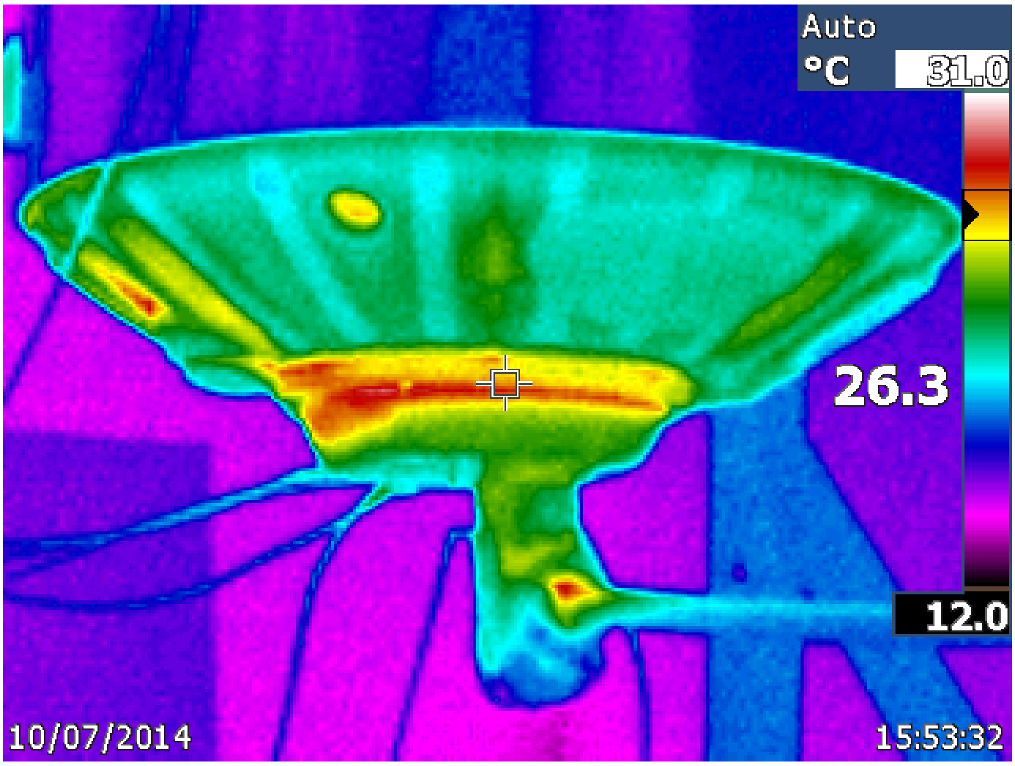


Figure 4-20: Water heater B (vertical), thermal image of the inlet faceplate.

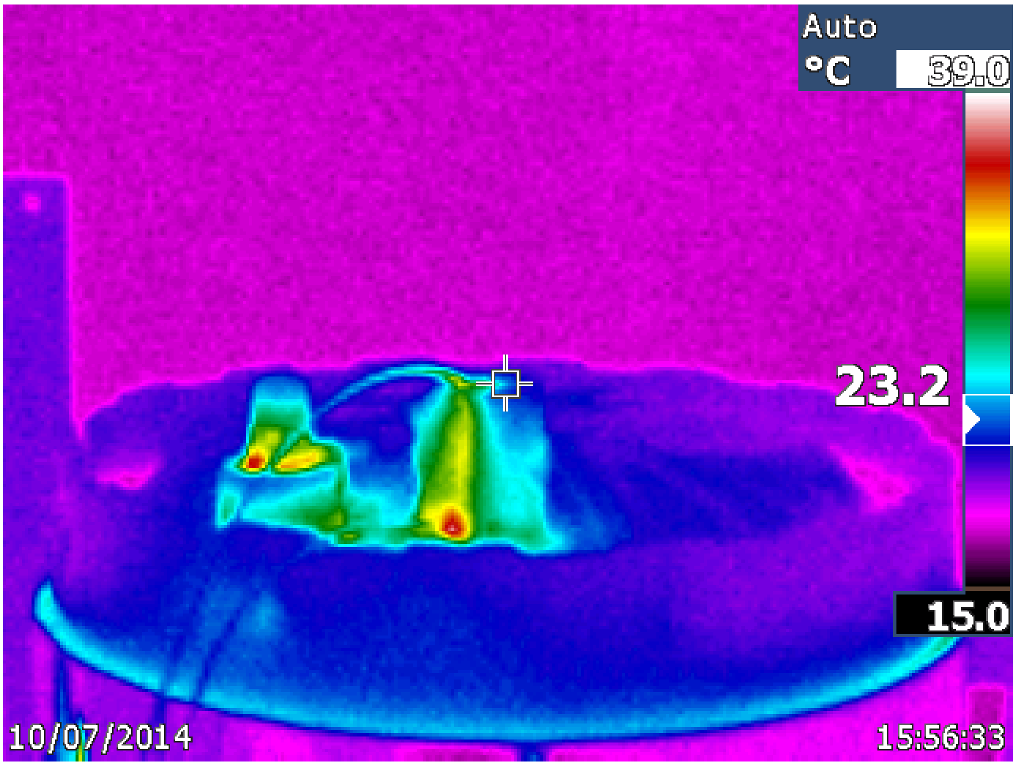


Figure 4-21: Water heater B (vertical), thermal image of the outlet faceplate with expansion valve and outlet pipe.

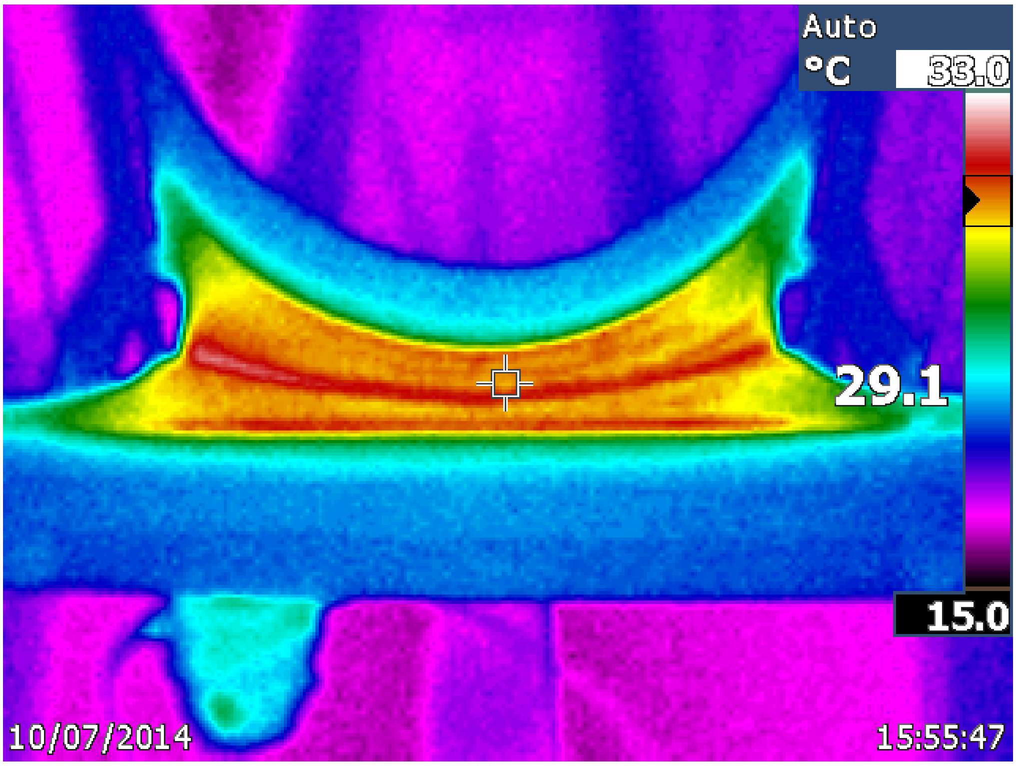


Figure 4-22: Water heater B (vertical), thermal image of the feet.

As with water heater A, water heater B has plastic faceplates completing the aluminium shell casing around the internal water barrel. They are seen to emit substantial amounts of heat in Figure 4-19 and Figure 4-20. Figure 4-20 shows the inlet plastic faceplate reaching an average temperature of 25 °C whereas the outlet or top faceplate only reaches a temperature of 24 °C at the rim and a more average ambient temperature over the rest of the plate suggesting that the top is insulated much better. However Figure 4-22 indicated that the feet reach 33 °C which would incur serious heat losses for the water heater. This would suggest that the internal support structure for the feet enables for heat energy to be carried through the insulation to be lost externally.

4.3.4 Horizontal Thermal Analysis

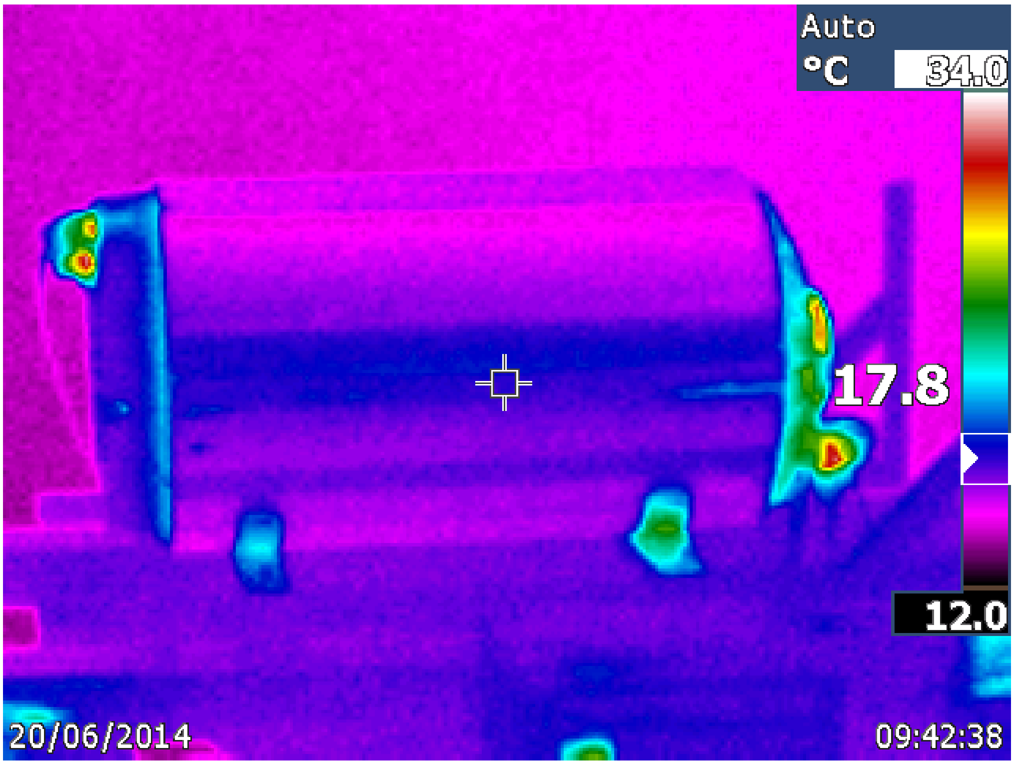


Figure 4-23: Water heater B (horizontal), thermal image of the water heater.

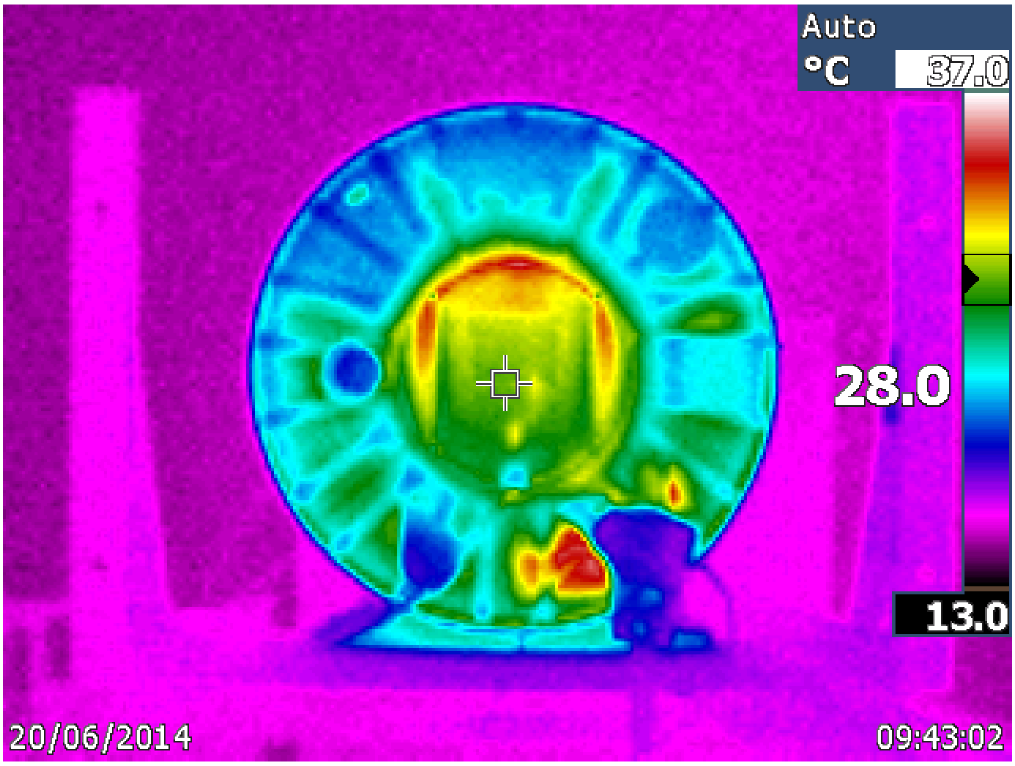


Figure 4-24: Water heater B (horizontal), thermal image of the inlet faceplate.

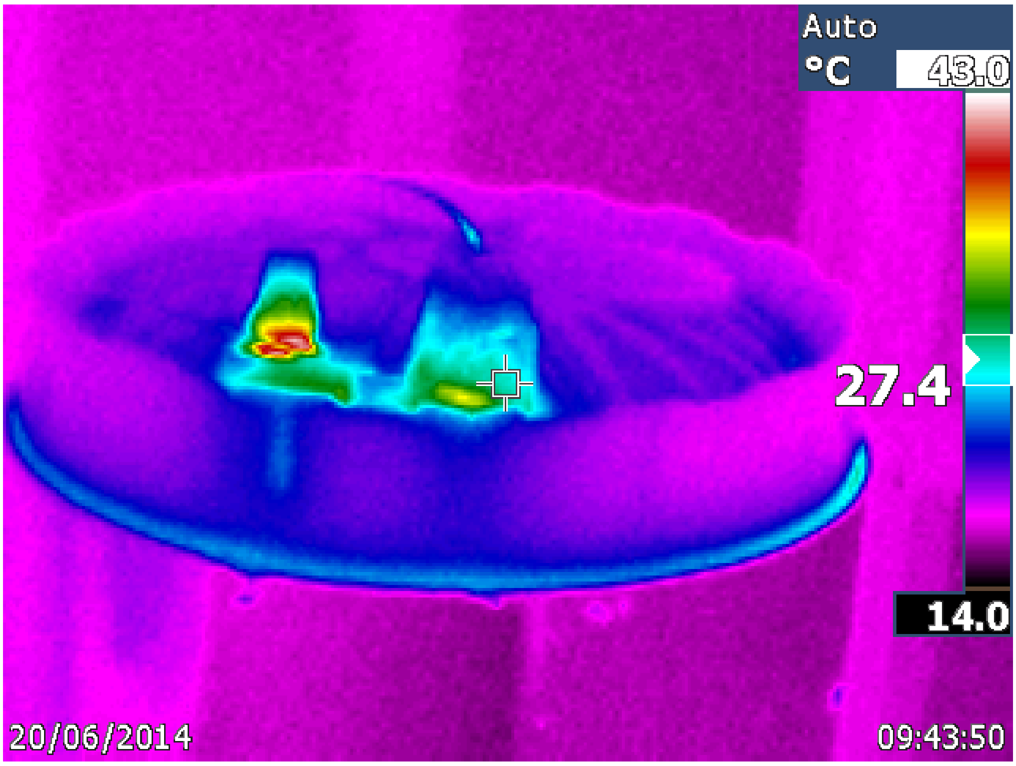


Figure 4-25: Water heater B (horizontal), thermal image of the outlet faceplate with expansion valve and outlet pipe.

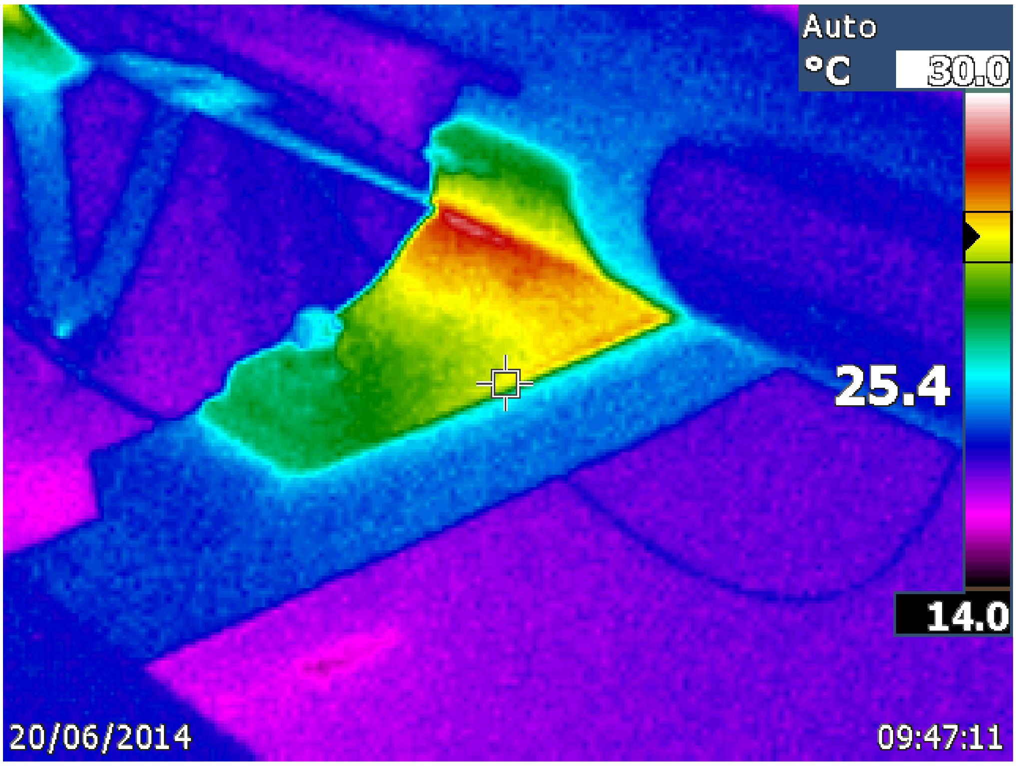


Figure 4-26: Water heater B (horizontal), thermal image of the feet.

In the horizontal position water heater B responds in the same manner thermally. The inlet faceplate still reaches a temperature of 28 °C and experiences a hotter area toward the bottom where the insulation seems to be thinner. The area around the element insert also reaches a higher temperature than the rest of the faceplate. This is probably due to the lack of insulation in the area.

As with the vertical orientation, the outlet faceplate also experiences a higher temperature around the rim of the faceplate and around the pipe inserts but again is also cooler over the rest of the surface as indicated in Figure 4-25.

When the water heater is mounted in the horizontal orientation, the feet reach a temperature of 30 °C, and the feet of the vertically mounted water heater reach a higher temperature, specifically 33 °C as seen in the IR images. A closer look will be directed at this area in the tear down of the water heater.

4.3.5 Tear Down Analysis

Water heater B was also designed to be mounted horizontally as can be seen from the measurements taken of the insulation thickness in Table XI.

Table XI: Water heater B insulation thickness.

Water heater insulation	**Thickness [mm]**
Bottom	10
Top	31

Looking at the water heater in the horizontal position, compared to the Slimline model the insulation at the bottom of the water heater is double the thickness whereas the insulation at the top is slightly thinner, 4mm to be exact. This would suggest that the insulation at the bottom has a huge impact on the standing losses. Based on the findings of the following tests the importance of this observation shall be determined.

Figure 4-27 and Figure 4-28 reveal the internal workings of the water heater. Figure 4-27 shows the sacrificial anode as well as the spiral element cavity on the left of the image. Figure 4-28 shows the cold water inlet cover designed so as to prevent mixing the cold water with the hot too rapidly. This is to insure that there is no major influence on the element behaviour.

The additional space for the insulation allows for a more trustworthy manufacturing process. This minimises faults in the products as seen in water heater A.

Figure 4-27: Water heater B; tear down side 1.

Figure 4-28: Water heater B; tear down side 2.

4.4 Water Heater C

Water heater C is made completely encased in a galvanized metal shell which is different in comparison to the previously tested models where the faceplates are made out of plastic. Another observation is that on the previous tests, the only heat losses captured by the thermal camera were on the plastic faceplates of the water heater, whereas the heat on the reflective metal shell was not picked up by the thermal camera at all.

4.4.1 Specifications

The entire casing of the water heater is made of galvanised metal sheeting. Thus, the water pressure and the different position of the expansion valve are the only different aspects in the context of water heater C.

A different pressure regulator is put in series with the water heater to regulate the water pressure.

A summary of the specifications are given in Table XII.

Table XII: Water heater C specifications.

Volts	Volume	Power	Pressure	Orientations
230V/50Hz	150l	3kW	400kPa	Horizontal Vertical

4.4.2 Standing Loss Test

The arrangement of the pipes doesn't have to be altered too much to accommodate the new water heater although the frame is modified to fit the dimensions of the feet.

Table XIII: Water heater C standing loss test results.

	Vertical orientaton			Horizontal orientation		
Measured entity [°C]	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
Ambient temperature	18.6	17.5	19.3	17.4	16.4	18.2
Control temperature	64.5	64.3	65.9	64.8	64.3	65.6
Cold water temperature	64.5	38.6	64.8	61.4	61.0	61.7
Hot water temperature	72.3	71.9	72.6	75.1	74.5	76.0
Standing losses [kWh]			1.79			1.87

Reviewing the results in Table XIII, certain derivations can be made.

In the context of the vertically mounted water heater an observable difference can be seen when compared to previous tests. The ambient temperature is within the required range and so is the controller temperature but the most noteworthy result in this case is how similar the temperatures inside the water heater are. The cold water temperature and controller temperature are very similar as expected for a vertically mounted water heater but the water on the cold water outlet side, the bottom, is basically the same temperature apart from one or two anomalies as seen in Figure 4-29.

In the context of the horizontally mounted water heater the results are quite surprising. For one the temperature variation inside the water heater is much smaller than those of the previous tests. Most noteworthy are the cold water averages. In previous tests the cold water side experienced temperatures of around 55 °C. In this test the temperature average is 61.4 °C, only 3.6 °C cooler than the control temperature. This could only be explained through much better insulation being used or a more even thickness of insulation around the internal water tank.

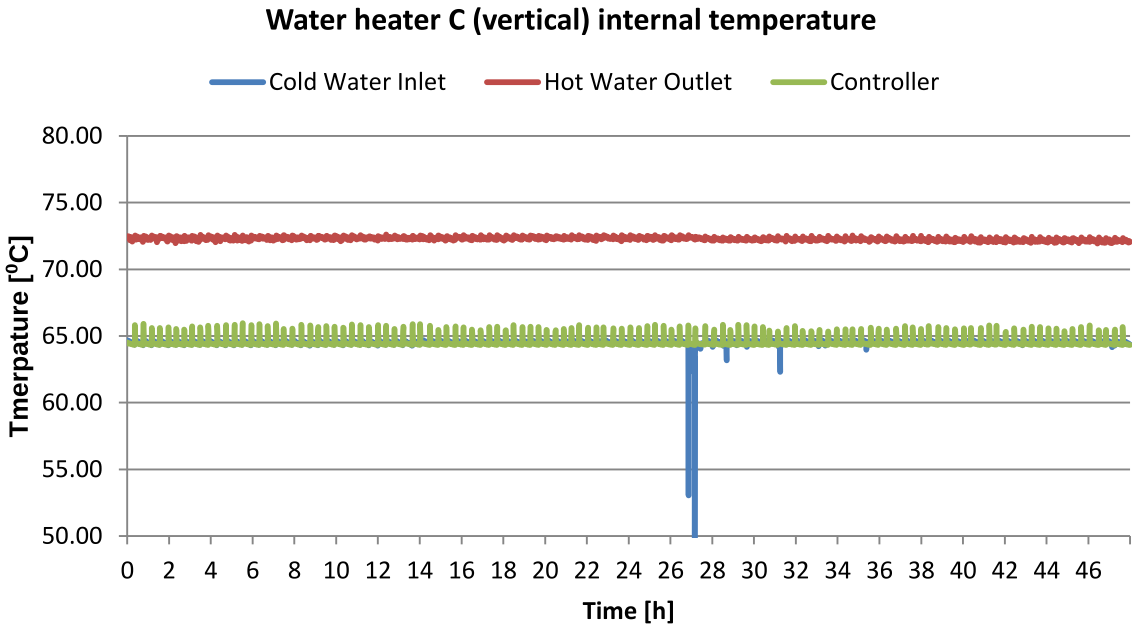


Figure 4-29: Water heater C (vertical) internal temperatures.

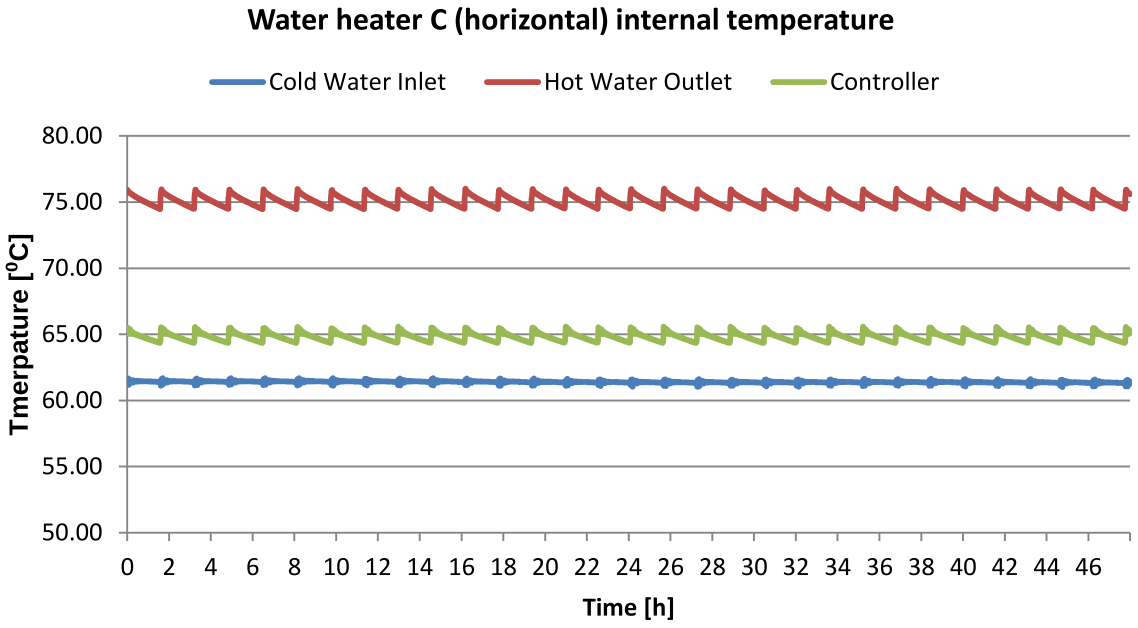


Figure 4-30: Water heater C (horizontal) internal temperatures.

With the element type being the same as the ones used in the previous tests, the results from the vertical test are not surprising. The fast switching nature of the element is still visible in Figure 4-31 and the regular on-off cycles are very evident in Figure 4-32 for the horizontal test.

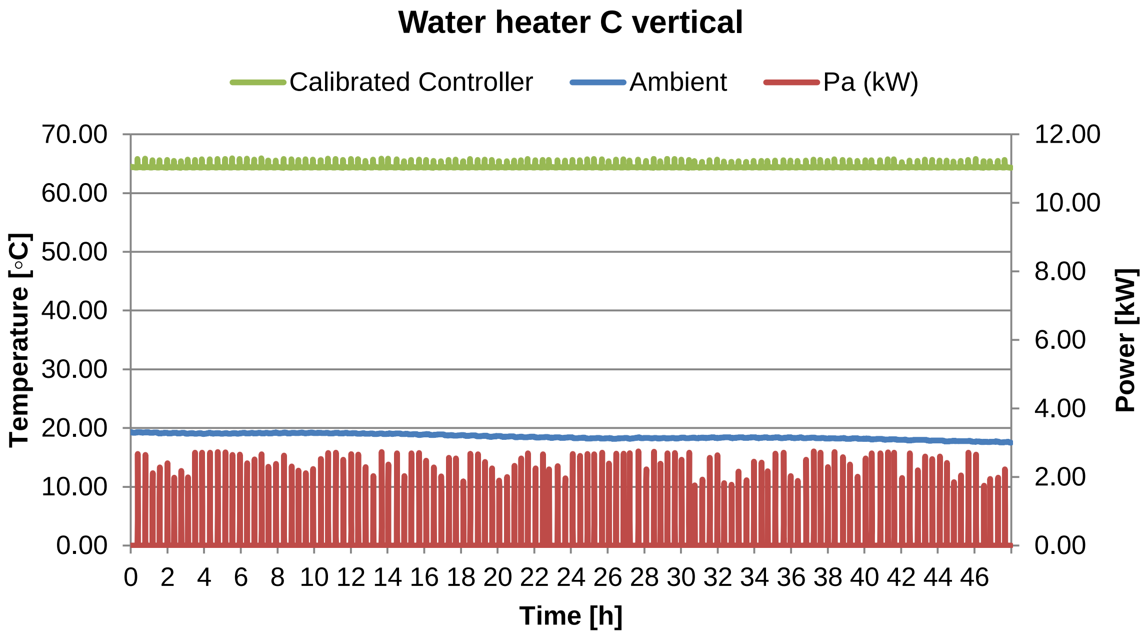


Figure 4-31: Water heater C (vertical) temperature and power usage profiles.

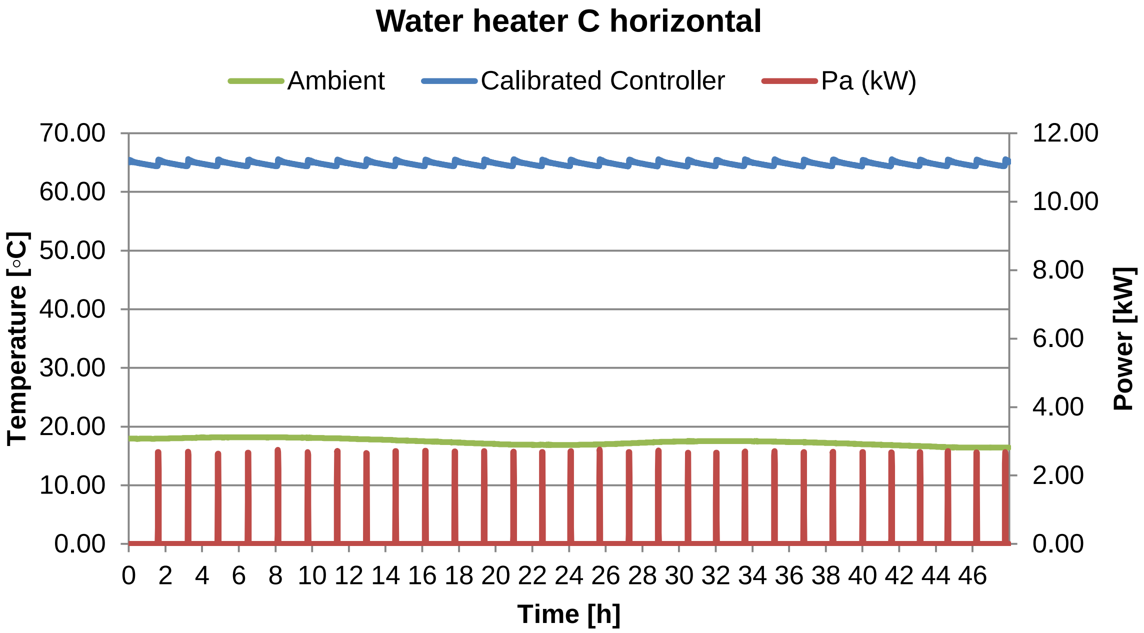


Figure 4-32: Water heater C (horizontal) temperature and power usage profiles.

4.4.3 Vertical Thermal Analysis

Water heater C is cased entirely in galvanized metal. Acquiring the infrared images didn't yield many results due to this. It did not feel very hot to the touch though.

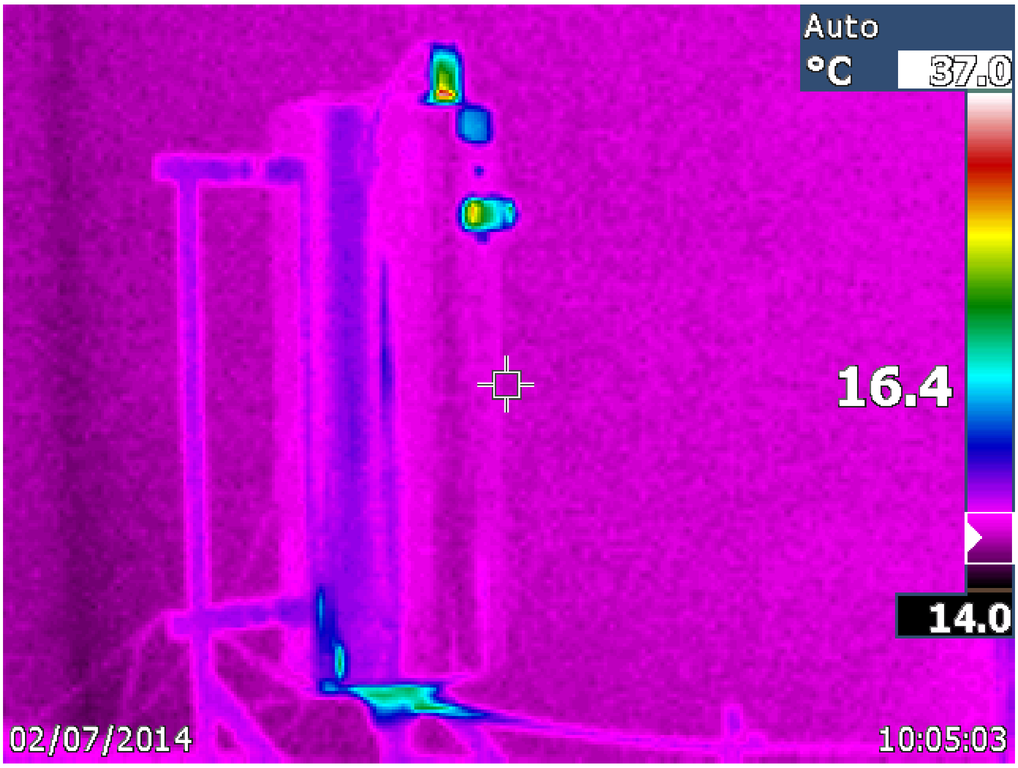


Figure 4-33: Water heater C (vertical), thermal image of the water heater.

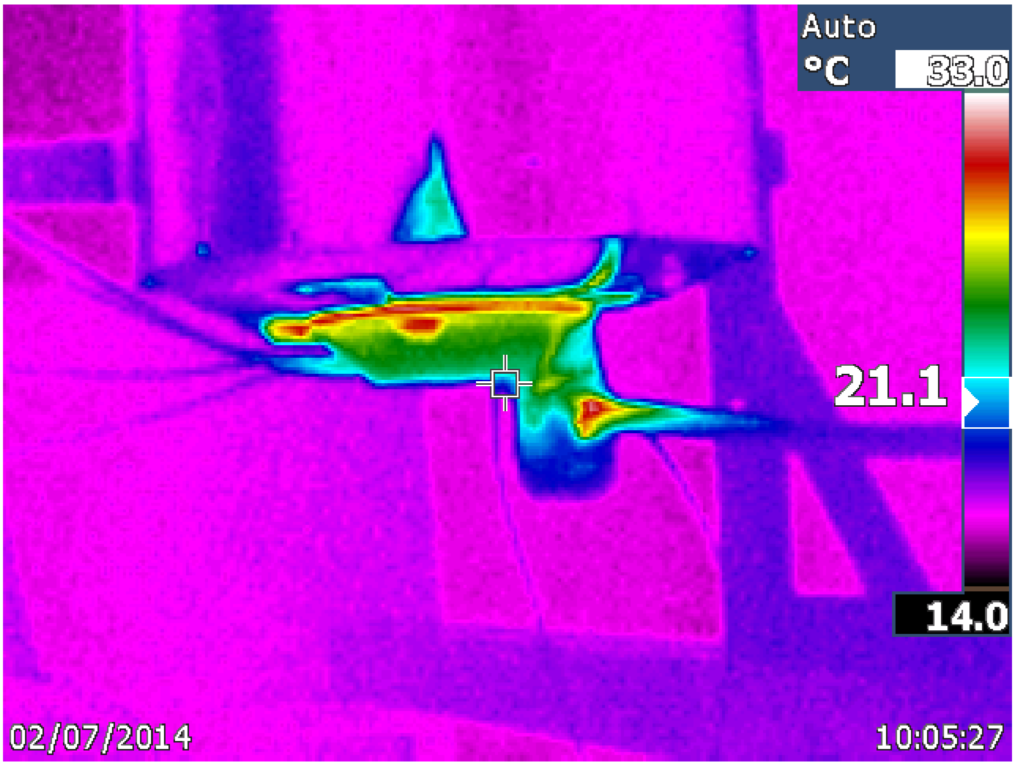


Figure 4-34: Water heater C (vertical), thermal image of the inlet faceplate.

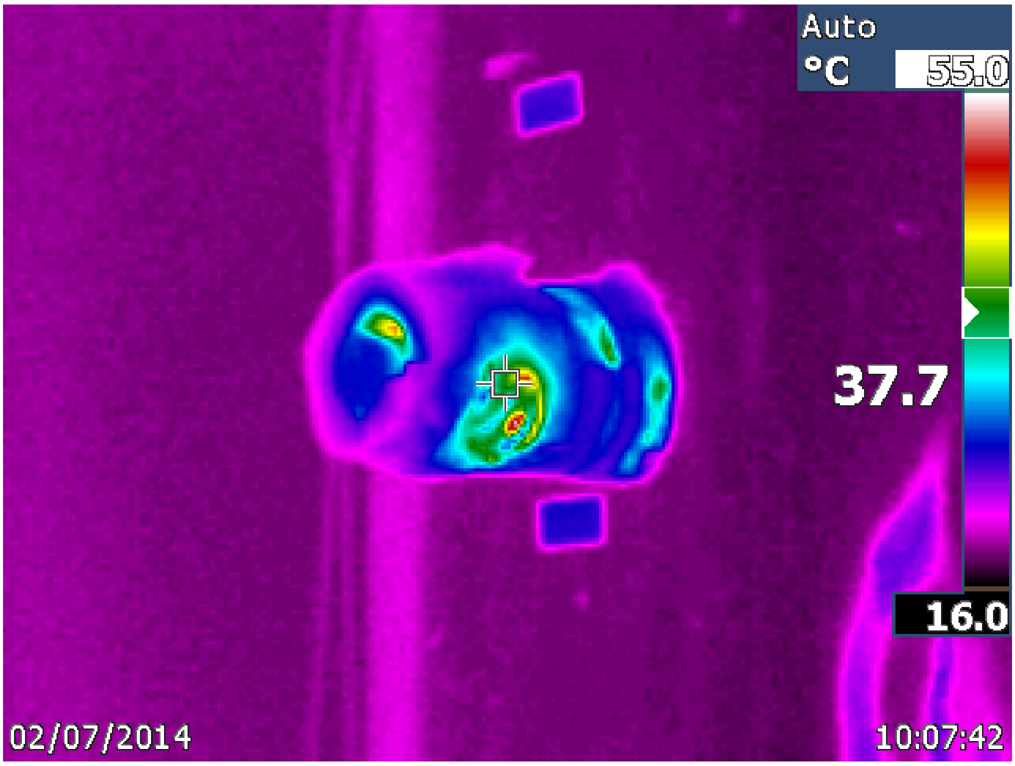


Figure 4-35: Water heater C (vertical), thermal image of the expansion valve.

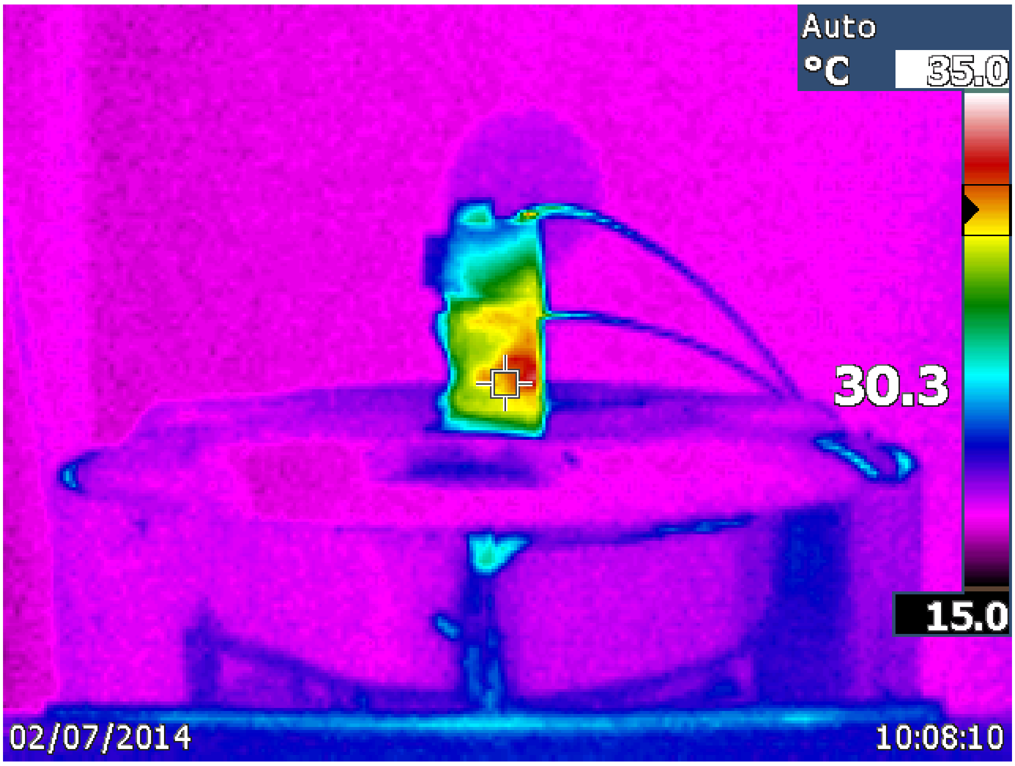


Figure 4-36: Water heater C (vertical), thermal image of the outlet faceplate.

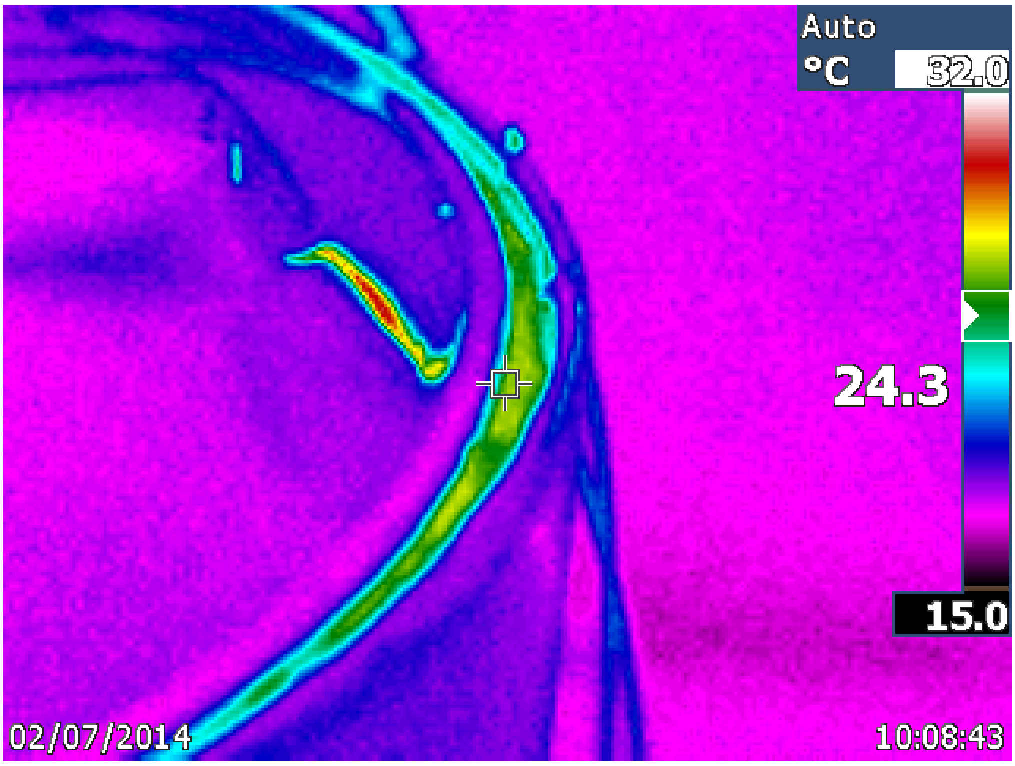


Figure 4-37: Water heater C (vertical), thermal image of the outlet faceplate rim.

Figure 4-33 shows the entire water heater. The problem areas are quite apparent and a general trend can be seen to develop. The heat losses appear to be around the element cover and element insert as well as the anode cap. Other problem areas are the expansion valve and the outlet pipe. The faceplates are of aluminium so the light is just reflected off instead of yielding any useful data.

Taking a closer look at the element insert area in Figure 4-34, it is apparent that the maximum temperature is 33 °C. This is a slightly higher temperature than the same area on water heater B (31 °C) but the much better than the 40 °C reached by water heater A in the same position. The model is similar to water heater A from a design perspective but much better from a thermal perspective.

4.4.4 Horizontal Thermal Analysis

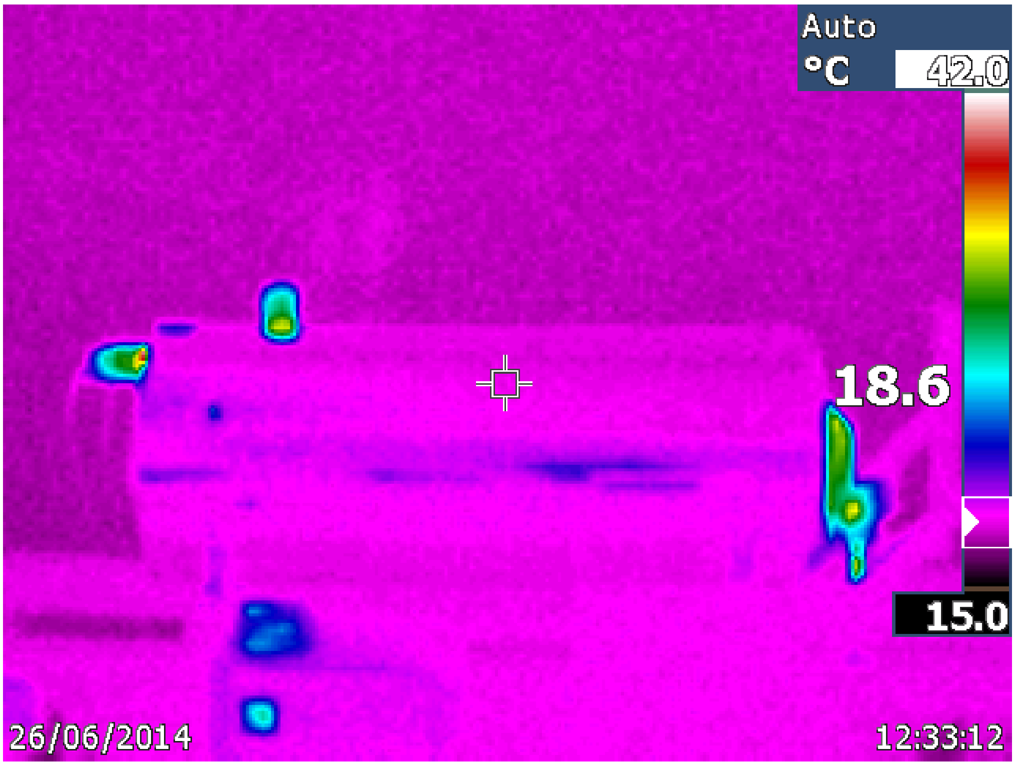


Figure 4-38: Water heater C (horizontal), thermal image of the water heater.

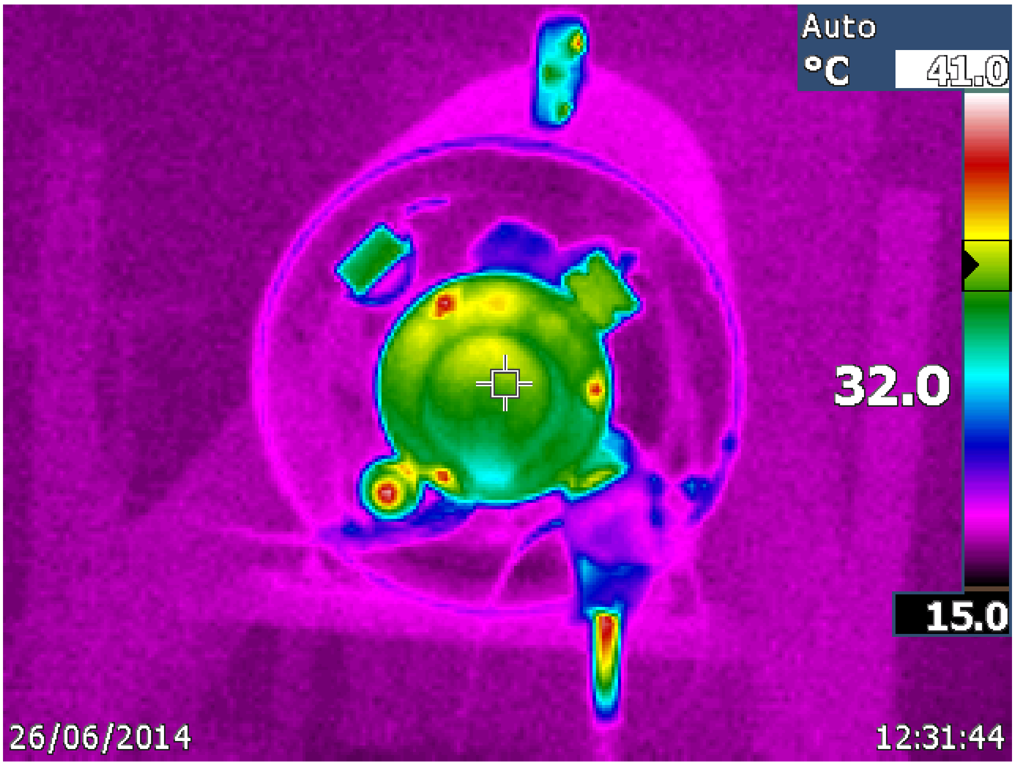


Figure 4-39: Water heater C (horizontal), thermal image of the inlet faceplate.

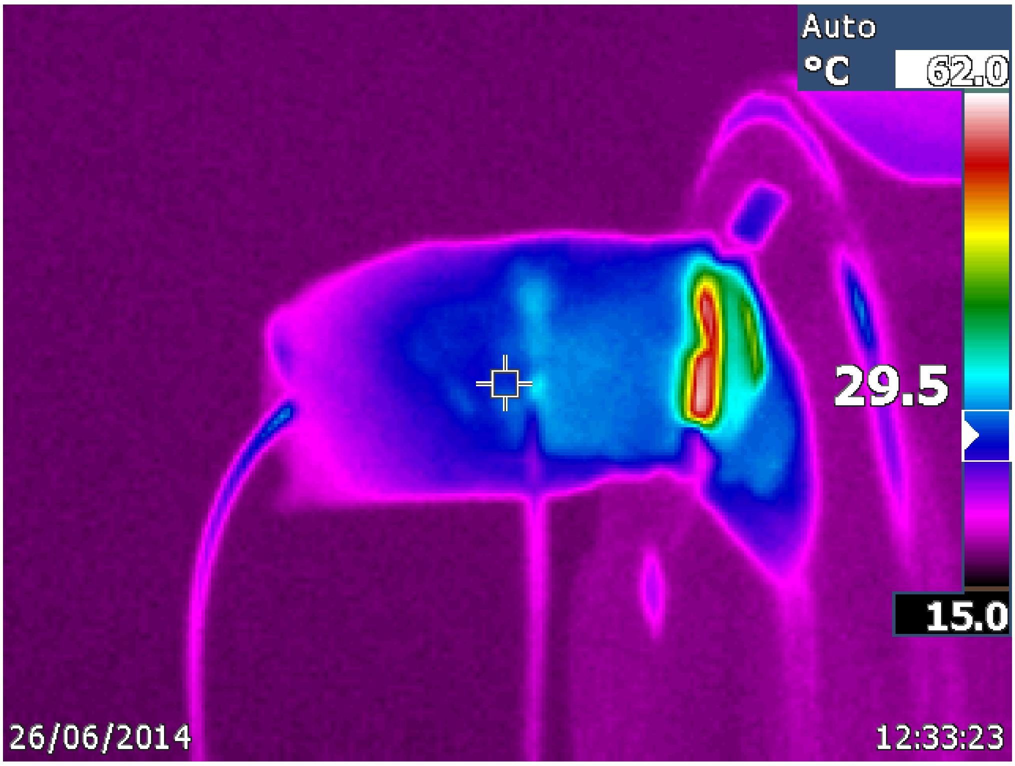


Figure 4-40: Water heater C (horizontal), thermal image of the outlet.

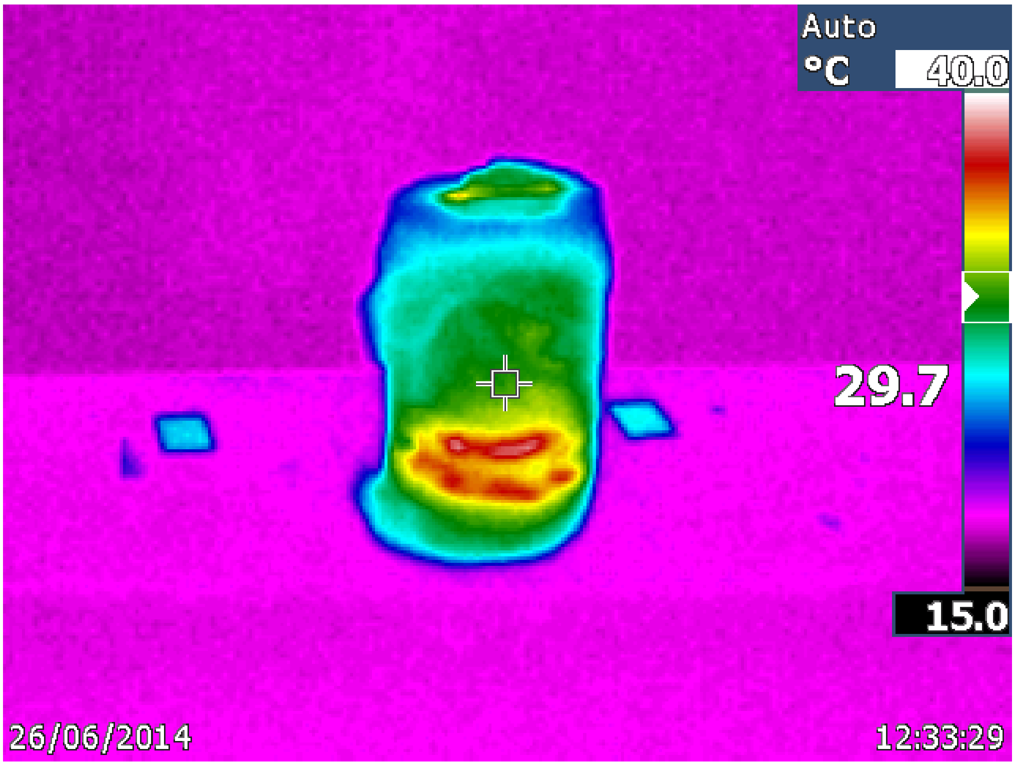


Figure 4-41: Water heater C (horizontal), thermal image of the explansion valve.

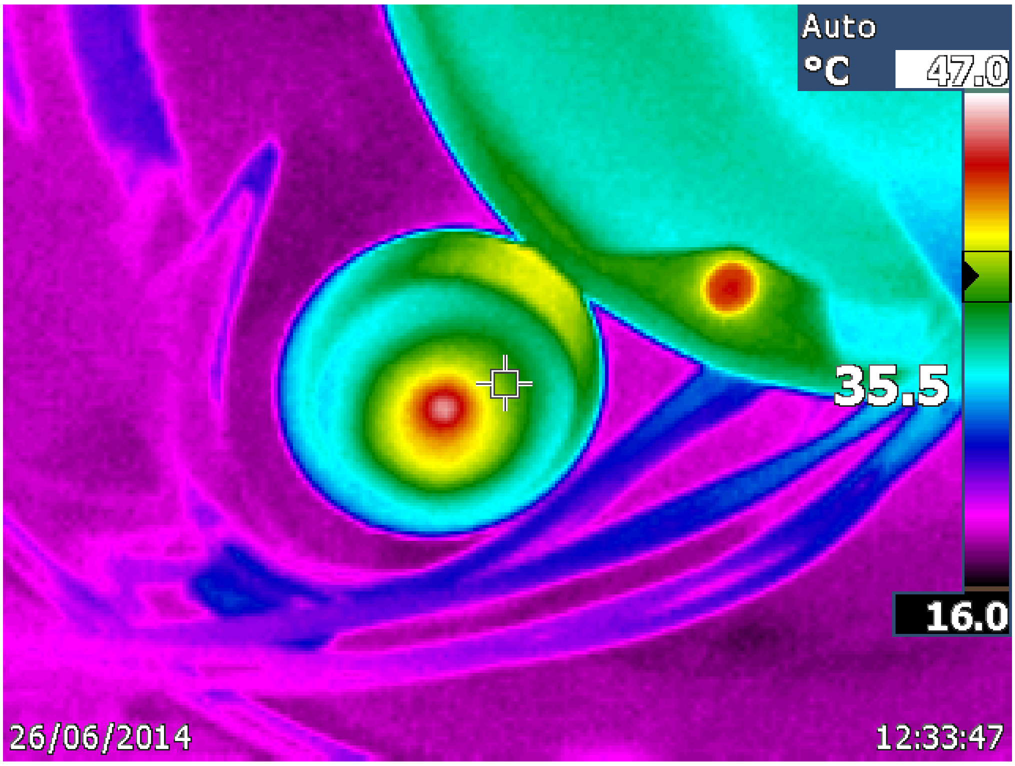


Figure 4-42: Water heater C (horizontal), thermal image of the anode cover and element cover screw.

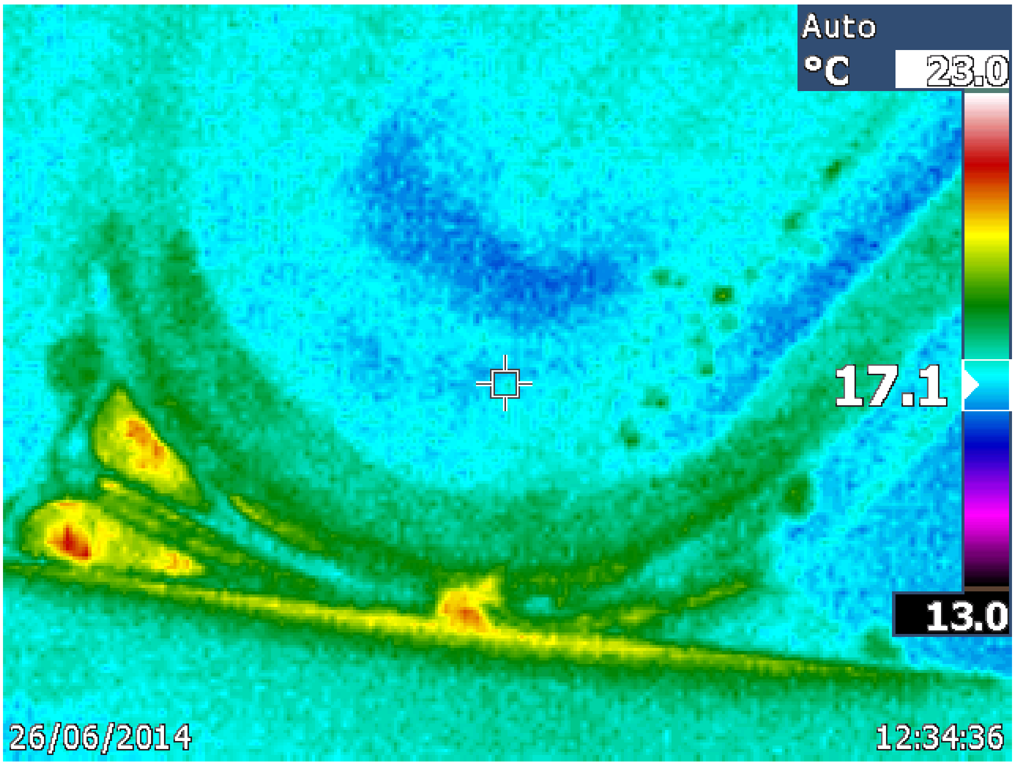


Figure 4-43: Water heater C (horizontal), thermal image of the feet.

In the vertical test the same problem areas occur as with the horizontal test. The element cover heats up to around 32 °C but the screws used heat up to 47 °C. Again this result is much better than the results from water heater A and B with the element area heating up to 65 °C, the set controller temperature.

The cover for the anode goes up to 47 °C incurring greater heat losses as can be seen in Figure 4-42.

The feet are made from the same galvanized metal as the outer barrel shell. This does not allow for the temperature of the feet to be measured due to the material being too reflective. The temperature that is measured by the camera is 23 °C which, if accurate, means that the support structure for the feet is designed with the heat efficiency in mind.

4.4.5 Tear Down Analysis

The results from the standing loss test are much better than the first two tests. Investigating the water heater further from an insulation perspective yields a very interesting find. The insulation of water heater C is almost uniform all around the internal water barrel. Another observation is that the insulation is much denser in comparison to the previous water heaters. The measurements taken of the thickness reveal that although the insulation thickness is not the same as that of the previous water heaters, it is much more uniform as can be seen in Table XIV.

Table XIV: Water heater B insulation thickness.

Water heater insulation	**Thickness [mm]**
Bottom	25
Top	27

The images show the uniformity of the insulation quite well. Figure 4-44 shows the sacrificial anode as well as the outlet points. The manufacturer made the water heater with versatility in mind. On the top right hand side of Figure 4-44 two outlet points can be seen. Either one can be used for either the expansion valve or the hot water outlet. Figure 4-45 shows the inlet on the bottom right just underneath the element cavity. The extension is designed to direct the inflow of cold water away from the controller temperature probe to avoid unnecessary on-off switching. Again it is evident that the insulation behind the element plate is non-existent and will incur heat loss.

Figure 4-44: Water heater C tear down side 1.

Figure 4-45: Water heater C; tear down side 2.

4.5 Water Heater D

A galvanized metal shell encases the entire water heater similar to the one in water heater C. The water heater has a dedicated hot water outlet at the top of the cylinder of the water heater, different from all the rest. This may be attributed to the fact that the water heater is only mountable in the horizontal position and therefore the hot water outlet may be placed anywhere along the top of the water heater.

4.5.1 Specifications

No IP rating was given with the previous water heater so the assumption was that it was the same as the previous water heaters. However water heater D has an IP rating of X1 thus meaning it is not protected from solids at all and can only withstand vertically falling drops. Otherwise the water heater is quite similar.

Table XV:Water heater D specifications.

Volts	**Volume**	**Power**	**Pressure**	**Orientation**	**IP**
230V/50Hz	150l	3kW	400kPa	Horizontal	X1

4.5.2 Standing Loss Test

Once again the frame has modified feet. The piping is altered to accommodate the new water heater. Instead of the heat-well used in previous experiments, the pipes are introduced to the water heater at a slight angle. This is due to limited piping and the alternate design of the water heater, the piping is connected in a different fashion. The results for the test are given in Table XIII.

Table XVI: Water heater D standing loss test results.

	Horizontal orientation		
Measured entity [°C]	**Mean**	**Min**	**Max**
Ambient temperature	21.0	20.3	21.5
Control temperature	64.5	64.3	66.6
Cold water temperature	64.5	63.8	65.3
Hot water temperature	69.7	69.0	70.5
Standing losses [kWh]			2.54

The ambient temperature is slightly higher than the required value, but still within range for the duration of the test. The controller temperature remains close to the required temperature but varies with 2.3 °C, slightly more than desired. The cold water temperature remains very close to the control temperature, which is characteristic of thicker insulation at the bottom and usually results in a better standing loss value but this water heater does not share that trait. The hot water temperature is also not as high as in previous water heaters so there might be heat losses towards the top. These heat losses cost the water heater energy, as can be seen in the calculated standing loss value. The maximum allowable standing loss value for South African water heaters in South Africa, as can be seen in Table I, is 2.59 kWh/day and this water heater comes very close to that. Even when using the standard 20 °C value in Equation 2.2.1 yields a result of 2.51 kWh/day.

Reviewing the recorded data, it is evident that the cold water stays at a similar temperature to the controller temperature when looking at Figure 4-46. The hot water seems to still be stabilizing at a very slow rate but the change in temperature is only 1.5 °C for the duration of the test.

In the context of Figure 4-47, the frequency of the power usage is very uncharacteristic of the horizontally mounted water heaters. In previous tests the element switched on once or twice every two hours maximum but in this test the water heater switches on around 4 to 5 times every two hours. This may be due to the element being different in shape (linear) or the temperature probe being displaced, or that the water heater is just less efficient in terms of heat storage. Reviewing the data, when the element switches on, the temperature climbs at a rapid rate, as seen in previous tests. What does not coincide is that the temperature drops at a similar rate suggesting that the hot water rising off the element shocks the thermocouple causing it to switch off before proper mixing has occurred.

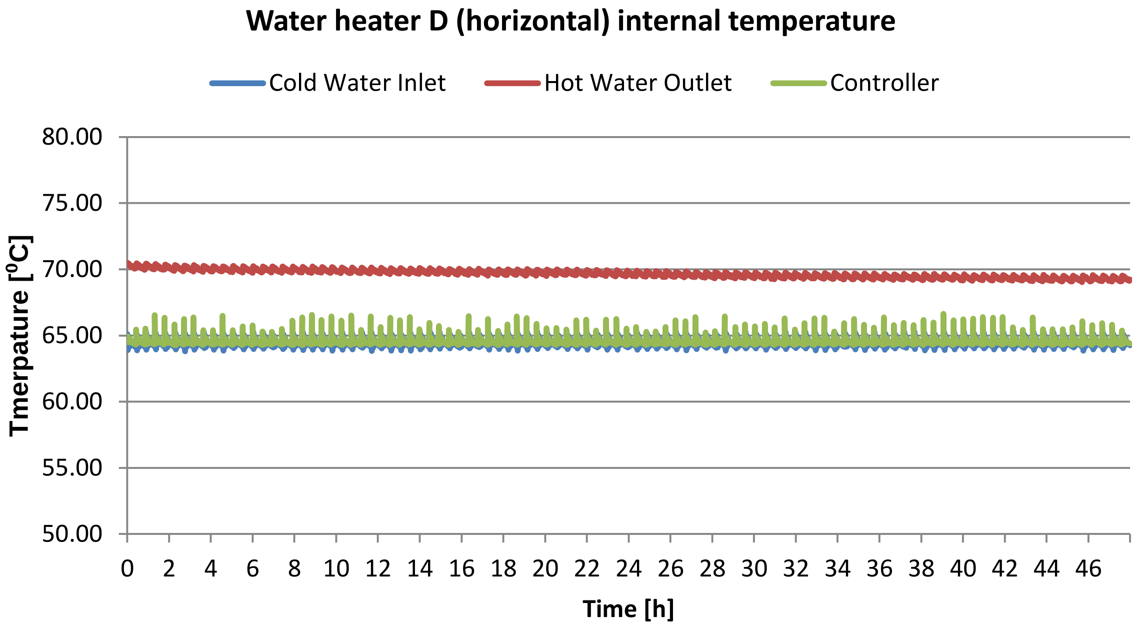


Figure 4-46: Water heater D (horizontal) internal temperature.

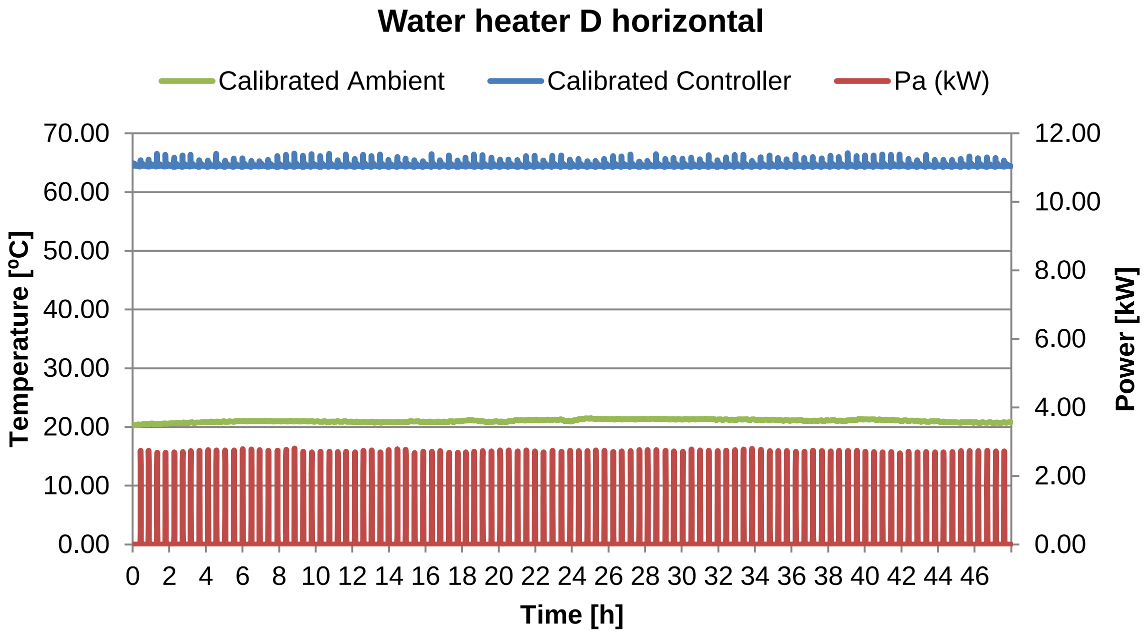


Figure 4-47: Water heater D (horizontal) temperature and power usage profiles.

4.5.3 Thermal Analysis

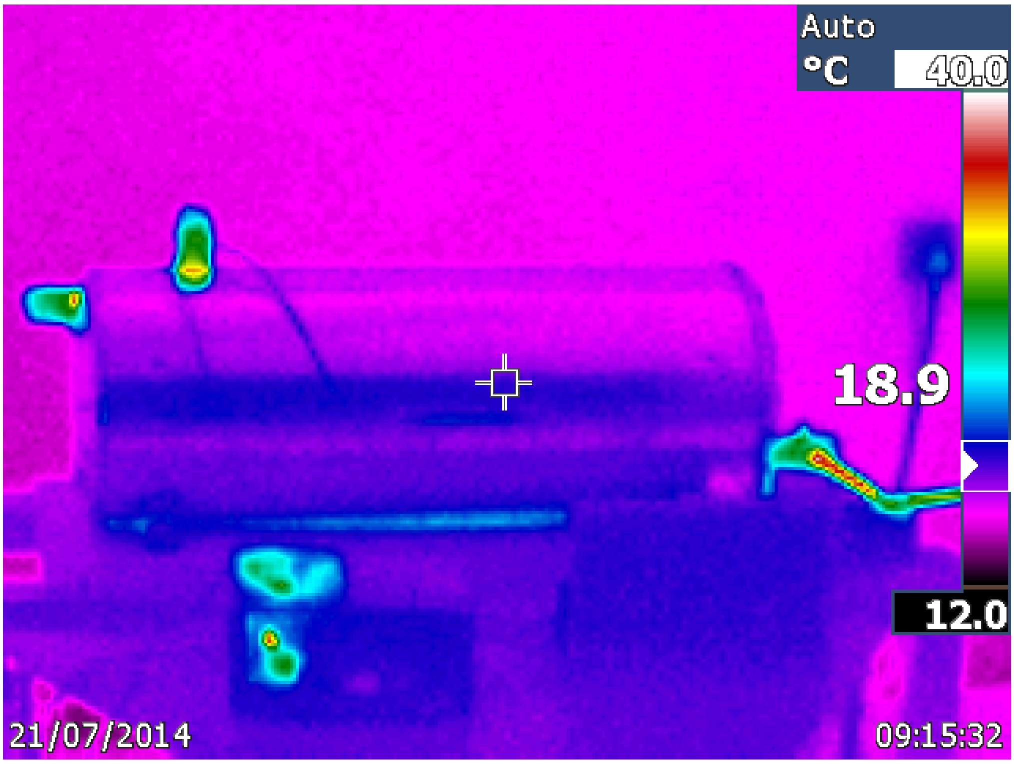


Figure 4-48: Water heater D (horizontal) thermal image of the water heater.

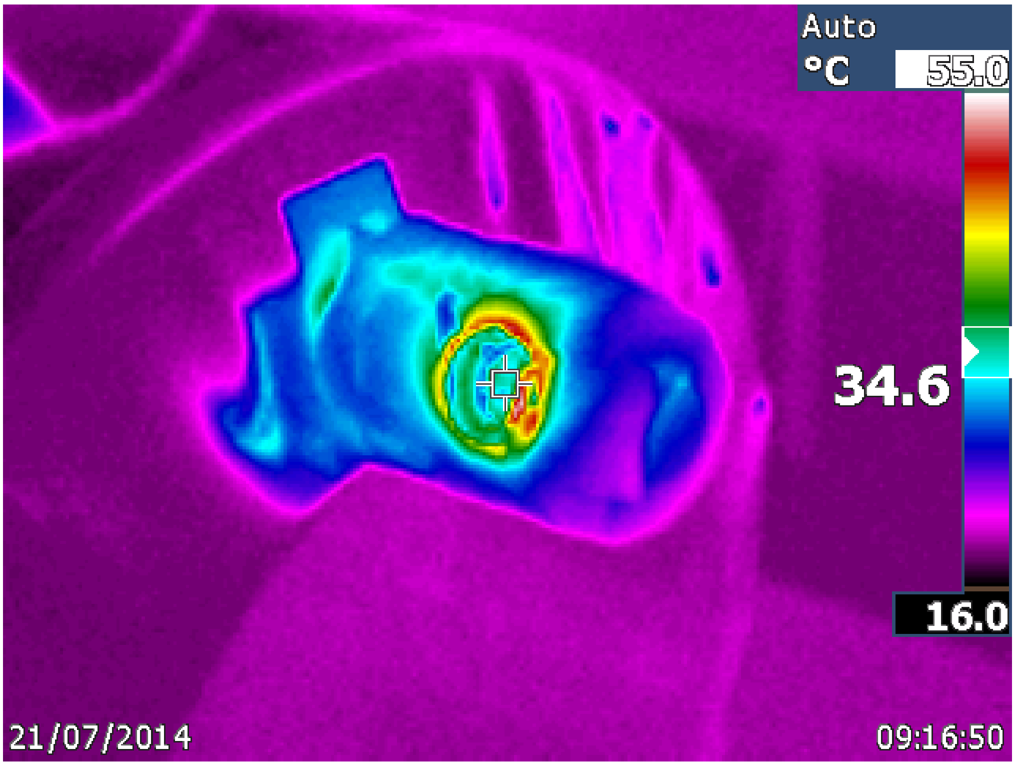


Figure 4-49: Water heater D (horizontal) thermal image of the expansion valve.

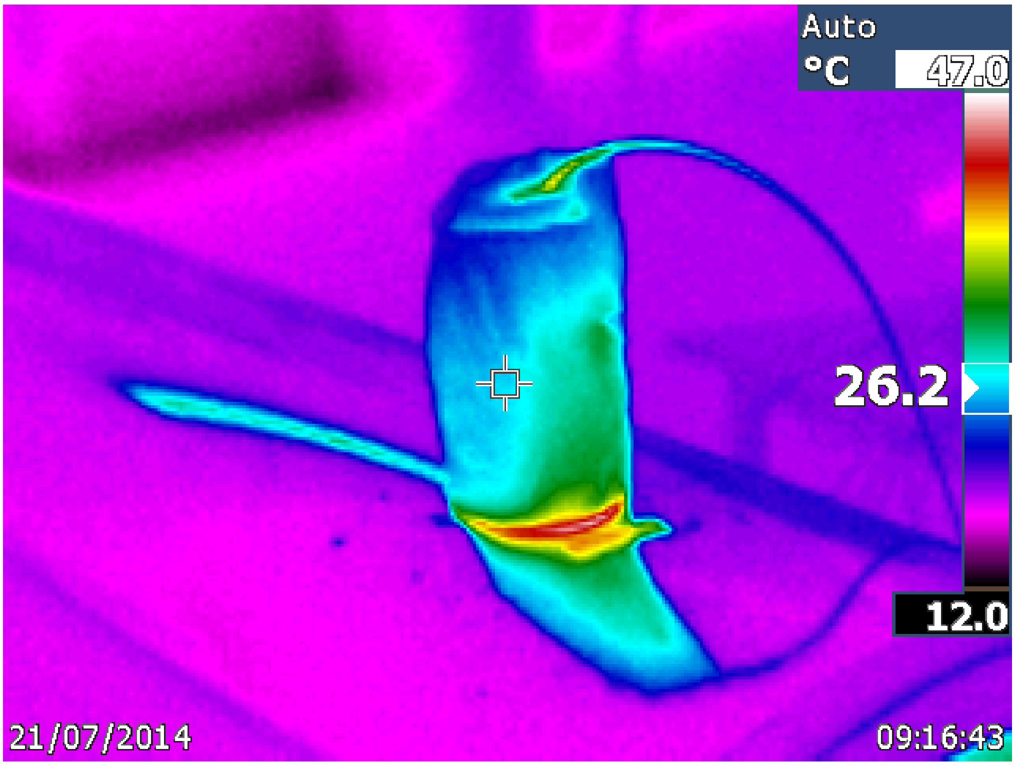


Figure 4-50: Water heater D (horizontal) thermal image of the outlet pipe.

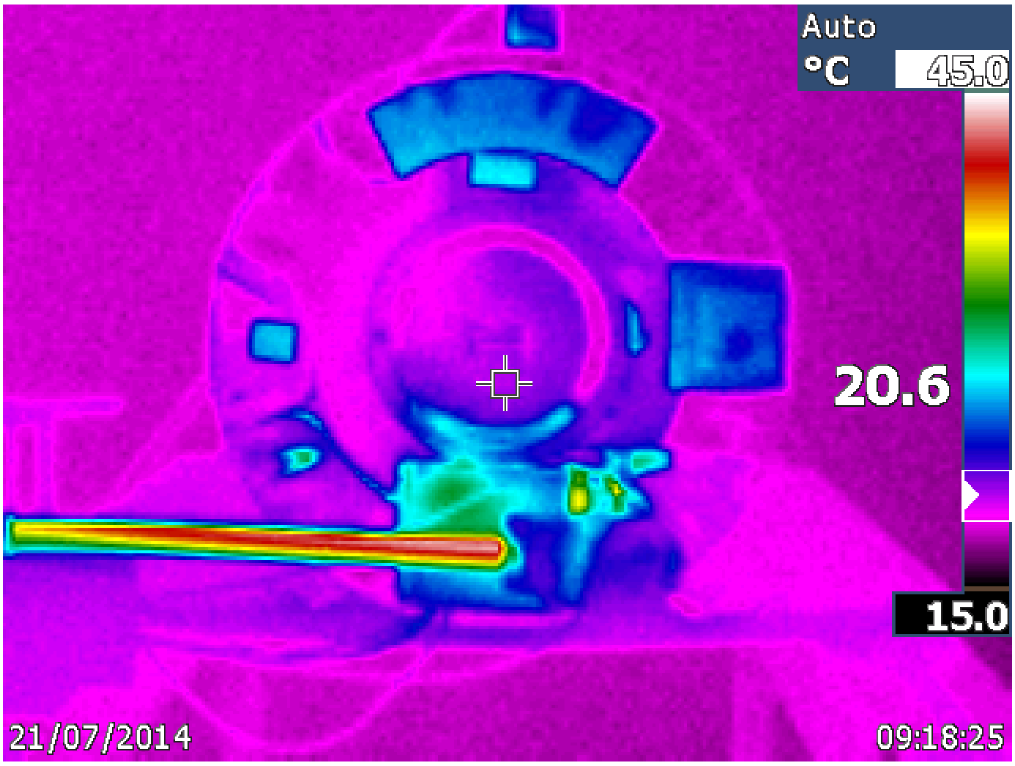


Figure 4-51: Water heater D (horizontal) thermal image of the inlet faceplate.

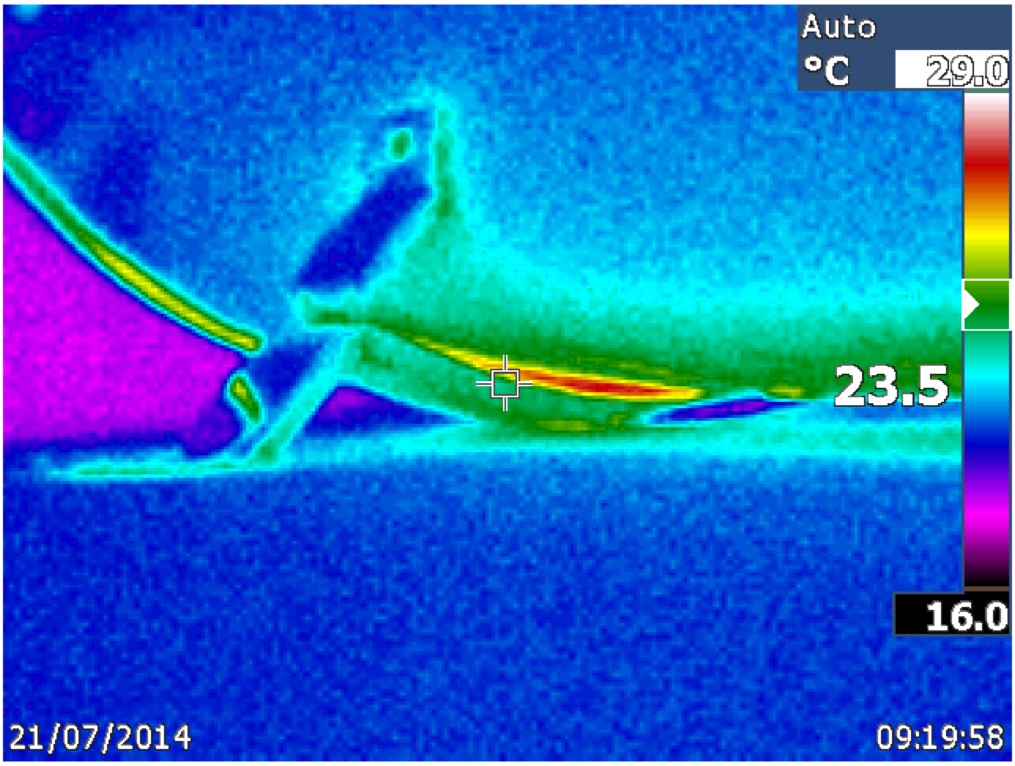


Figure 4-52: Water heater D (horizontal) thermal image of the feet.

Water heater D is also covered entirely in a galvanised metal shell thus making the results inconclusive again. The only areas that are looked at are the pipe inserts and the feet. In Figure 4-49 the expansion valve reaches a temperature of 55 °C.

The insulation around the outlet pipe reaches a temperature of 47 °C making it probable that the insert is quite heat conductive.

The temperature probe cover is made from metal sheeting. This resulted in the IR imaging being inconclusive. To get a better idea of the temperature around the area, the pipe is taken into consideration. The cold water pipe reaches a temperature of 45 °C in steady state (Figure 4-51) thus suggesting that the insulation isn't enough and the inlet isn't well designed.

The stickers on the water heater in Figure 4-51 reach a temperature of 25 °C. Seeing as they are not reflective the heat profile in the region can be trusted to a certain degree. If the shell of the water heater reaches a heat of 25 °C all the way around it means that the insulation is sub-grade and the water heater is not very efficient.

4.5.4 Tear Down

The results of the insulation measurement as seen in Table XVII show that the water heater has much thinner insulation at the top. The bottom is thicker than that of water heater A and B. the results indicate that the water barrel is fairly centred. The spacers that held the internal water barrel in place can be seen in Figure 4-53 and Figure 4-54 at the top of the water heater. The material used is polystyrene and is quite heat conductive, coming in with an R-value of R5. This is not as good as the foam's R-value which is still unknown but should be better.

Table XVII: Water heater D insulation thickness.

Water heater insulation	**Thickness [mm]**
Bottom	20
Top	23

Figure 4-53 shows the hot water outlet pipe on the top left of the water heater and the cold water inlet at the bottom right. The inserts are directly attached to the internal barrel and have no plastic innards or sleeves and thus allow for significant heat transfer into the water pipes. The cold water inlet is merely covered by a metal bowl and does nothing to minimise the speed of the cold water mixing with the hot water. This may lead to the element being exposed to the cold water coming in faster and thus switching on and off at a greater frequency as is seen in the results of the test (Figure 4-47).

Figure 4-54 shows the other half of the hot water outlet pipe at the top right of the water heater and the element at the bottom left of the water heater. The cavity where previously the spiral element was inserted is designed to only house the temperature probe. Thus any heat plumes coming off the element would influence the measurement directly and result in the element switching off. Then, once the water has mixed, the element switches on, resulting in heat plumes rising again and this trend continues leading to an endless cycle of switching.

The hole for the anode is above the element but, for the tear down analysis, the anode has been removed. The expansion valve insert is on the top right of the faceplate of the water heater.

Figure 4-53: Water heater D tear down side 1.

Figure 4-54: Water heater D tear down side 2.

4.6 Water Heater E

The manufacturer of water heater E has a main focus on integrating water heaters into the solar water heating environment.

The water heater is designed with a galvanised cylindrical shell and is capped off with two plastic faceplates. The element design is similar to water heater D where the element is placed below the temperature probe to the left. The hot water outlet is on top of the water heater again and the expansion valve is on the opposite faceplate to the element.

4.6.1 Specifications

The design of the water heater is such that it omits the use of a sacrificial anode. The inside is coated with a Cross-linked Polyethylene coating and the pipe inserts are coated with the same to prevent corrosion.

Table XVIII:Water heater E specifications.

Volts	Volume	Power	Pressure	Orientation	IP
230V/50Hz	150l	3kW	400kPa	Horizontal	X4

4.6.2 Standing Loss Test

The water heater is only designed for horizontal orientation, which is the only orientation tested. The results for the standing loss test are available in Table XIX.

Table XIX: Water heater E standing loss test results.

	Horizontal orientation		
Measured entity [°C]	**Mean**	**Min**	**Max**
Ambient temperature	21.6	21.1	22.5
Control temperature	64.4	64.3	66.1
Cold water temperature	60.8	60.6	60.9
Hot water temperature	71.2	70.9	71.5
Standing losses [kWh]			1.92

The ambient temperature is slightly above the required temperature but still within the specifications of the SANS 151 testing guidelines. The control temperature is also within spec and only varies by 1.8 °C. The cold water temperature is only 3.6 °C below the controller temperature suggesting that the insulation at the bottom is thick. The hot water temperature is 6.8 °C above the controller temperature which is similar to most of the previous tests. Figure 4-55shows the distribution of the internal temperatures of the water heater.

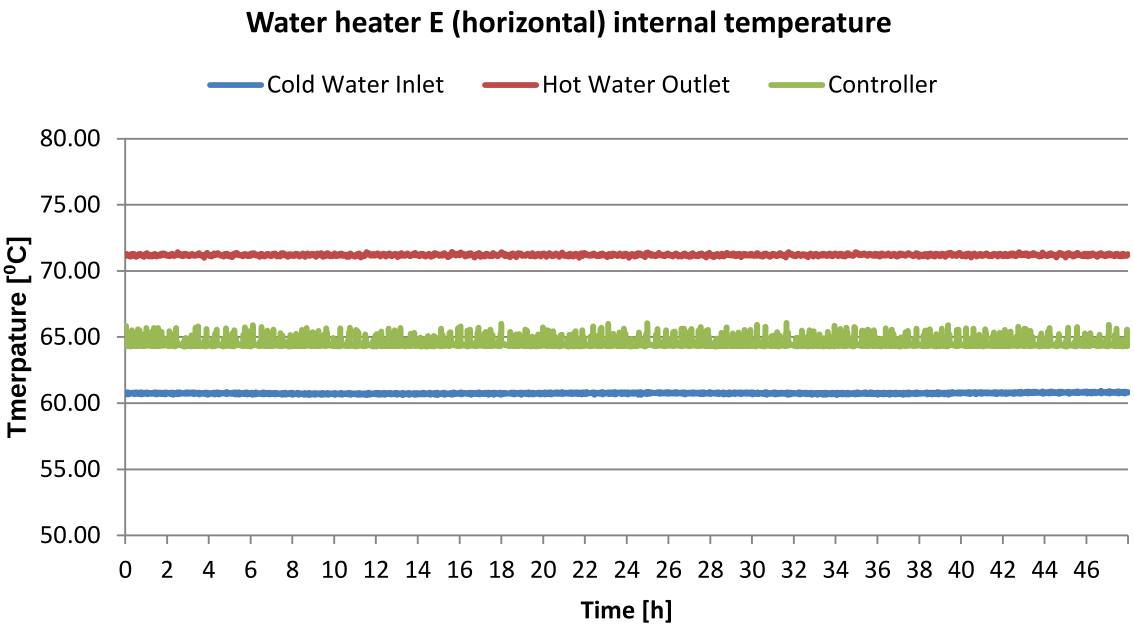


Figure 4-55: Water heater E (horizontal) internal temperatures.

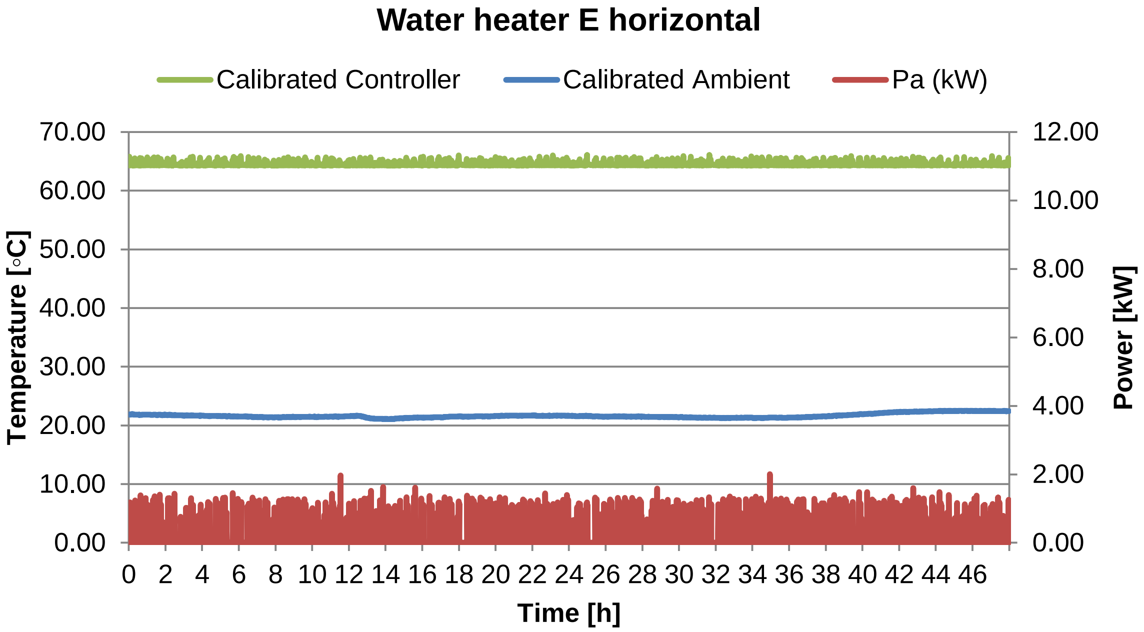


Figure 4-56: Water heater E (horizontal) temperature and power usage profiles.

The theory stated with the previous water heater, that the heat plumes influence the temperature probe of the water heater. This is confirmed by the results in Figure 4-56. The elements fast switching nature can be attributed to the water heater temperature probe being placed above the element resulting in a more unpredictable behaviour.

The ambient temperature does not affect the calculations significantly. The standing losses calculated using the standard ambient mean of 20 °C results in a standing loss of 1.90 kWh/day.

4.6.3 Horizontal Thermal Analysis

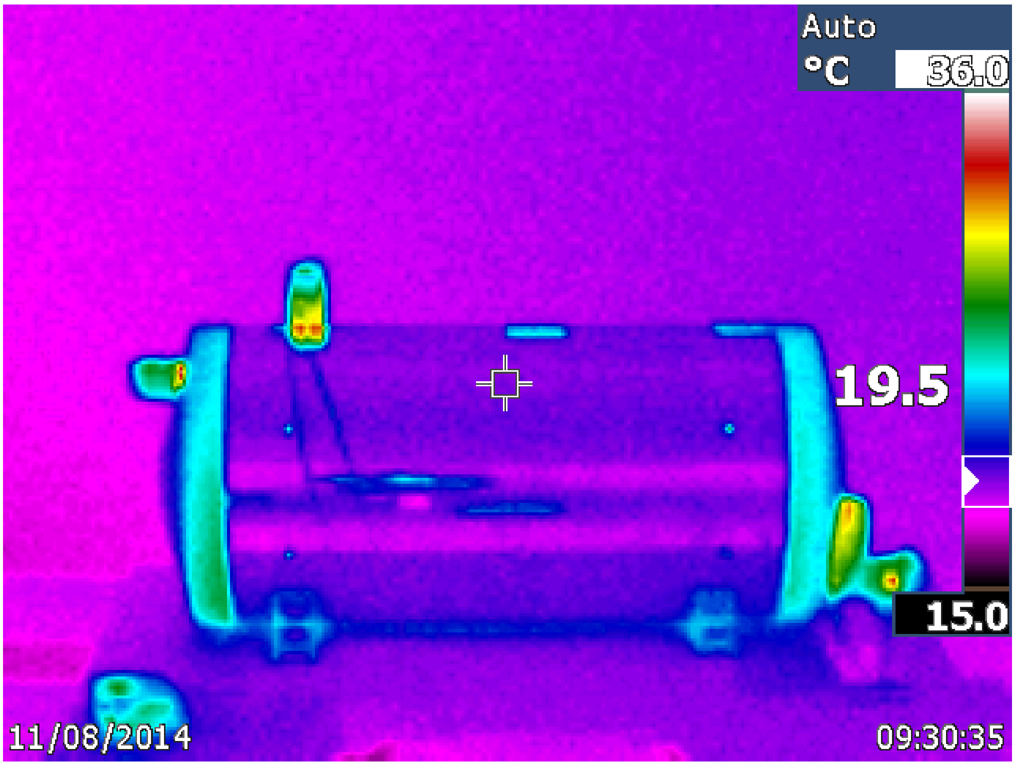


Figure 4-57: Water heater E (horizontal) thermal image of the water heater.

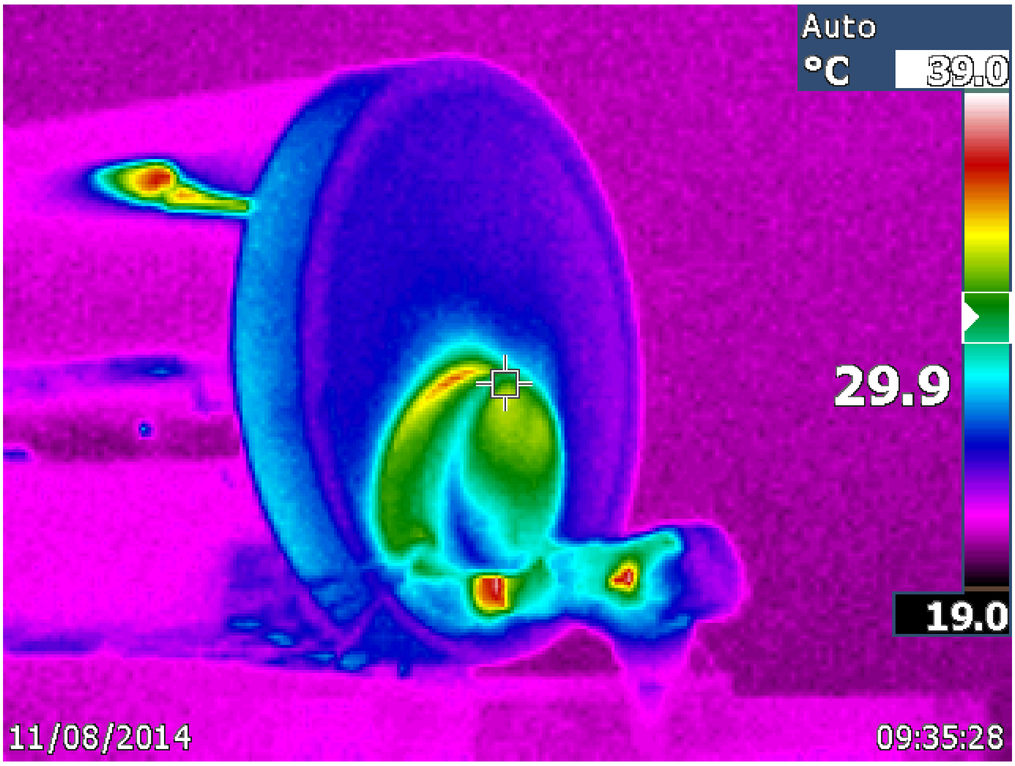


Figure 4-58: Water heater E (horizontal) thermal image of the inlet faceplate.

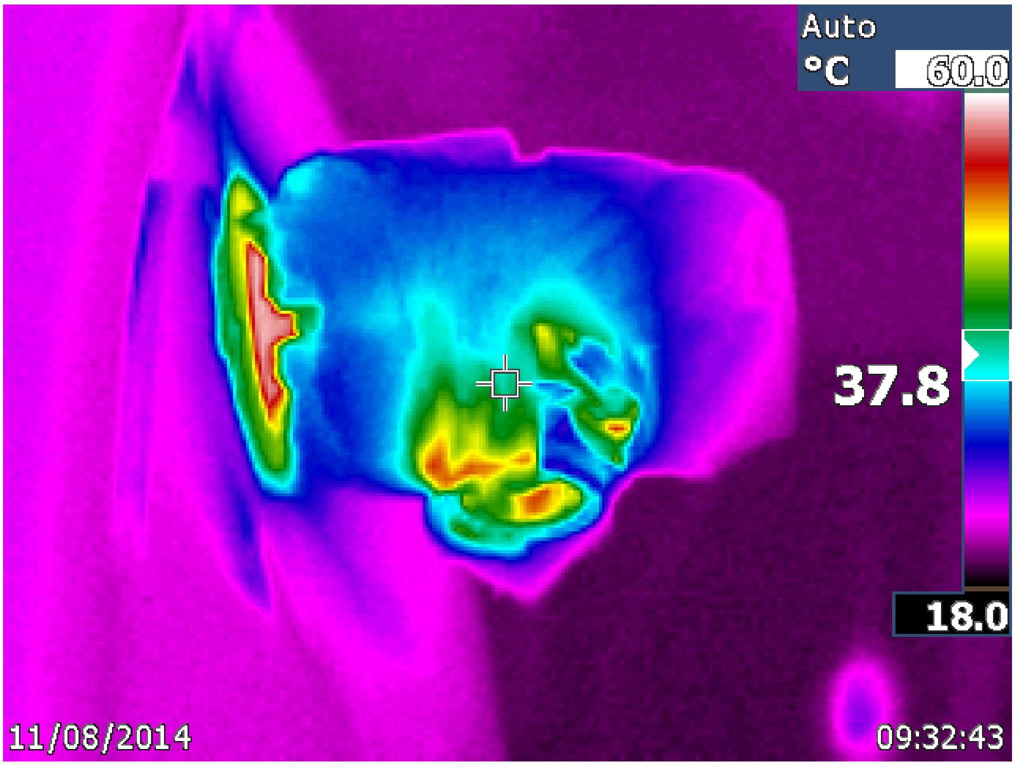


Figure 4-59: Water heater E (horizontal) thermal image of the expansion valve.

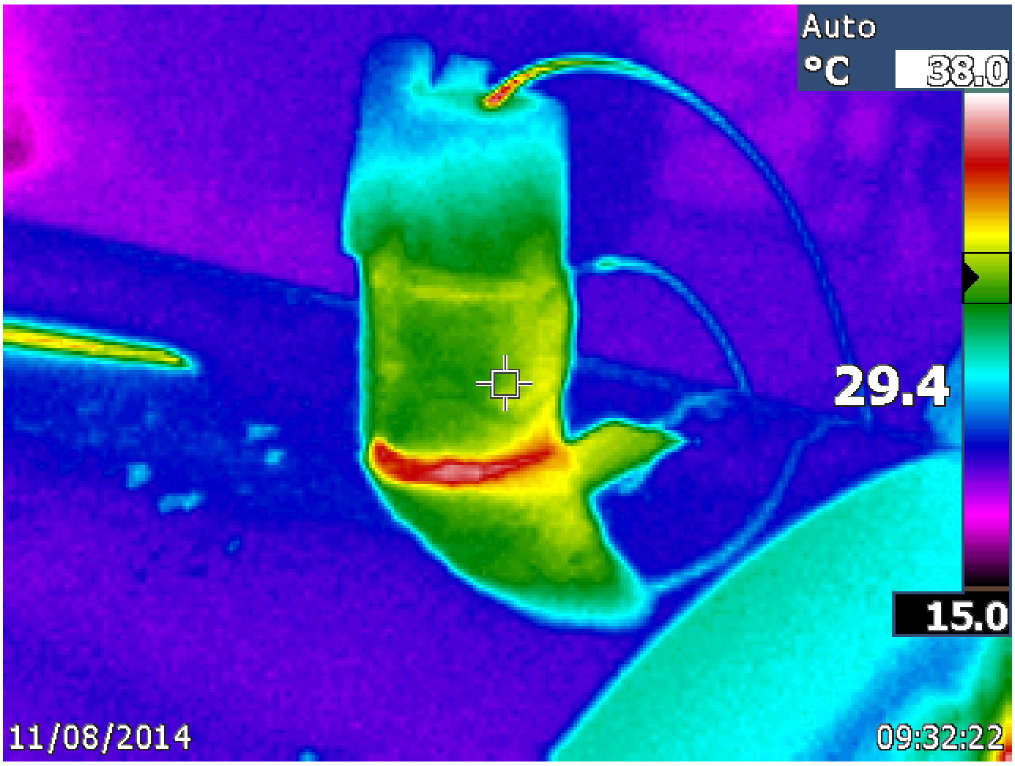


Figure 4-60: Water heater E (horizontal) thermal image of the outlet pipe.

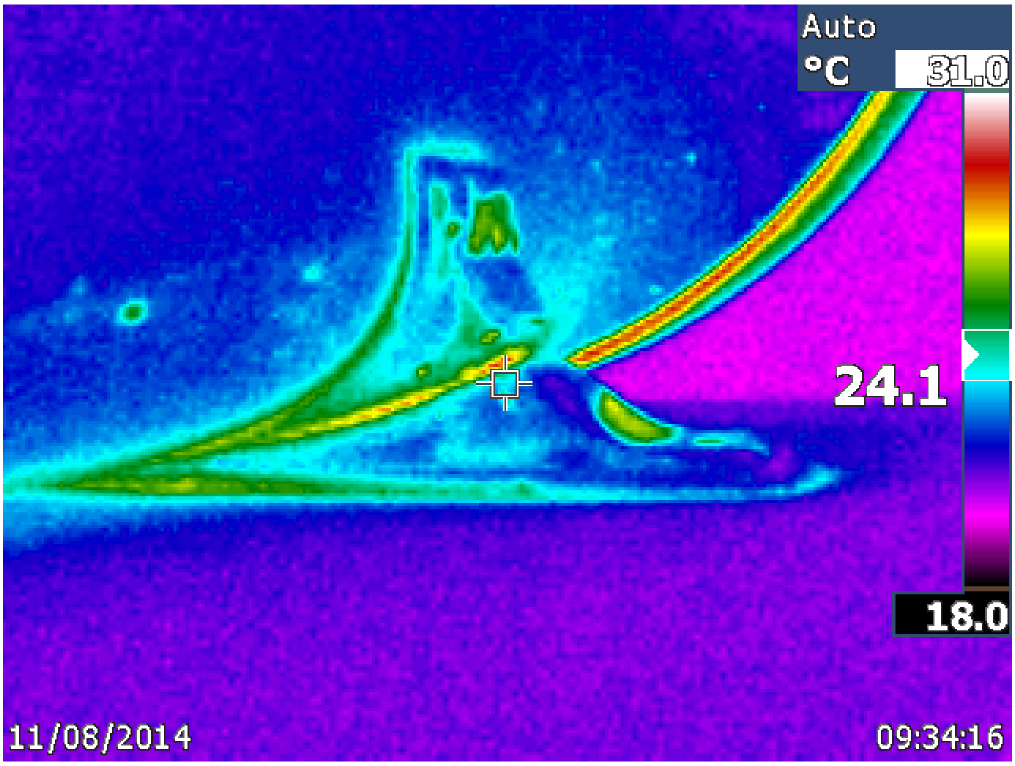


Figure 4-61: Water heater E (horizontal) thermal image of the feet.

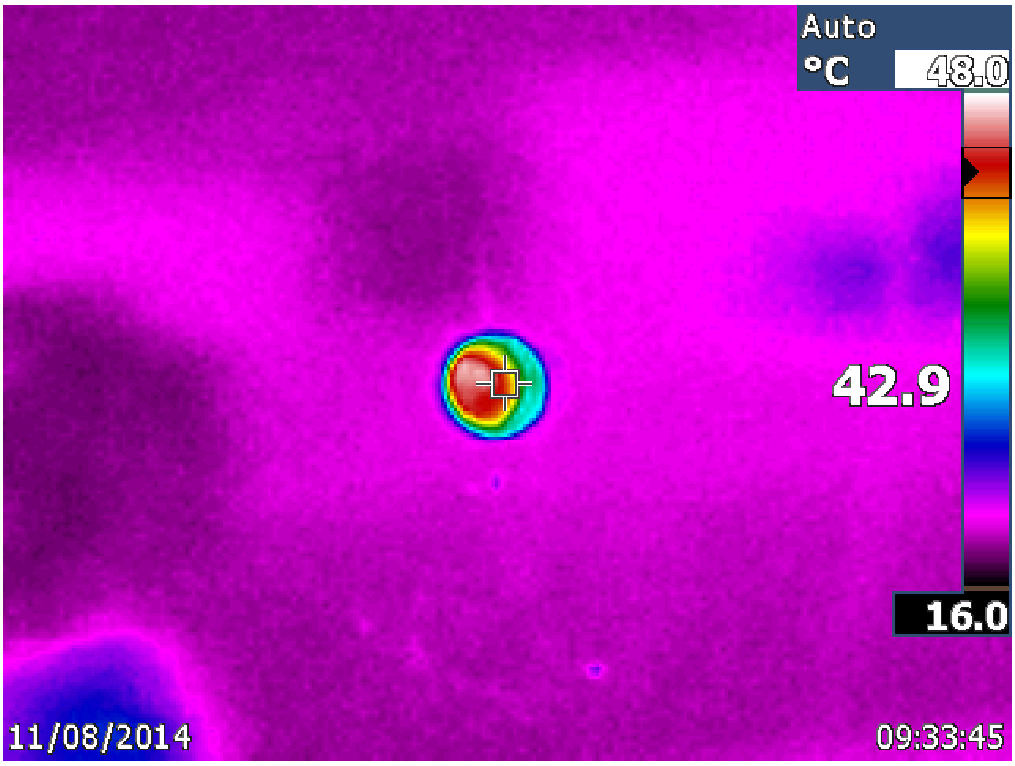


Figure 4-62: Water heater E (horizontal) thermal image of the additional support screw inserts.

Water heater E has plastic faceplates, so the heat analysis is easier to complete. The faceplates reached a temperature of 25 °C, 5 degrees higher than the nominal ambient temperature. A closer look at the inlet faceplate in Figure 4-58 reveals that the area around the element reaches a temperature of 30 °C to 40 °C in the extremes.

The expansion valve on the other faceplate has an internal temperature of 60 °C seen in Figure 4-59 revealing a very heat conductive insert built into the water heater. The same can be said for the hot water outlet pipe where 38 °C is the highest recorded temperature.

A look at the feet reveals that the design is somewhat better than the previous models with a temperature of only 30 °C being reached. It’s important to note the reflection of the foot in Figure 4-61 shedding some light into how the heat of the shell is not picked up by the infrared camera

In the first figure, Figure 4-57, a few small hot spots were noticed. On closer inspection they turned out to be extra screw inserts for feet positions. This is a bad oversight on the part of the designers as the heat losses there are quite substantial as seen in Figure 4-62.

4.6.4 Tear Down

The insulation is quite thick on the ends of the water heater. This lead to the water heater not being cut quite straight.

In Figure 4-63 the left side has a wedge which occurred when the water heater split open. The wedge is also visible on the right side of the water heater in Figure 4-64. The hot water outlet pipe is also visible on the top left of the water heater in the same image.

In the context of Figure 4-63, starting from the bottom in order of appearance, the cold water inlet dispenser is visible in white, then the element which appears much smaller than the spiral element (used in the first three water heaters). Above the element, the temperature probe sleeve is seen. The tip of the sleeve does not extend further than the element and thus any heat rising off the element affects the temperature measured.

To the right the hot water outlet is seen on the top of the water heater and on the right faceplate, the expansion valve. Closer inspection of the pipe inserts yields that they are also coated in the Cross-linked Polyethylene coating as can be seen in Figure 4-65.

Table XX: Water heater E insulation thickness.

Water heater insulation	**Thickness [mm]**
Bottom	18
Top	30

The measurements taken of the insulation revealed that the internal water barrel is not mounted perfectly horizontal in relation to the outside shell. Thus the measurements in Table XX only represent the averages. The top side the insulation had a maximum measurement of 32mm and tapered off to 25mm. On the bottom side the measurements taken were in the range of 10 to 20mm. If all water heaters are designed in a similar fashion, then the heat loss distribution will not be even across the entire water heater insulation and results will be skewed.

Figure 4-63: Water heater E tear down side 1.

Figure 4-64: Water heater E tear down side 2.

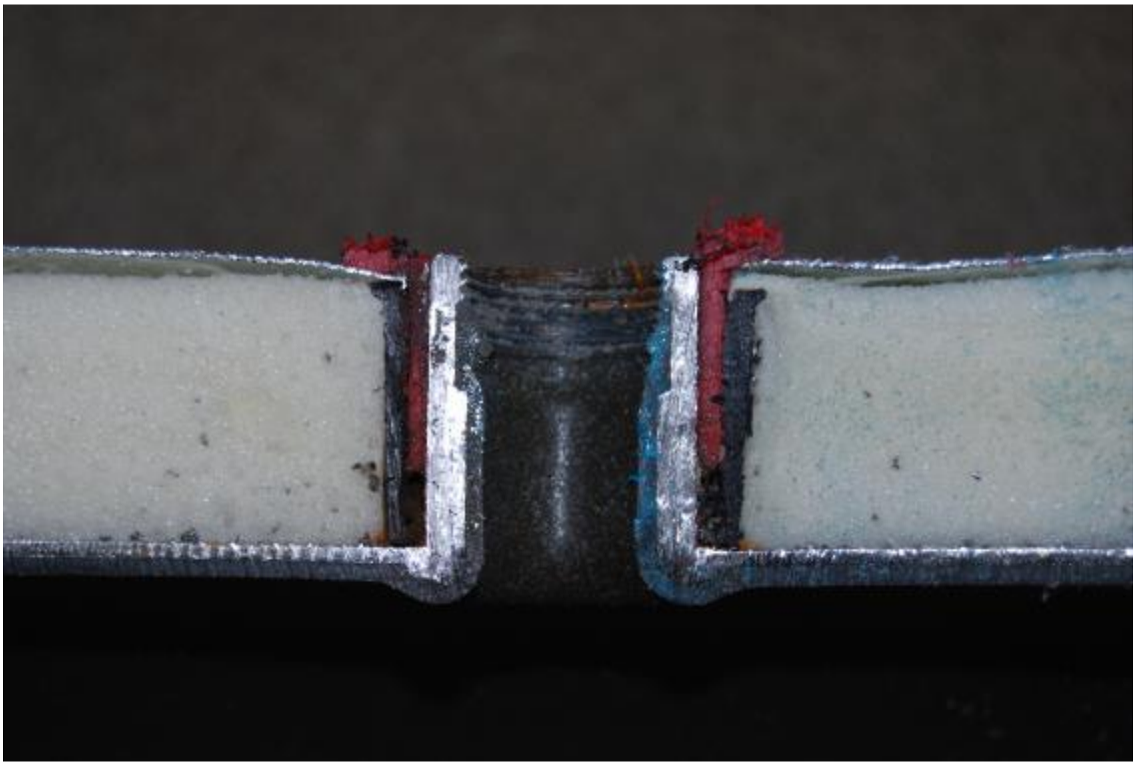


Figure 4-65: Water heater E tear down pipe insert inspection.

4.7 Water Heater F

Water heater E and F have the same manufacturer. The goal of the manufacturer is to produce a water heater that is a deluxe model, one that doesn't consume as much energy as the other models. Thus extra precautions are made in the design and manufacture of the water heater.

4.7.1 Specifications

The specifications do not change for the water heaters, but what does differ is that the pipe inserts have a plastic joint connected to a male thread that is fused to the internal water barrel. Any connecting pipes are then inserted to the plastic fitting, with extreme care so as not to break it. This supposedly gives much better heat insulation and will diminish heat losses.

Table XXI: Water heater F specifications.

Volts	Volume	Power	Pressure	Orientation	IP
230V/50Hz	150l	3kW	400kPa	Horizontal	X4

4.7.2 Standing Loss Test

The water heater is only slightly larger than the previous one and the pipe fittings are all identical. One of the only physical differences is that the water heater shell is covered in a paint coat. It is yet to be seen if this helps with the thermal analysis.

In the specifications it was mentioned that the pipe fittings were made of plastic. One of the fittings broke and resulted in a leak. The fitting was replaced and another test was done. The results in Table XXII are the results from that second test.

Table XXII: Water heater F standing loss test results.

	Horizontal orientation		
Measured entity [°C]	**Mean**	**Min**	**Max**
Ambient temperature	19.9	17.6	21.5
Control temperature	65.0	64.3	65.6
Cold water temperature	60.3	59.5	61.3
Hot water temperature	66.6	65.8	67.25
Standing losses [kWh]			1.83

The results in Table XXII show that the mean ambient temperature is very close to the suggested SANS 151 temperature so the calculated standing losses will not differ widely is the SANS 151 value is used.

The control temperature is perfectly within spec. The mean cold water temperature and the variation suggest that the bottom insulation is quite thick which is yet to be seen in the Tear Down Analysis.

The hot water mean temperature is uncharacteristically low for a water heater (refer to Figure 4-66). Thus either the thermocouple of the water heater is closer to the top of the water heater or the insulation at the top is not as thick.

The standing loss value differs by 0.09 kWh/day, when compared to the previous water heater standing loss value. The water heater was advertised as a deluxe model but this result does not support that claim. However the water heater power usage profile does look improved from the profile of water heater E as can be seen in Figure 4-67 suggesting that the thermocouple sleeve and element have a different design.

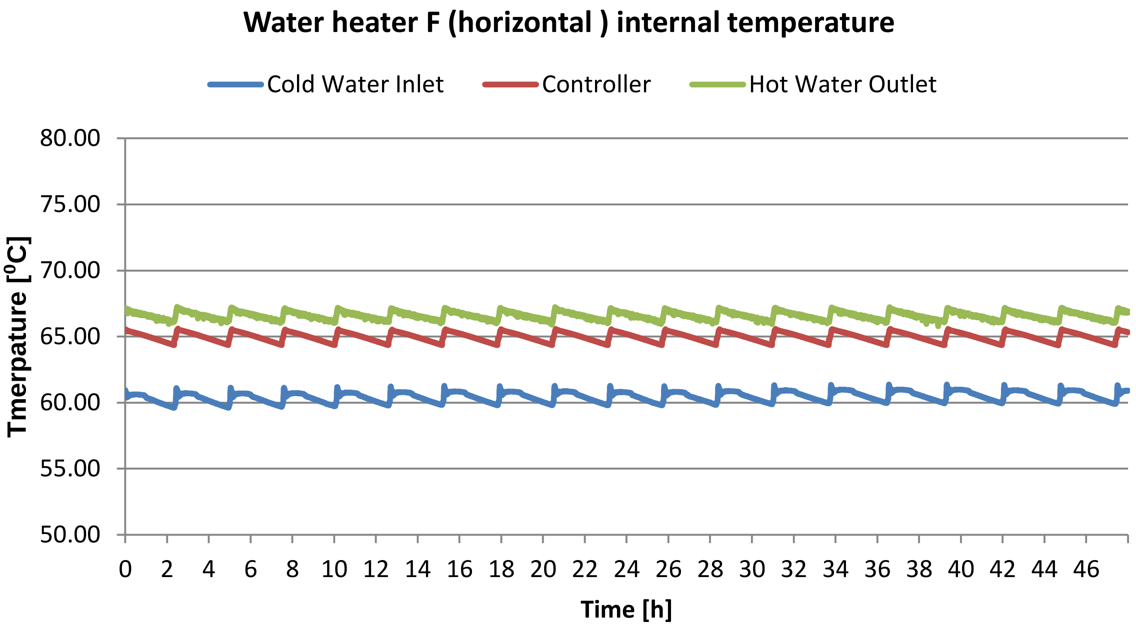


Figure 4-66: Water heater F (horizontal) internal temperatures.

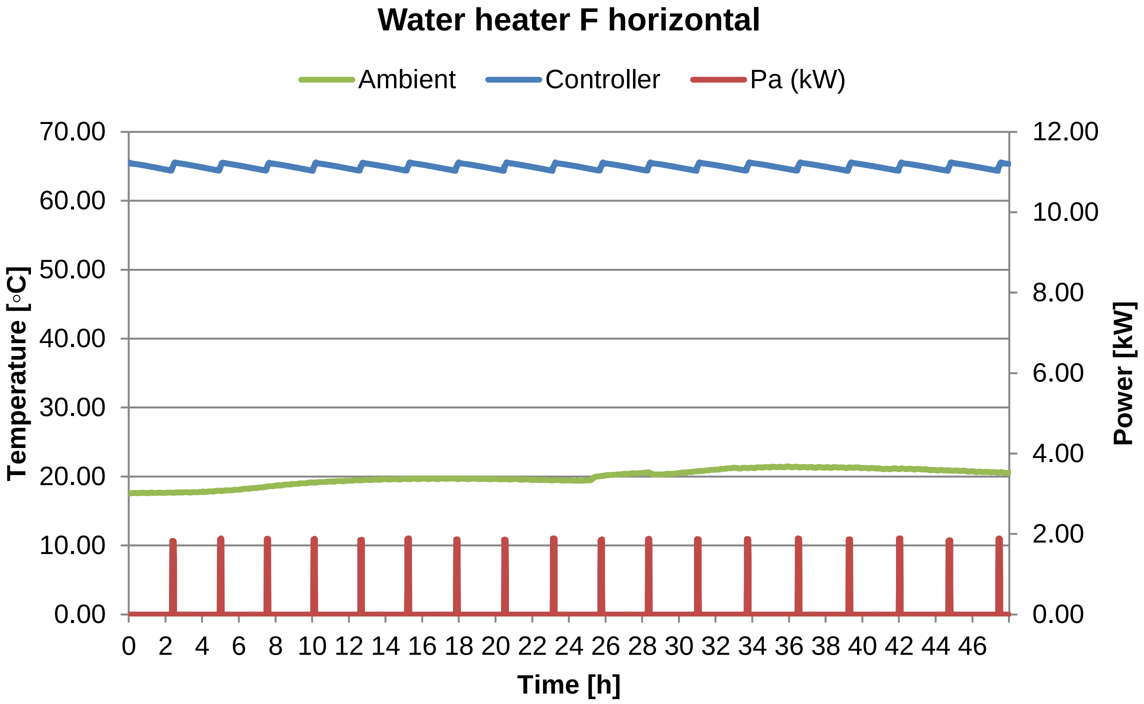


Figure 4-67: Water heater F (horizontal) temperature and power usage profiles.

4.7.3 Thermal Analysis

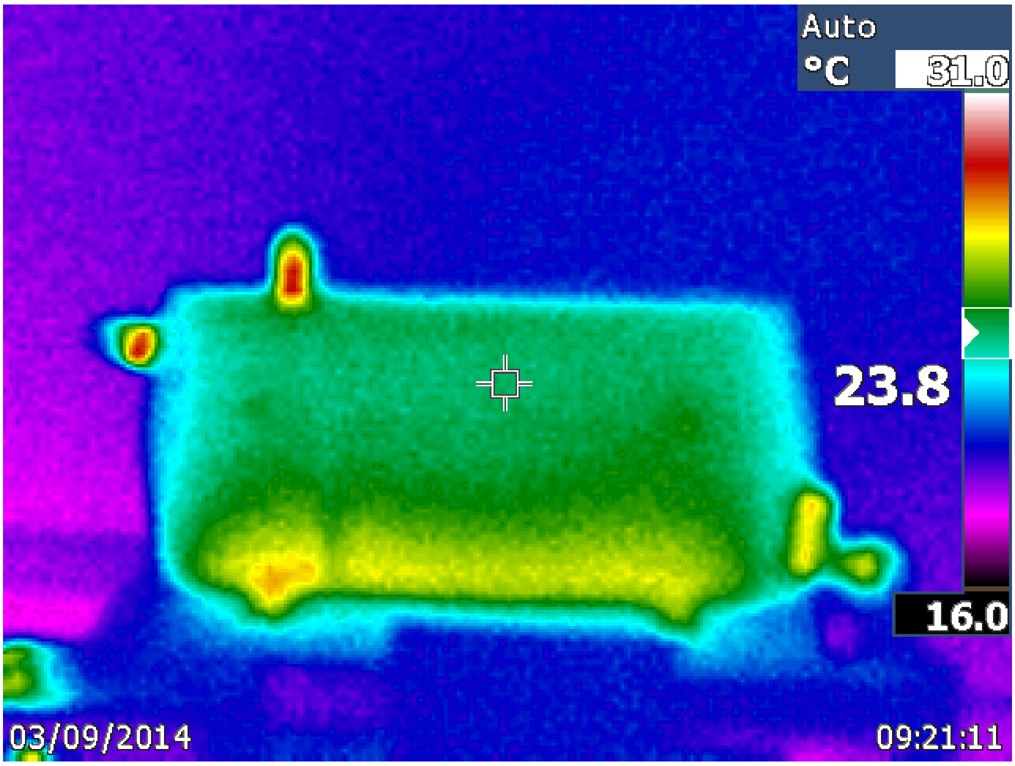


Figure 4-68: Water heater F (horizontal) thermal image.

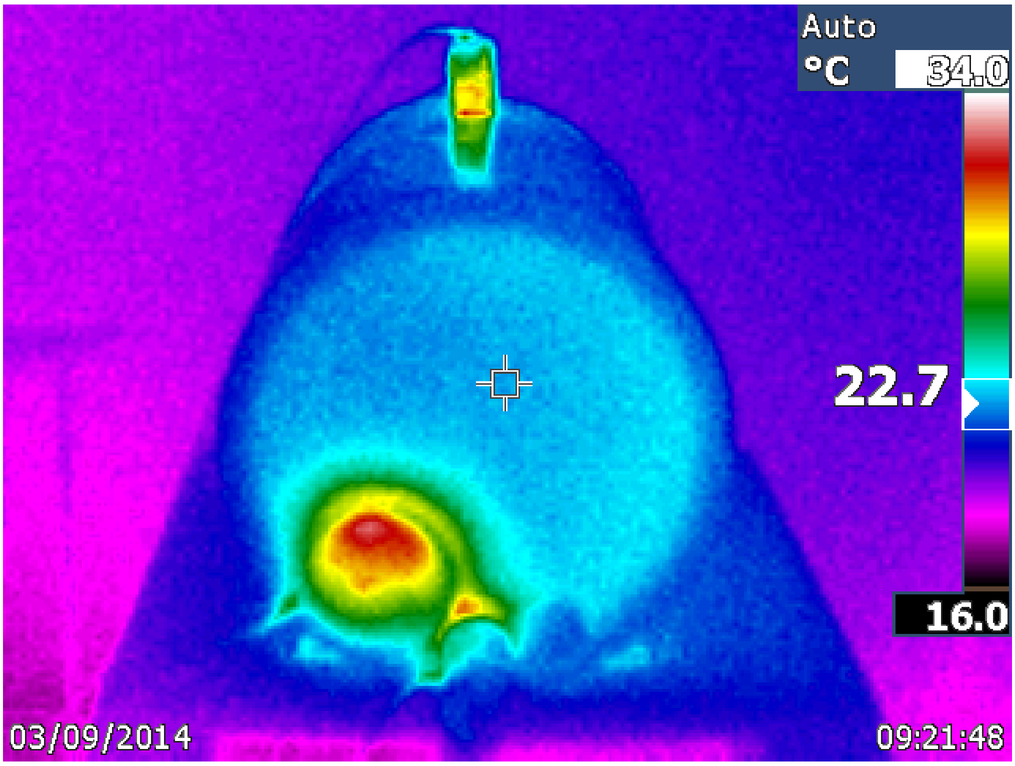


Figure 4-69: Water heater F (horizontal) thermal image of the inlet faceplate.

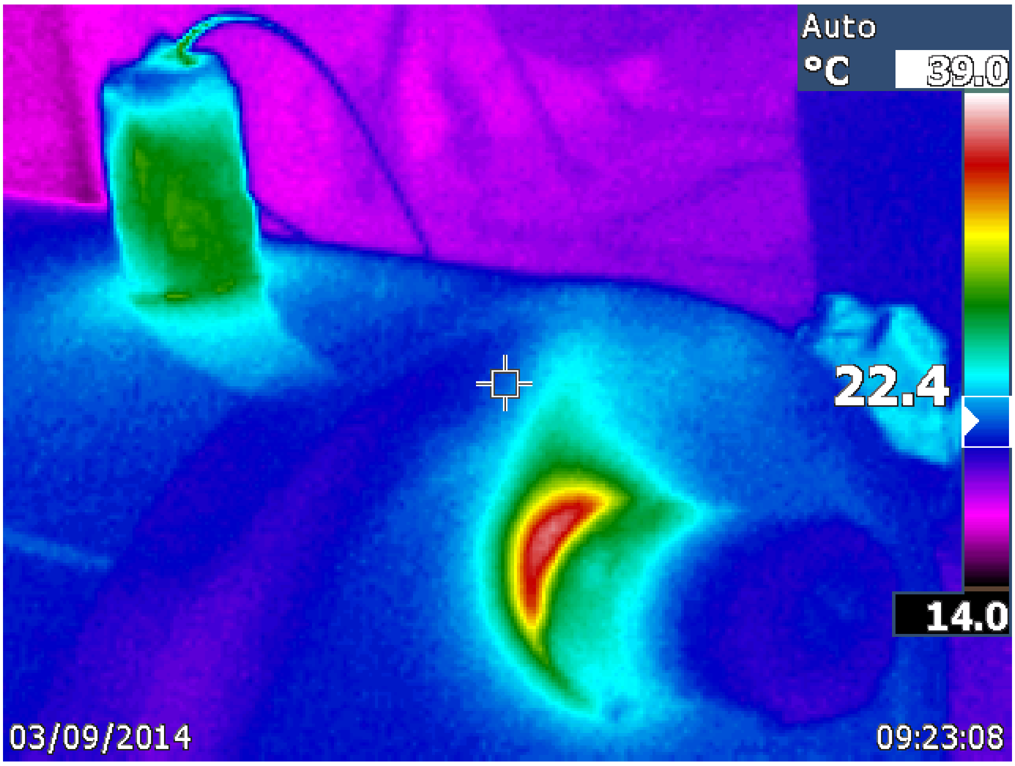


Figure 4-70: Water heater F (horizontal) thermal image of the outlet pipe and expansion valve.

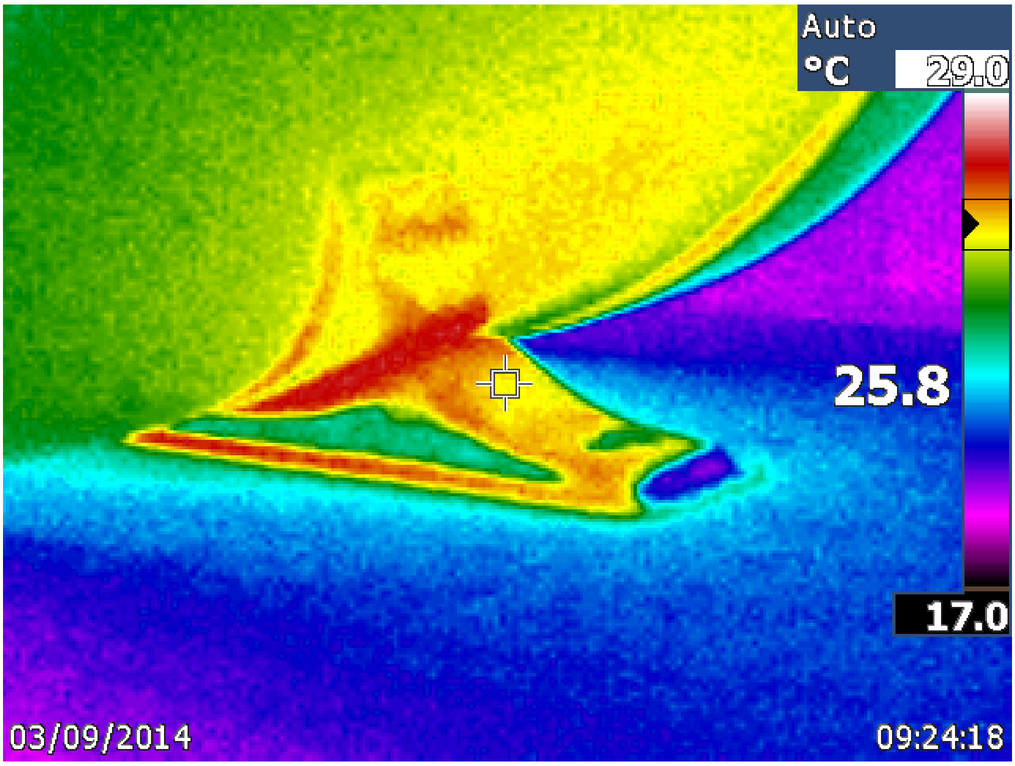


Figure 4-71: Water heater F (horizontal) thermal image of the water heater feet.

Figure 4-68 shows the entire water heater. The shell is visible with a notable temperature. This is interesting as a paint covering over the shell of any galvanised part would reveal the temperatures of the water heater shell of any of the water heaters from the previous tests.

Figure 4-69 shows the plastic cover for the element and probe cavity as well as the cold water inlet pipe. The pipe doesn't reach any noticeable temperatures, except for at the ingress to the water heater. This suggests that the plastic pipe segments connecting the water to the water barrel through the insulation do not contribute much to heat losses. Figure 4-70 also yields a similar result showing that the base of the expansion valve achieves a temperature of 39 °C. The hot water outlet pipe is well insulated and no heat is showing through the image.

The feet of the water heater reach the same temperature, similar to the results from the majority of the previous tests. But in this image the body of the water heater can also be analysed. The bottom of the water heater reaches a temperature of 25 °C. Couple that with the temperature read from the top of the water heater in Figure 4-68 (23 °C) and it becomes evident that there are heat losses over the entire surface of the water heater. All the previous water heaters felt warm to the touch but the temperature could never be verified due to the reflective nature of the outer shell. In future tests, it is a good idea to spray a strip of paint onto a galvanised part in order to read the temperature.

4.7.4 Tear Down

Competitiveness in the South African market was one of the manufacturers concerns and therefore conditions were set before the testing could commence. The manufacturer requested not to have a tear down analysis completed on the water heater.

4.8 Review

4.8.1 Specifications

Most of the water heaters have the same specifications with the exception of the water pressure, the IP rating and the available orientations. The IP rating for water Heater D is X1 meaning that the protection against liquids is substandard.

4.8.2 Standing Loss Test

A summary of the results of the standing loss tests can be seen in Table XXIII.

Table XXIII: Summary of recorded standing loss test mean temperatures.

Water heater	Orientation	Mean temperatures [°C]			
		Ambient	Controller	Cold water	Hot water
A	**Vertical**	16.3	64.9	63.8	72.4
	Horizontal	18.2	65.2	56.9	77.2
B	**Vertical**	20.4	64.5	62.7	71.8
	Horizontal	20.3	64.7	55.2	75.2
C	**Vertical**	18.6	64.5	64.5	72.3
	Horizontal	17.4	64.8	61.4	75.1
D	**Horizontal**	21	64.5	64.5	69.7
E	**Horizontal**	21.6	64.4	60.8	71.2

First analysing the mean ambient temperatures, the only one out of spec is the Vertical test for water heater A. This doesn’t affect the standing loss value significantly but the test results are therefore questionable.

The recorded controller temperatures are all very close to the set control temperature. The variations of the hot and cold water temperatures give more insight into the internal mechanics of the water heaters.

In the extreme cases the lower cold water temperature is achieved by water heater B in the horizontal position with water heater A, in the same position, not far behind. The insulation on both water heaters at the bottom is very thin compared to other water heaters. This suggests that the insulation thickness is causal and not consequential when related to the cold water temperature. To explain, designers of water heaters assume that due to convection the temperature at the bottom of the water heater is significantly colder than that of the water at the top of the water heater. Thus the insulation at the bottom is designed to be much thinner. In all instances the insulation of the bottom of the water heater is thinner. The results in Table XXIII suggest otherwise, that the thinner the insulation is, the more heat losses will occur at the bottom of the water heater and through the feet. Thus the greater heat losses are a consequence of the thinner insulation.

The hot water temperatures are all very similar with a few outliers, one being again the temperature of water heater A and the other being that of water heater B. Water heater A has the most variance to the others. A possible explanation is that because of the longitudinal design of the water heater the water takes longer to mix and circulate when heated by the element. Thus higher temperatures are experienced on the other side of the water heater.

The standing losses vary quite substantially. The summary of the standing losses in Table XXIV gives insight into which water heaters are made with keeping heat losses in mind.

The water heater with the worst performance is water heater D. After that water heater A has the next highest standing loss value when mounted horizontally.

The water heater with the best performance is water heater C when mounted horizontally. When mounted vertically the water heater also has very good performance.

Table XXIV: Summary of standing losses.

Water Heater	**Orientation**	**Standing losses [kWh/24h]**	
		SANS 151 equation	**Alternate equation**
A	**Vertical**	2.23	2.22
	Horizontal	2.33	2.34
B	**Vertical**	1.9	1.91
	Horizontal	2.24	2.26
C	**Vertical**	1.86	1.87
	Horizontal	1.77	1.79
D	**Horizontal**	2.51	2.54
E	**Horizontal**	1.9	1.92
F	**Horizontal**	1.83	1.83

No direct correlation can be seen with regards to the orientations and the standing loss value. In the first two tests the standing losses of the vertically mounted water heaters is less than that of the same water heaters when mounted horizontally. In contrast water heater C behaves in the opposite fashion. When horizontally mounted, the water heater performs better. In the tear down test it was found that the insulation on Water heater A and B was either very thin or compromised. This could explain the larger heat losses when compared to the other water heaters but does not explain why the losses are lower when the water heater is mounted vertically. Theoretically the hot water would rise to the top of the water heater. If the insulation at the top of the vertically mounted water heater is thinner, which it is in the A and B, then the standing losses should be less.

The water heaters are ranked on performance based on their standing losses. Further on in the report, the water heaters are analysed based on the thermal data collected in the tests. Should any of the alternative tests yield a different ranking order, Table XXV will allow for a more comprehensive comparison to be made.

Table XXV: Water heaters ranked by standing losses.

Water Heater	Orientation	Standing losses [kWh/24h]	
		SANS 151 equation	Alternate equation
C	**Horizontal**	1.77	1.79
F	**Horizontal**	1.83	1.83
C	**Vertical**	1.86	1.87
B	**Vertical**	1.9	1.91
E	**Horizontal**	1.9	1.92
A	**Vertical**	2.23	2.22
B	**Horizontal**	2.24	2.26
A	**Horizontal**	2.33	2.34
D	**Horizontal**	2.51	2.54

4.8.3 Thermal and Tear Down analysis

From a design aspect the water heaters differ substantially. Galvanised metal sheeting is used in all cases for the cylindrical shell but the material used for the faceplates differs. It does not however seem to have an effect on the standing losses. Water heater A, B, E and F all have plastic faceplates but very different standing loss values.

The elements used by the water heaters differed as well, some being designed in a spiral fashion and other just after a linear model. The spiral design incorporated the thermocouple into the design. The thermocouple extends beyond the element, thus making the effect of convection on the measured temperature minimal. With the linear element design, the thermocouple sometimes does not extend past the element and thus influences the measured temperature via the heat plumes rising off due to convection.

The cold water inlets all have a design meant to disperse the incoming cold water and allow for mixing of the hot and cold water. This would only influence the measurement if a flow test was done, but for the static test the effect is minimal. It does however help with preventing heat loss through the cold water pipe, but only to a degree.

Only two of all tested water heaters have a Cross-linked Polyethylene coating that prevents oxidation and replaces the use of a sacrificial anode. They rank as fairly good in the standing loss test. The advantage with not having a sacrificial anode is the cost of replacing the anode. The disadvantage is that, if there is any exposed metal due to age or shock, the exposed area will start oxidising immediately.

The insulation thickness is under scrutiny. Some of the water heaters have uneven thicknesses of insulation and in the case of water heater A, no insulation at all. This is worrisome and begs the question, whether all the water heaters are made in a similar fashion or if there are variables in the manufacturing process that make the final product quality completely random, and the actual process unreliable.

A summary of the measured insulation thicknesses is displayed in Table XXVI. The water heater with the thickest top insulation is water heater A. But because the bottom insulation is so thin, in fact the thinnest, the standing losses are ranked amongst the highest in the test group.

The water heater with the thickest bottom insulation is water heater C which ranks as one of the best when it comes to standing losses. That coupled with the thick top insulation ensure a very low heat loss.

Table XXVI: Summary of water heater insulation thickness.

	Insulation thickness [mm]	
Water heater	**Top**	**Bottom**
A	35	5
B	31	10
C	27	25
D	23	20
E	30	18

The feet need to be connected to the internal water barrel in order to support the weight of the water. This design results in the heat loss through the feet being quite substantial. The only way of mitigating the heat loss there would be to increase the distance of the feet from the water barrel, in effect increasing the thickness of the insulation. Either that or changing the design on the support structure or the materials used in carrying the weight of the water barrel and water contained within.

A ranking order based on the insulation thickness will not yield a very useful result due to discrepancies in the change of insulation thickness and compromises in the insulation as seen in water heater A. in conjunction, with the different lengths of the water heaters, the total surface area exposed to the different thermodynamic gradients will differ.

As mentioned before, a tear own analysis was not carried out on water heater F due to a request from the manufacturer not to do so. The reason given was so that competitors would not steal intellectual property.

5 Insulation Modelling

5.1 Overview

The previous chapters focused primarily on the thermal data collected through tests. The amount of variables that affected test conditions made the tests a challenge to complete. With a view to eliminate some of the varying test conditions, the insulation must be further analysed. This chapter focuses on the insulation of the water heater by calculating the thermal conductivity of the water heaters tested in Chapter 4. This is done to see if a pattern emerges as to what technical designs might cause the losses in the tests.

The Analysis of data is defined as the following in the Oxford Dictionary [69]:

> *"Analysis: The detailed examination of the elements or structure of something."*

The purpose of analysing the collected data is to gain a greater insight and understanding of how the water heater works. By examining the collected data, real life insight is given into the internal mechanisms of the water heaters.

One of the analyses done was to calculate the standing loss value for each water heater. This was covered in Chapter 4. One of the issues with the testing was discussed in Chapter 2 and was the fact that the insulation grading was not given. Another issue that has become apparent throughout the testing is that the standing loss test is very inefficient and time and energy wasteful.

This chapter has a look at and calculates the insulation grading for each water heater. In addition the chapter also explores a new way of calculating the standing losses of a water heater in a manner that is less time consuming and more energy efficient.

5.2 Insulation Grading

In Chapter 2 it was mentioned that the insulation grading of the water heaters, or the R-value, was not given with the water heaters. One issue discussed was, that the majority of the water heaters had insulation with varying thickness. But still, an R-value for the insulation could be given in a per-unit of area and used as an approximate R-value over the entire area of the water heater.

5.3 Mathematical Model

In order to calculate the R-value, an equation was deduced in Chapter 2. To recapitulate this, equation 2.4.7 went as follows:

$$R = \frac{A\ (\Delta T)}{Standing\ Loss} \qquad 5.3.1$$

In order to calculate the surface area over which the heat loss occurs, the diameter and height have to be determined. In this case, the constant for all the water heaters is the volume. The diameter and length change as the water heaters change, but the volume remains the same.

Due to the varying nature of the shapes of the water heaters, equation 5.3.1 can be modified so that the process is simplified. In this case the volume is taken of the water heater instead of the dimensions. The result is a rating that is akin to the R-value. Evaluating the equation, the problem is reduced to the following:

$$R = \frac{V\ (\Delta T)}{Standing\ Loss} \qquad 5.3.2$$

where V denotes the volume of the water heater.

In the case of this investigation the volume of all tested water heaters is 150 litres.

One of the issues is that the insulation thickness varies from bottom to top as shown in Table XXVI. Thus the calculated R-value for a water heater will differ when calculated for the horizontal and vertical tests. Notwithstanding that, the resulting R-values will yield valuable insight into the design and quality of the water heaters.

In order to achieve the most accuracy with this investigation, the mean controller and ambient temperatures are used to acquire ΔT and the calculated standing losses are used to gain the R-value using Equation 5.3.2.

5.4 Results

To gain a reference point for the calculated R-value, the maximum allowable R-value is calculated. In this case the volume is still 150 litres but the standing losses are 2.59 kWh per day and the difference in temperature is 45 °C, attained from the desired temperatures for the controller (65 °C) and the ambient (20 °C). Thus the R-value calculated using those values is 2.61 m^3 °C/Wh. This indicates that the water heater insulation conducts heat well. A value lower than the attained value will result in more losses experienced by the water heater whereas a higher value indicates that the water heater insulation is of a higher grade and less heat loss will occur. This stands to reason as the standing losses are inversely proportional to the R-value. Thus the higher the standing losses, the lower the R-value, i.e. the lower the thermal resistance.

The standing losses used are from the alternative equation, which yields a more accurate result and are attained from Table XXIV. ΔT is calculated using the data in Table XXIII by subtracting the mean ambient temperature from the mean controller temperature. This and the resulting R-value are recorded in Table XXVII.

Table XXVII: Calculated R-values for the water heaters.

Water heater	Orientation	Standing losses [kWh/24h]	ΔT [°C]	R-value [m^3 °C/Wh]
A	**Vertical**	2.22	48.6	3.28
	Horizontal	2.34	47	3.01
B	**Vertical**	1.91	44.1	3.46
	Horizontal	2.26	44.4	2.95
C	**Vertical**	1.87	45.9	3.68
	Horizontal	1.79	47.4	3.97
D	**Horizontal**	2.54	43.5	2.57
E	**Horizontal**	1.92	42.8	3.35
F	**Horizontal**	1.83	45.1	3.7

The highest R-value calculated is for water heater C in the horizontal position. The corresponding standing loss is also the lowest in the group.

Reviewing the data in Table XXVII, the highest recorded standing losses are experienced by water heater D and as expected it has the lowest R-value. When compared to the apparent minimum allowable R-value calculated (2.61 m^3 °C/Wh using an ideal scenario) it is below it at a value of 2.57 m^3 °C/Wh. This can either be attributed to the fact that the difference in temperature is below the necessary mean of 45 °C by 1.5 °C or to the possibility of the quality of the insulation being quite low. The standing losses are however quite high and would lend itself to lowering the R-value further.

The balance of the water heaters fall between the two water heaters discussed above with only water heater A showing a deviation from the expected results when tested in the horizontal position. When compared to Water heater D and Water heater B in the Horizontal position it is evident that the expected R-value would lie between 2.57 and 2.95 m^3 °C/Wh but instead yields an R-value of 3.01 m^3 °C/Wh. This could be attributed to the high difference in temperature. If the difference in temperature had been measured at 45 °C then the R-value would have been 2.88 m^3 °C/Wh which is closer to the expected value.

If the water heaters are ranked, based on the attained R-value, as seen in Table XXVIII, the only observable difference with Table XXV, where the water heaters are ranked according to their standing losses, is that water heater A, in the horizontal position, performs better than water heater B in the horizontal position. When their standing loss values are compared, there is a 0.09 kWh/24h difference. This is possibly due to the thicker insulation at the top of the water heater. However, water heater B does perform better in the vertical orientation due to a thicker mean insulation thickness.

Table XXVIII: Water heater rankings based on R-value.

Water heater	**Orientation**	**R-value [m^3 °C/Wh]**
C	**Horizontal**	3.97
F	**Horizontal**	3.7
C	**Vertical**	3.68
B	**Vertical**	3.46
E	**Horizontal**	3.35
A	**Vertical**	3.28
A	**Horizontal**	3.01
B	**Horizontal**	2.95
D	**Horizontal**	2.57

5.5 Conclusion

This method of benchmarking the water heaters gives qualitative and quantitative insight into the design and manufacture of water heaters.

6 Test Methodology Concept

6.1 Overview

The water heaters were previously tested using the SANS 151 testing methodology which was reviewed in Chapter 2.The test conditions weren't described to the authors satisfaction as a few aspects of the test were never touched upon. This chapter explores a different test methodology. It is not a replacement of the existing testing methodology, but a means to investigate the effects of different insulation measures. All this test proposes is that the focus is placed on the insulation, with a view to eliminate the effects of switching, hot water plumes, element placing and vortices induced by forced convection around the element. The results will allow for a more comprehensive understanding of the design and manufacture of the water heater insulation.

The standing loss test as described by the SANS 151 document incurs energy and time losses that could be minimised through time management techniques and critical thinking. But even so, that would still not guarantee greater energy efficiency and the stabilization times would still have to be taken into account. This chapter proposes a new test methodology that could potentially be more power efficient and accurate.

6.2 Existing Test Methodology

The standing loss test, as defined by the SANS 151 document, is covered in Chapter 3 and it describes the test as follows: The water heater is attached to the piping and testing equipment and switched on. Once the water heater's internal temperatures have stabilized, the standing loss test commences for a duration of 48 hours. This is very time and energy inefficient. If the test is done incorrectly, collected data would have to be discarded and time would be lost redoing the test.

The test in the SANS 151 document depends on a constant difference between the mean ambient temperature and the controller temperature and a dependable power measurement device. As seen in Chapter 4, a slight change in the mean ambient temperature can influence the standing loss value if the mean ambient temperature is used in the formula provided. And if the power measurement has even a slight error or is in any way unreliable, then the standing loss value would be false.

6.3 Concept Development

If the SANS 151 test could possibly be done with only 24 hours of energy usage then the energy consumption of the test would be significantly less but the integrity of the calculated standing loss value would be diminished. The longer the test is done, the more reliable and accurate the recorded data and calculated standing losses are.

A proposed test methodology is to let the water heater stabilise at a higher temperature and then allow the water heater to cool down by switching the element off while continuing with the thermal tracking. Once the data has been collected and a thermal profile or trend is established, a regression formula can be extrapolated from the data in order to get the rate of heat loss. From the rate of heat loss, the rate of energy loss can be determined for any temperature differential along the regression line. In this instance, the rate of energy loss would be determined at 45 °C, which is the difference between the controller and ambient temperatures in the ideal situation.

The regression formula would have to be applied to a profile that resembles the difference between the ambient and controller temperature. This would make the extrapolation of a formula much more streamlined and would make the ambient temperature control obsolete. The water heater will always loose heat energy until the water heater temperature and room temperature reach equilibrium. Because the room is so large, the ambient temperature change is minimal (In the ideal case). The difference in temperatures thus would tend towards zero. Theoretically the equation would be an exponential function, but it is yet to be seen whether an exponential function or a polynomial function represents the data better.

To represent this mathematically, and to find a relationship between the heat loss and energy loss, a few assumptions need to be made.

6.4 Mathematical Representation

The first step is to quantify the amount of heat energy in the water. The equation used is one to quantify the thermal energy stored in a liquid or a solid without it changing phase [70]. The equation to calculate the energy stored at a certain temperature above 0 Kelvin is defined by the following integral between two temperatures:

$$E = c_p m \int_{T_1}^{T_2} dT \qquad 6.4.1$$

where E denotes the energy [kJ], c_p denotes the specific heat capacity [kJ/kg K], m denotes the mass of the body of water [kg] and T denotes the temperature of the body of water [K].

In the context of this investigation, the mass of the water contained in the water heaters is 150 kg and the heat capacity of the water is 4.18 kJ/kg K.

For the thermal energy stored in the water to be calculated, T has to be represented by an equation. The equation representing the difference in temperature could either be reduced to an exponential or polynomial regression function. But for now the temperature is defined as an arbitrary function.

$$T(t) = T_{ambient}(t) + \Delta T(t) \tag{6.4.2}$$

$$\Delta T(t) = T - T_{ambient} + e(t) \tag{6.4.3}$$

where $e(t)$ denotes an error signal and T is the measured controller temperature.

As the water heater temperature tends towards the ambient temperature, the function $\Delta T(t)$ should be exponential. Due to the fact that the ambient temperature oscillates, the level of complexity greatly increases.

For the thermal energy inside the water to be calculated, the energy of the surrounding environment would have to be subtracted from the energy inside the water heater. Equation 6.4.1 yields a difference between the total energy in the system and the energy of the surrounding environment:

$$\Delta E(t) = E - E_{ambient} \tag{6.4.4}$$

$$= c_p m \left(T(t) - T_{ambient}(t)\right) \tag{6.4.5}$$

$$= c_p m \, \Delta T(t) \tag{6.4.6}$$

$$= c_p m \left(\Delta T(t) + e(t)\right) \tag{6.4.7}$$

In order to get rate of change in energy in the body of water equation 6.4.7 has to be differentiated with regards to time.

$$\frac{d\Delta E}{dt} = \frac{d}{dt}\left(c_p m \left(\Delta T(t) + e(t)\right)\right) \tag{6.4.8}$$

As c_p and m are constants, they can be removed from the derivative, yielding:

$$\frac{d\Delta E}{dt} = c_p m \frac{d}{dt}\left(\Delta T(t) + e(t)\right) \tag{6.4.9}$$

Any error signal encountered would for the most part be a calibration error. These are usually constant and thus the derivative of that would be zero leading to the following equation.

$$\frac{d\Delta E}{dt} = c_p m \, \frac{d}{dt} \Delta \dot{T}(t) \tag{6.4.10}$$

The resulting equation takes into account, and zeros, any errors in the calibration and gives the rate of change of the heat loss in kJ. The conversion from kJ to kWh involves a simple scaling factor of 2.778x10^{-4} or dividing by 3600. The resulting number indicates the rate of energy loss per unit of time measured.

The possible approximations of the decaying function are as an exponential decay, a polynomial function, a linear or logarithmic approximation. Theoretically the approximation should be exponential but a polynomial approximation would also work.

6.4.1 Case 1: Exponential function

If the temperature is in the form of an exponentially decaying function it will take the form in equation 6.4.11.

$$\Delta T(t) = A \, e^{-at} + e(t) \tag{6.4.11}$$

where A denotes the initial quantity of ΔT at t = 0 and a denotes the exponential decay constant [71]. The error signal will always be prevalent in any temperature measurement.

Taking the derivative of equation 6.4.11 yields the following result:

$$\frac{d\Delta T(t)}{dt} = A(-a)e^{-at} \; + \frac{de(t)}{dt} \tag{6.4.12}$$

If the above equation is used in equation 6.4.10, then the equation calculating the standing losses will be a scaled linear representation of the rate of change in temperature and will yield a negative result. Also, assuming that the error signal is a constant calibration error and thus independent of time, the derivative thereof will yield a result of zero.

$$\frac{d\Delta E}{dt} = c_p m \left(A \, (-a)e^{-at} + \frac{de(t)}{dt} \right) \tag{6.4.13}$$

$$= -c_p m \, Aa \, e{-}^{at} \tag{6.4.14}$$

After the kWh’s have been determined, the figure will have to be scaled to fit the right interval.

6.4.2 Case 2: nth order Polynomial function

The polynomial function with an nth order can be used in the approximation of the decaying temperature function. Should the polynomial function yield a better result, this method could be used instead of the exponential approximation.

In this instance, the temperature does not have to decay to 0. The equation includes a constant which gives the temperature its offset and thus the true controller temperature could be used. However, the ambient temperature does change, affecting the rate of heat loss and therefore including it in the formula is essential.

In this case the function for the temperature is represented by a polynomial function of the following form.

$$\Delta T(t) = c_0 + c_1 t + c_2 t^2 + c_3 t^3 + \cdots + c_{n-1} t^{n-1} + c_n t^n \qquad 6.4.15$$

where c_n denotes the constant of nth order t.

The derivative of the differential temperature, namely the difference in temperature of the controller and the ambient temperature, yields a polynomial function of the order of n-1. The constant c_0 also disappears. Thus again any error signal that contributes a constant offset is instantly rendered zero.

$$\frac{d\Delta T(t)}{dt} = c_1 + 2\,c_2 t + 3\,c_3 t^2 + \cdots + (n-1) c_{n-1} t^{n-2} + (n) c_n t^{n-1} \qquad 6.4.16$$

Substituting equation 6.4.16 into equation 6.4.10, the resulting equation will again be a linearly scaled representation of the rate of change in temperature. However in this instance the result will be positive.

$$\frac{d\Delta E}{dt} = c_p m\,(c_1 + 2\,c_2 t + 3\,c_3 t^2 + \cdots + (n-1) c_{n-1} t^{n-2} + (n) c_n t^{n-1}) \qquad 6.4.17$$

$$= c_p m\, c_1 + 2 c_p m\, c_2 t + 3 c_p m\, c_3 t^2 + \cdots + (n-1) c_p m c_{n-1} t^{n-2} + (n) c_p m\, c_n t^{n-1} \qquad 6.4.18$$

6.5 Regression Approximation

The amalgamation of the equations above is used to evaluate the rate of change of energy in a water heater by evaluating the regression curve of the internal temperature of a water heater in relation to the external ambient temperature.

The above equations eliminate any fixed calibration errors that might offset the measurements and take into account the fluctuations in the internal controller and ambient temperatures. This is done with a view to make testing constraints more versatile and will allow for unforeseen variations in the ambient temperature to occur.

Thermal decay data is only collected for four different water heater arrangements, namely the following:

- Water heater A in the horizontal and vertical positions.
- Water heater B in the vertical position.
- Water heater F in the horizontal position.

The tests are carried out after the complete 48 hour data set is collected for the SANS 151 test. Once the data is collected and examined for errors or data loss, the water heater controller temperature is increased to 70 °C. Once the water heater reaches a stabilized state, the power is switched off and the water heater temperature is allowed to run down while thermal measurements continue. Depending on the quality of the materials used, this may take up to 10 days. Thus the thermal measurements are concluded after 2 to 3 days.

As discussed in the beginning of this chapter, the possible regression formulas available in Microsoft Excel (2010), as well as in MathWorks, MATLAB, are numerous. It is found that the exponential and polynomial regression algorithms fit the data with more precision than the other options presented in Excel. However, for the higher order polynomial functions, this only holds for the first few time steps.

With a view to get the standing losses, the equations collected from the aforementioned programs are parsed through equations 6.4.14 and 6.4.18 for exponential and polynomial functions respectively. The result acquired is the rate of change of energy. The result then is divided by 3600 to convert from Joules to Watt-hours.

6.5.1 Water heater A (Horizontal)

The tests for water heater A, when mounted in the horizontal position, revealed high standing losses of 2.22 kWh/day, but the difference in the controller and ambient temperatures is the highest in the collected data set, measured at 48.6 °C. This would give rise to a more accurate approximation of the gradient at $\Delta T(t) = 45$°C.

The data collected post standing loss test consists of the run down data. For water heater A, the data collected consisted of a test interval of 21 hours and 33 minutes. The results in Figure 6-1 reveal that the test interval must be increased. Nevertheless the results are used to gain a better comprehension of the heat retention of the water heater.

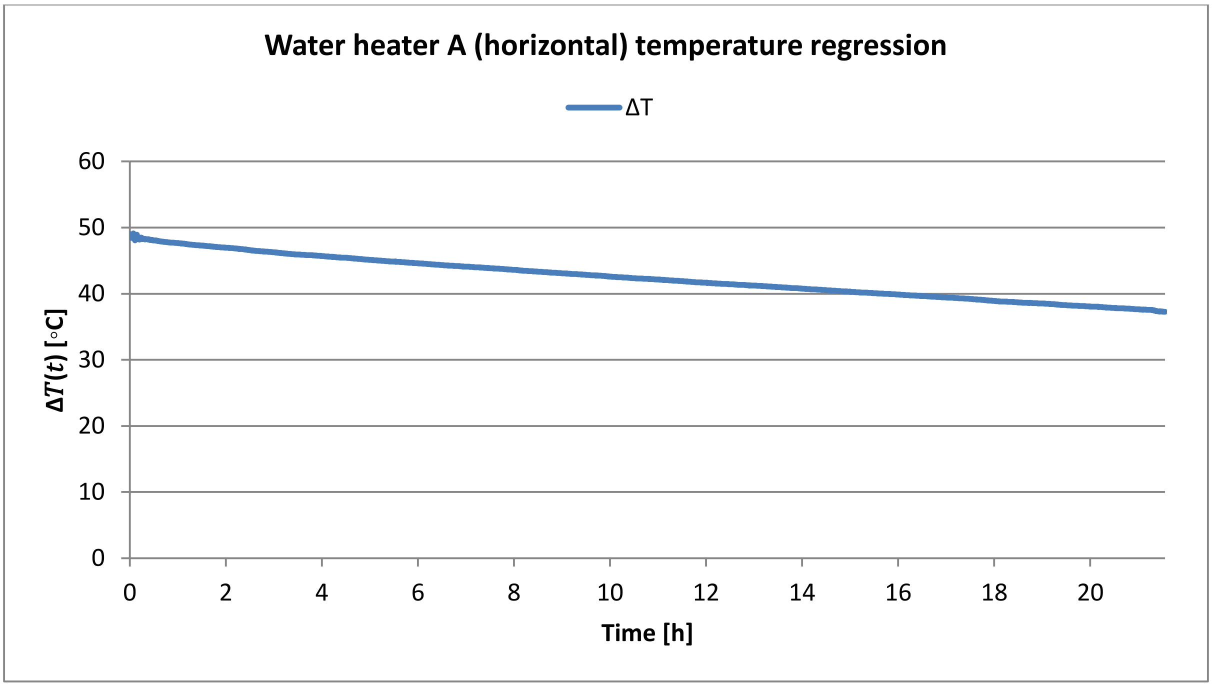


Figure 6-1: Water heater A (horizontal) temperature regression of $\Delta T(t)$.

The collected data is parsed through an analytical regression function. The programs used to analyse the data are Microsoft Excel (2010) and MathWorks MATLAB (2009).

Table XXIX shows the equations acquired from Microsoft Excel (2010) as well as the resulting kWh calculated from the equations.

Table XXIX: Resulting Excel regression equations for $\Delta T(t)$ for water heater A (horizontal).

Function	Order	Equations (ΔT)	Approximated losses at 45°C
Exponential	**2nd**	$47.957\, e^{-0.0001\, t}$	-2.39
Polynomial	**2nd**	$(4 * 10^{-7})\, t^2 - 0.0051\, t + 48.148$	-2.54
	3rd	$(-3 * 10^{-10}) t^3 + (1 * 10^{-6})\, t^2 - 0.0061\, t + 48.368$	-3.02
	4th	$(2 * 10^{-13}) t^4 - (1 * 10^{-9}) t^3 + (3 * 10^{-6}) t^2 - 0.0069 t + 48.472$	-3.33
	5th	$(-1 * 10^{-16}) t^5 + (1 * 10^{-12}) t^4 - (3 * 10^{-9}) t^3 + (5 * 10^{-6}) t^2 - 0.0076 t + 48.536$	-3.60

Reviewing Table XXIV, it is seen that the standing loss value acquired from the 48 hour SANS 151 test is 2.23 kWh/day. Comparing this with the calculated values in Table XXIX, it becomes evident that these methods give varying answers, the closest of them being from the exponential regression. Here a difference of only 0.16 kWh/day can be seen and, although this is quite a large difference, the test is not yet refined.

With a view to confirm that the regression fits actually represent the data to a certain degree, a figure, showing the approximated fits, can be seen in Figure 6-2. The exponential curve and the 2nd order polynomial fit represent the data in the most reliable manner. However, as the order of the polynomial increases, the worse the regression fit becomes. Excel seems to try to approximate the best fit of the data in the initial few data points. Following that, any small contribution made by higher order polynomials at the start results in a much larger contribution to the regression fit as the data points increase. This would explain how come the approximated standing losses become larger as the order of the polynomial increases.

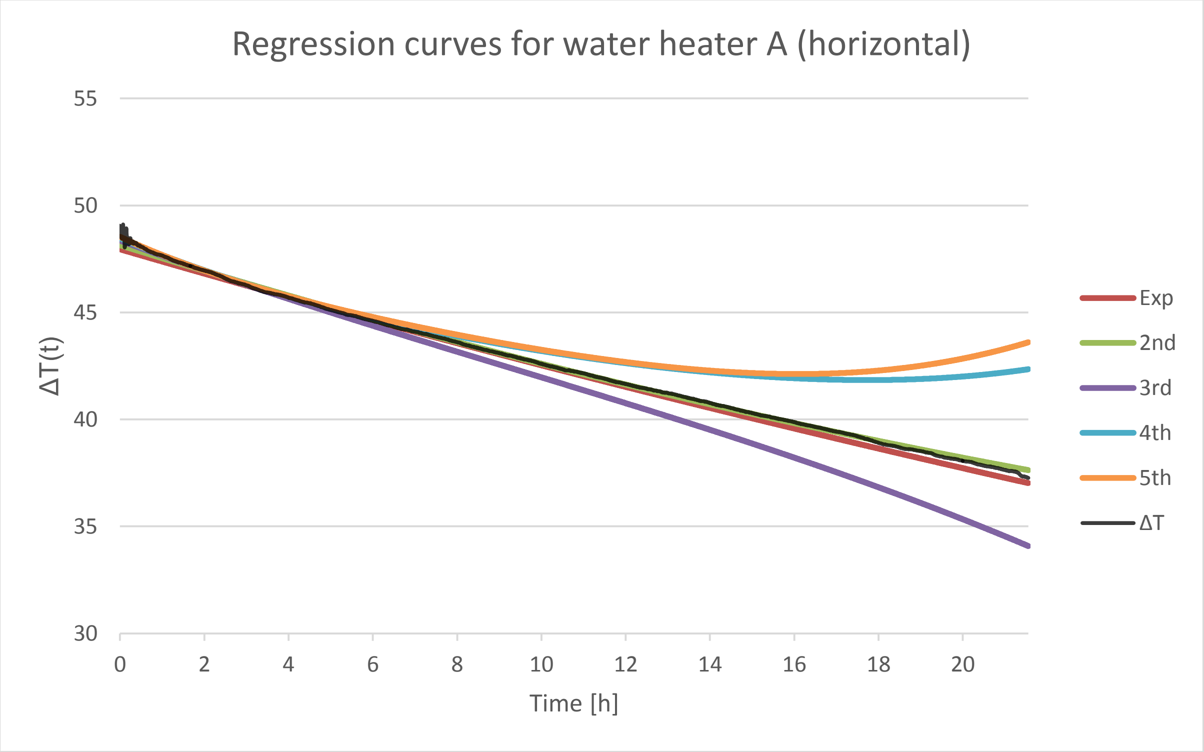


Figure 6-2: Regression curve fits for water heater A (horizontal).

The polynomial regression function yields answers that only increase with value as the order of the polynomial increases. Theoretically the polynomial function should fit the regression data more reliably as the order increases but in this case it is seen that the standing loss value is not reliably accurate. This is due to the rate of heat loss, closer to the switch off point, being higher due to the system not stabilising or reaching equilibrium. Allowing the water heater to stabilise at a higher temperature could possibly solve this issue.

When analysing the data in MathWorks MATLAB (2009), the results of the regression curve fit can either be represented by a single term exponential model or two term exponential model [72]. The single term polynomial closely resembles the one fitted by Microsoft Excel (2010) to 3 decimal places in the constant and the exponent, thus that analysis can be ignored. The two-term exponential is a much better fit. When the two term exponential fit is used, the resulting equation and standing loss result is shown in Table XXX.

Table XXX: Water heater A (horizontal): MathWorks MATLAB two-term exponential regression curve fit for $\Delta\boldsymbol{T}(\boldsymbol{t})$.

	Equation (ΔT)	Approximated losses at 45°C
Two-term exponential	$0.791\ e^{-0.0047t} + 47.61\ e^{-0.000093t}$	-3.75

This is expected. When the order of the polynomial regression curve fits increased, as seen in Table XXIX, the standing loss value increases. It stands to reason then that the better fitting exponential regression curve would also yield a higher standing loss value.

When the data collected in the run down test is scrutinised, it is seen that at the 45 °C mark the graph is not influenced by sudden heat changes and therefore the resulting standing losses are a true representation of the gradient at that point but not a true reflection of the actual standing losses of the water heater.

One possible reason for the outcomes seen from the regression curves, is that the hot and cold water did not mix sufficiently, resulting in the temperature decay at the first few time steps to occur at a much faster rate. In this case, a higher starting temperature would have to be reached before starting the thermal decay test.

No conclusions can yet be made as to the viability of this test insofar that the following tests will be needed to gain better insight into whether or not the application of this test methodology is robust.

6.5.2 Water Heater A (Vertical)

To gain insight into how orientating a water heater differently will affect the calculations, water heater A is mounted in the vertical position and the data is collected for the run down test.

The test is done over a duration of 2 days and 21 hours. As mentioned before, the longer the test, the more accurate the regression approximations and the final values are. Figure 6-3 shows the temperature regression of ΔT, the difference between the ambient and controller temperatures.

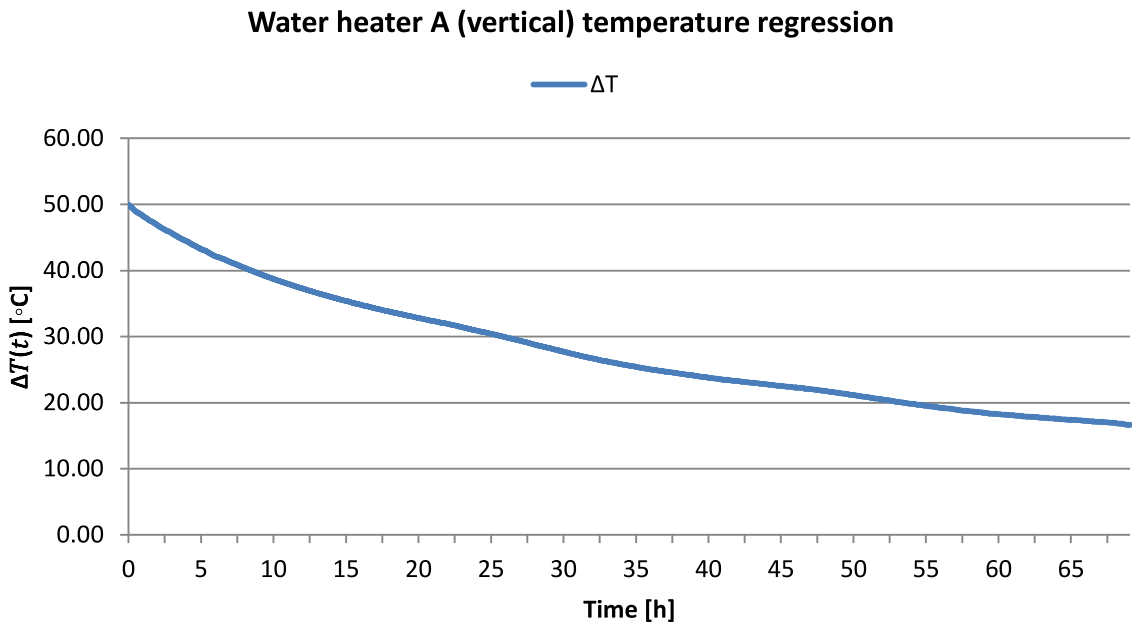


Figure 6-3: Water heater A (vertical) temperature regression of $\Delta T(t)$.

Slight oscillations are observed on the temperature regression. A major contribution of that is from the ambient temperature, which changed throughout the course of the day, reaching a colder mean temperature at night and a higher mean temperature during the day.

The resulting equations from Microsoft Excel (2010) are shown in Table XXXI. The expected trend as the polynomial order increases is a rise in the standing loss value as seen in the previous test.

Table XXXI: Resulting Excel regression equations for $\Delta T(t)$ for water heater A (vertical).

Function	Order	Equations (ΔT)	Approximated losses at 45°C
Exponential	2nd	$45.128e^{(-0.0001\,t)}$	-2.25
Polynomial	2nd	$4 * 10^{-7}\,t^2 - 0.0067\,t + 47.076$	-3.34
	3rd	$-5 * 10^{-11}\,t^3 + 1 * 10^{-6}\,t^2 - 0.0086\,t + 48.358$	-4.27
	4th	$1 * 10^{-14}\,t^4 - 2 * 10^{-10}\,t^3 + 2 * 10^{-6}\,t^2 - 0.0102\,t + 49.019$	-5.03
	5th	$-3 * 10^{-18}\,t^5 + 8 * 10^{-14}\,t^4 - 7 * 10^{-10}\,t^3 + 3 * 10^{-6}\,t^2 - 0.0119\,t + 49.491$	-5.84

Table XXIV shows that the standing losses measured for water heater A, in the vertical orientation, using the SANS 151 test methodology as being 2.34 kWh/day. Contrary to the previous test, the exponential output regression approximation is lower than the measured value, suggesting that the water heater has better heat storing capacity than previously thought.

The results of the polynomial analysis follow the trend set by the previous test. The standing loss value increases as the order of the polynomial increases, further solidifying the suspicion that this analysis might not be viable.

With the MathWorks MATLAB (2009) regression approximation, the one-term exponential fit again closely matches the exponential fit suggested by Microsoft Excel (2010) up to two decimal places. The two-term exponential fit suggested by MathWorks MATLAB (2009) will be a better fit, but the suspicion is that the resulting standing loss value will closely resemble the figures in Table XXXI.

Table XXXII: Water heater A (vertical) MathWorks MATLAB two-term exponential regression curve fit for $\Delta T(t)$.

	Equation (ΔT)	Approximated losses at 45°C
Two-term exponential	$9.855\ e^{-0.00059t} + 37.8\ e^{-0.0001t}$	-4.77

As suspected the resulting standing loss value acquired is twice that of the standing losses calculated using the SANS 151 test. Again the confidence in this line of thinking is questioned.

In comparison to the horizontally mounted water heater, when mounted vertically, the rate of change in the calculated standing loss value is quite dramatic. This aggressive change may be attributed to the design flaws pointed out in the tear down of the water heater in Section 4.2.5.

6.5.3 Water Heater B (Vertical)

Water heater B is made by the same manufacturer as water heater A, but is designed to be more insulating and have a smaller surface area for heat to dissipate over. This is seen when taking a look at the standing losses as displayed in Table XXIV that reflect the water heater standing losses. The measured standing loss values for water heater A are 2.23 and 2.33 kWh/day for the vertical and horizontal orientations respectively. Water heater B standing loss values were measured at 1.90 and 2.24 kWh/day for the vertical and horizontal orientations respectively, clearly showing that it has better thermodynamic properties. These figures are taken from the results of the SANS 151 equation.

The run down test is executed with a view to further justify this observation. After the SANS 151 standing loss test is completed, the power to the element of the water heater is cut off and thermal data collection continues. The regression data collected is shown in Figure 6-4. As with the previous test, the regression has slight oscillations. These are mainly caused by the variation of ambient temperatures over the course of the test throughout the day. Data collection in this instance is done over a period of 3 days and 18 hours.

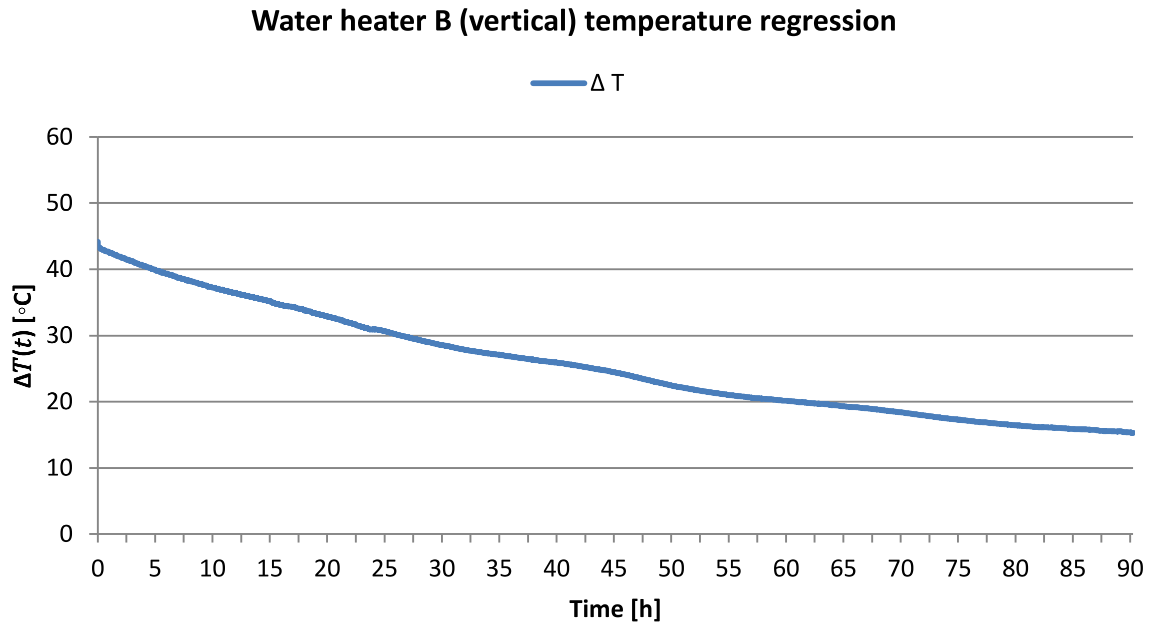


Figure 6-4: Water heater B (vertical) temperature regression of $\Delta T(t)$.

Table XXXIII shows the resulting regression formulas attained from Microsoft Excel (2010). The expected trend is that the standing loss values attained from the regression formulas equate to lower values than those from water heater A.

Table XXXIII: Resulting Excel regression equations for $\Delta T(t)$ for water heater B (vertical).

Function	Order	Equations (ΔT)	Approximated losses at 45°C
Exponential	**2nd**	$41.336e^{-0.0001\,t}$	-2.06
Polynomial	**2nd**	$2 * 10^{-7}\,t^2 - 0.0043\,t + 42.39$	-2.15
	3rd	$-7 * 10^{-12}\,t^3 + 3 * 10^{-7}\,t^2 - 0.0048\,t + 42.809$	-2.39
	4th	$1 * 10^{-15}\,t^4 - 3 * 10^{-11}\,t^3 + 4 * 10^{-7}\,t^2 - 0.0052\,t + 43.015$	-2.59
	5th	$-1 * 10^{-19}t^5 + 4 * 10^{-15}t^4 - 6 * 10^{-11}t^3 + 6 * 10^{-7}t^2 - 0.0054\,t + 43.088$	-2.68

The results in Table XXXIII show that water heater B is indeed of better manufacturing and build standards than water heater A. This is evident when looking at the standing loss values of the second order standing loss results.

The measured SANS 151 standing loss value, as seen in Table XXIV, is 2.26 kWh/day. Contrary to the previous tests, the value is higher than the value attained using the exponential regression function. Only when a 3rd order polynomial regression function is used to represent the data is the difference smaller.

The exponential regression equation has the same exponent as the previous water heater though, so the temperature decay seems to occur at the same rate as water heater A. Although the standing losses calculated are lower, the exponent indicates that the thermal capacity of water heater B is similar to that of water heater A.

In comparison, the polynomial regression equations tell a much better story. The standing loss values calculated are substantially lower when compared to water heater A and thus are indicative of the fact that the water heater is designed better than water heater A.

When the single term exponential fit is acquired in MathWorks MATLAB (2009) the similarity to the Microsoft Excel (2010) fit is again extensive and concur up to two decimal places on the gain and up to 6 decimal places on the exponent.

Table XXXIV: Water heater B (vertical) MathWorks MATLAB two-term exponential regression curve fit for $\Delta T(t)$.

	Equation (ΔT)	Approximated losses at 45°C
Two-term exponential	$40.37\ e^{-0.000124t} + 2.379\ e^{0.0000622t}$	-2.58

2.58 kWh/day is the best result from the two-term exponential fit so far even though it is above the maximum allowable standing losses. Even if it was considered as a viable result, the previous tests have discredited this solution.

6.5.4 Water Heater F (Horizontal)

With a view to gain some depth for the investigation a water heater from a different manufacturer is explored. Water heater F is only designed for horizontal orientation. It also ranked as the water heater with the lowest standing losses under the SANS 151 test methodology, using only 1.83 kWh/day.

The description of the water heater can be found in Chapter 4.7, but just to summarize, the water heater is manufactured for the high-end market with a unique internal coating to minimise oxidisation and eliminate the need for an anode. The fittings in the tank of the water heater are made from plastic to minimise heat conduction and the insulation is slightly thicker.

The run down test data sample was taken over a larger interval, that being 5 days and 18 hours. Figure 6-5 shows the regression curve of the temperature difference in controller and ambient temperature.

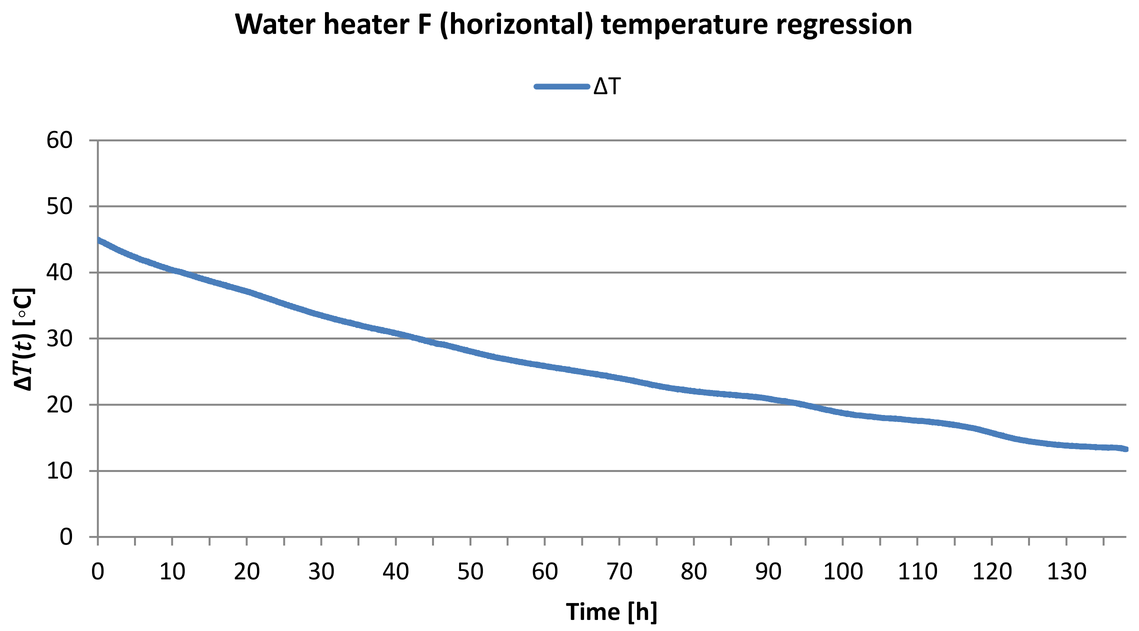


Figure 6-5: Water heater F (horizontal) temperature regression of $\Delta T(t)$.

When compared to the previous water heater regression curves, the first noticeable difference is the time it takes for the temperatures to decay. Water heater B, the most efficient water heater in this chapter so far, reaches a temperature difference of 20 °C after 60 hours whereas water heater F reaches that same temperature after 94 hours.

This difference must reflect in the decay or exponent of the exponential regression curve acquired from Microsoft Excel (2010). The standing loss values for the polynomial regression curves must also differ but that is yet to be seen.

Table XXXV: Resulting Excel regression equations for $\Delta T(t)$ for water heater F (horizontal).

Function	Order	Equations (ΔT)	Approximated losses at 45°C
Exponential	**2nd**	$43.812e^{-0.00007\,t}$	-1.51
Polynomial	**2nd**	$7 * 10^{-8}\,t^2 - 0.0029\,t + 43.568$	-1.45
	3rd	$-5 * 10^{-12}\,t^3 + 2 * 10^{-7}\,t^2 - 0.0037\,t + 44.733$	-1.85
	4th	$-6 * 10^{-17}\,t^4 - 3 * 10^{-12}\,t^3 + 2 * 10^{-7}\,t^2 - 0.0037\,t + 44.672$	-1.85
	5th	$6 * 10^{-20}\,t^5 - 3 * 10^{-15}\,t^4 + 3 * 10^{-11}\,t^3 - 6 * 10^{-8}\,t^2 - 0.0031\,t + 44.362$	-1.56

The results in Table XXXV show the lowest value in this investigation so far. This is expected as this is the best performing water heater in Chapter 4. In that chapter the standing losses calculated are 1.83 kWh/day. Comparing that value to the values in Table XXXV a remarkable difference is seen.

When the exponential regression curve is used to calculate the standing losses, a value of 1.51 kWh/day is acquired. If a smaller time interval is used starting from the switch off point, then the value increases. For a time interval of 36 hours, a standing loss value of 1.78 kWh is acquired. This suggests that if the limit of the gradient of the measured data regression curve is taken as it approaches 45 °C, the acquired standing loss value should become more accurate. But the purpose of this investigation is to define a regression curve equation that best fits the regression curve in order to find the standing losses at temperature differential of 45 °C.

When using the polynomial regression curves to calculate the standing losses, an interesting trend is seen. When the third and fourth order polynomial regressing curves are used, the acquired standing loss values are the most accurate. But after that the standing loss value decreases when the 5th order polynomial is used. Under further scrutiny, the most contributing factor in the equation, the constant, decreases after the 4th order polynomial. This trend is not observed in any of the other regression formulas. This may be due to the longer time interval of the test.

If a smaller test interval is used to analyse the data, for example one day and 12 hours then the resulting acquired standing loss values change.

Table XXXVI: Water heater F: Shorter test interval (36 hours).

Function	**Order**	**Approximated losses at 45°C**
Exponential	**2nd**	-1.78
Polynomial	**2nd**	-1.70
	3rd	-1.84
	4th	-2.62
	5th	-2.62

The results in Table XXXVI reflect a much better representation of the data. The most accurate results are acquired when the 3rd order polynomial regression formula is used with only a difference if 0.01 kWh/day from the measured SANS 151 standing loss value.

After the 4th order polynomial the results don't change as the regression line fully represents the data at the 4th order polynomial fit.

The exponential regression curve, although somewhat more of a better fit, still results in a lower standing loss value than that measured in the SANS 151 test.

Based on what has been seen with the previous water heaters, a MathWorks MATLAB (2009) analysis would not be relevant anymore, but for the sake of the investigation one last one shall be done.

The two-term exponential fit attained from the program is shown in Table XXXVII

Table XXXVII: Water heater F (horizontal): MathWorks MATLAB two-term exponential regression curve fit for $\Delta T(t)$.

	Equation (ΔT)	Approximated losses at 45°C
Two-term exponential	$1.942\, e^{-0.000549t} + 42.85\, e^{0.0000693t}$	-2.01

Unlike in the previous tests the result in Table XXXVIII resembles the SANS 151 standing losses more but is still not as accurate.

6.6 Conclusions

The objectives of this chapter were to investigate a possible way to streamline the testing process used to find the standing losses of a water heater. The proposed test methodology supposedly is significantly more efficient and eliminates variables that would otherwise affect the collected data.

The tests were only executed on a few selected water heaters to gain a broader view on the inquiry. A summarised version of the results can be seen in Table XXXVIII as well as the respective standing losses calculated using the SANS 151 test methodology.

Table XXXVIII: Summary of standing losses aquired through regression formulas.

Function	**Order**	**Water heater A (horizontal)**	**Water heater A (vertical)**	**Water heater B (vertical)**	**Water heater F (horizontal)**
Exponential	**1 term**	-2.39	-2.25	-2.06	-1.78
Polynomial	**2nd**	-2.54	-3.34	-2.15	-1.7
	3rd	-3.02	-4.27	-2.39	-1.84
	4th	-3.33	-5.03	-2.59	-2.62
	5th	-3.6	-5.84	-2.68	-2.62
MATLAB exponential	**2 term**	-3.75	-4.77	-2.58	-2.01
Actual		2.23	2.34	2.26	1.83

The results in Table XXXVIII show a diverse picture. From the first two tests the assumption could be made that the exponential regression formula is the most suited when calculating the standing losses.

In the last two tests it is indicated that the 3rd order polynomial represents the collected data more accurately and that the exponential regression curve results in a much lower standing loss value than the one measured in the SANS 151 test.

The exponent of the exponential regression curve does show some potential in giving insight into the decay of the temperature. This could be used to classify the insulation grading, but a system for that already exists as shown in Chapter 5.

In the context of the order of the polynomial equations, the general trend for an increased order in the polynomial regression curves shows an increase in the resulting standing losses calculated. These are blatantly wrong and should be ignored. As was seen in the representation of the regression curves in Figure 6-2, as the order of the polynomial increases, the more reactive the regression becomes. Any change at the start of the data set results in larger differentials further on in the data set.

With the oscillating nature of the ambient temperature, a polynomial increase would be needed for each change in trend of the ambient temperature. What would be a better strategy would be to, for one, have a much larger data set, but to also approximate the ambient temperature signal using Fourier transforms. Superimposing that on an exponential regression curve for the controller temperature, and the result could be more accurate and satisfactory. This would include the oscillations of the ambient temperature.

In this instance, it is difficult to discern which results to use as a base for ranking the water heaters. The regression curve, showing the most promise, is the exponential one. If the water heaters are ranked according to the exponential equation, as seen in Table XXXIX, it can be seen that water heater F is placed first, followed by water heater B in a vertical orientation.

Table XXXIX: Water heater ranking based on exponential regression curve.

Water heater	**Approximated losses at 45°C**
F (horizontal)	-1.78
B (vertical)	-2.06
A (vertical)	-2.25
A (horizontal)	-2.39

When the figures are scrutinized, it is seen that for both tests for water heater A, the temperature regression starts at a $\Delta T(t)$ of 50°C. This buffer in the tests might allow for a more accurate result when compared to the standing losses measured in the SANS 151 test.

All in all, this line of investigation has shown some potential in calculating the standing losses using the regression curves of the temperature difference. Further time and research would need to be dedicated to the idea in order to verify whether or not this method of testing can eventually be applied in any capacity.

7 Theoretical Thermal Analysis

7.1 Introduction

Over the course of the investigation many heat loss sources are observed. The causes of the heat losses are not fully understood. Further study is needed to explore how the heat losses occur and why certain areas of the water barrel seem to allow more energy to escape. This chapter proposes a simplification to the design of the water heater structure so that simple CFD analyses can be completed with a view to understand the thermal behaviour of the water inside the water barrel.

The issue with simulating a water heater, is that there are many uncontrollable variables in any practical test, inter alia insulation integrity, vortexes in the water, element placement and element shape. This chapter simplifies the model of the water heater in order to create simulations to analyse the thermal behaviour of a water heater. The strategy is to eliminate as many of the dependant variables in the simulation and create a first order approximation of the design to minimise computational limitations.

The water heaters tested are all uniquely designed, but there are common design strategies. All are designed in the cylindrical form and can either be mounted horizontally or vertically. The water tank is off-centre towards the bottom of the outer casing to prevent high standing losses at the top of the water heater where, due to convective effects, the hot water supposedly accumulates. The thermostat in the water heater, designed to measure the temperature in the centre of the water heater, is slightly displaced towards the element along the centre line. The elements on the other hand, have the most variation in terms of design and placement inside each water heater. The complexity of the elements cannot be ignored due to their varying effects on heat distribution and potential flow patterns in the water barrel.

One of the elements used is linear consisting of a straight looped conductor that is bent back on itself to heat water localized around the conductor more effectively. This element type is usually placed towards the bottom of the water heater away from the thermostat but still extends inwards inside the water heater, enough to reach the same depth as the thermostat and influence the temperature readings. This element type can be seen in water heaters D and E.

The other type of element encountered was the spiral element. This element design consists of the conductor spiralling in a circular fashion around the thermostat in the centre of the water heater. Both the thermostat sleeve and element are attached to a faceplate. The element and thermostat sleeve are inserted through a cavity in the water heater and fastened to the water heater via nuts and bolts. The element does not however extend far enough into the water heater to reach the end of the thermostat sleeve. However, it is yet to be seen whether the heating element still affects the readings of the thermostat to a great degree.

Water heaters A, B and C all are designed with spiral elements but the faceplate is removed from the images in Chapter 4.

The reason for mentioning the depth of the element types is that, due to the convection effect, any hot plumes of water rising off the element will have a direct impact on the temperature measurements if the element is near the point of measurement, i.e. the end of the thermostat sleeve. In order to investigate this further, a specific look must be cast to the temperature dissipation and distribution inside the water heaters.

This is done via simulations in different software packages. It is critical that the packages used in this investigation have the necessary tools available to investigate different principles associated with fluid dynamics.

An explorative analysis was conducted on the principles used in modelling the thermodynamic behaviour of water in the literature study. Following that, a look was cast upon programs that might possibly be used to analyse the thermal behaviour inside the water heater. The simulations are carried out in this chapter with a view to analyse them for possible deviations to the current knowledge of where the greatest heat losses are. These findings are then compared with the findings in the previous chapters. The main objectives of this study can be summarised as follows:

- Conduct an exploratory study with the view to determine if CFD simulations can be used to gain an understanding of the thermodynamic behaviour of the water heater for different topologies of water heater orientation, heating element design and heating element position inside the water barrel.
- Gain an understanding of the flow patterns caused by the heating element for different water heater orientations.
- Identify any specific trends that arise in different water heater orientations and element positions inside the water barrel.

In view of the complexity of the problem and the multitude of uncontrollable variables that influence the measurements, inter alia the surface temperature of the heating element, the study attempts to achieve a qualitative rather than a quantitative analysis. The purpose of the investigation is to identify any trends that arise due to the different topologies. The aim of using the CFD software is not to propose changes to the design of water heaters but rather to gain insight into the thermodynamic behaviour of the water inside the water barrel. However, from the results, recommendations can be made based on the results of the simulations.

Before any simulations are carried out, the various testing arrangements need to be explored in order to establish the geometric shapes needed for the simulations. The water heaters are only tested in two possible positions, namely in the horizontal and vertical orientations. No matter in what orientation the water heater is mounted, the cold water inlet will always be towards the bottom of the water heater and the outlet will always be towards the top of the water heater.

The types of water heaters to be investigated are those with the spiral element shape, fitted in the centre of the one faceplate of a water heater, and those with the linear element shape, displaced off-centre and downwards. In order to minimize the computing power needed and time taken for completion of simulations, a model design is used to represent a simplified model of the water heater.

Those with the spiral element type are modelled as being axisymmetric about its centre axis if the element is modelled as an array of donut shaped rings. Otherwise the shape of the water heater is already axisymmetric. The linear element can be modelled as a cylinder going into the water heater at a depth deeper than the spiral element. This design is not axisymmetric and definitely requires a 3 dimensional model. The design of the linear element type water heaters induces a different flow and a simple 2 dimensional simulation will not suffice due to the heat transfer changing due to the flow. This is verified in the next few sections.

7.2 Geometries

To recapitulate, the aims of this investigation are to:

- Observe where the heat accumulates to better gauge where the heat losses occur.
- Determine whether the current designs of the water heaters available on the market do actually work, or if recommendations need to be made to improve their overall efficiency.

In order to gauge what kind of simulation is best suited for the task, a 2D temperature and flow analysis is done in MathWorks MATLAB. In the cases where symmetry is needed, an additional look will be taken at the flow patterns. 3D simulations will also be completed to confirm the results in the 2D simulations.

The MathWorks MATLAB model will consist of a square array of elements at a starting temperature of 20 °C. The heating element will be imposed on a few of the elements to best represent the shape and position of the heating element inside the water heater.

In the case of the spiral element, the 3D model can be built with donut shapes in place of the element. The structure is then axisymmetric around its centre axis. Because the element is placed in the centre of the water heater as viewed along the central axis, the flow should be symmetrical to either side of the centre of the water heater but this is yet to be confirmed. The 2D simulation will not include this level of complexity but the 3D model, completed in COMSOL, will include this level of complexity.

COMSOL Multiphysics includes a CFD module capable of completing a host of different flow meshes and models. One of the packages that is used to carry out this investigation, is the laminar flow module. For the purposes of this investigation a 3D Non-Isothermal Laminar Flow model is built. The mesh is built without any insulation around the body of water to represent the simplified ideal scenario where no heat is lost.

The data will be acquired as follows. The simulation will be run over the course of 2 minutes from a cold start. The element temperature will be set at 338 K or 65 °C and the initial temperatures will be set at 293.15 K or 20 °C. A thermal analysis will be done at 0.5 second intervals to try and get the best resolution of the thermal behaviour within the water heater. Once the simulations are complete, a pointwise thermal investigation is done as well as a flow analysis.

The results given in COMSOL include the pressure differential, velocity and temperatures along the boundary of the mesh as well as contours of the temperature throughout the water heater. First the geometry used for each subsection will be shown. After that the temperatures corresponding to the practical investigation will be shown. Lastly the 2D and 3D geometries will be presented showing the subsequent temperatures and accompanying velocities. The samples of the geometries will be taken in 2^n time steps where n ranges from 0 to 7.

7.2.1 MathWorks MATLAB

A MathWorks MATLAB Rayleigh-Bénard Convection example by Suraj Shankar is modified to show Rayleigh-Bénard convection in 2 dimensions with a view to gauge the internal water flow and heat dissipation inside the water heater [73]. In the code, the spiral element is reduced to two linear heat sources representing a simplified cross section of the element as viewed from the side.

The equations used for the boundaries are the Dirichlet Boundary conditions for the sidewalls and the Neumann Boundary conditions for the top and bottom walls. The convection equations used in the software are the Rayleigh-Benard convection equations.

The linear element water heat type will be different. The water barrel will still be symmetrical about its centre axis but the element will need to be added after the geometry for the barrel has been revolved about its axis. The consequences of this are that the water heater cannot be simulated as an axisymmetrical model. Nevertheless a 2 dimensional model can be built in MathWorks MATLAB.

One of the obstacles in the 2 dimensional model is that, because the linear element is placed off-centre, the water flow will not be symmetrical either, making the simulation a futile effort. However, a 2 dimensional simulation can reveal where the hot areas around the element are and therefore is still carried out.

7.2.2 COMSOL

To simplify the mesh, the body of the water heater is simulated as a cylinder with half of an ellipsoid modelled onto either side of the cylinder. The element is represented by an array of square rings. The model can be seen in Figure 7-1. The model is scaled to a quarter of the original size to minimise computing power yet still retain the amount of complexity in the mesh. With the smaller size, the time taken for the water heater to settle is also reduced.

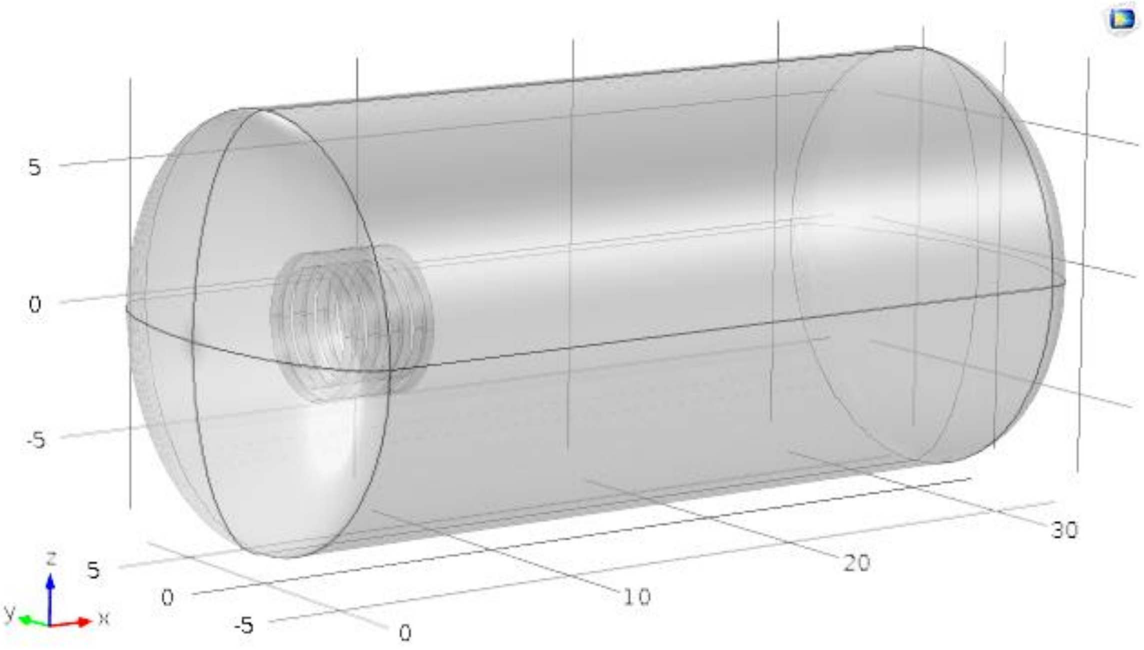


Figure 7-1: COMSOL geometry: Spiral element water heater.

This model is used in all other simulations and is rotated from the x to the z axis for the case of the water heater in a vertical orientation. The simulation is set as time dependant and the mesh is set to normal. The focus lies around the element and at the boundary of the water barrel inside the water heater.

Once the simulation is done, a preliminary investigation is done to view the temperatures in the same positions as those in the practical investigation in Chapter 4. One sample point is positioned at a position just ahead of the element to represent the thermostat, one at the top boundary opposite the element position to represent the hot water outlet pipe, and one below the element on the boundary of the geometry to represent the cold water inlet pipe.

Following the spiral element type water heater investigation, the linear type is investigated. The only change to the model for the linear element is that the rings are replaced with a rod extending towards the centre of the water heater at the bottom left of the water barrel structure. The probes are still placed at the same coordinates and the dimensions are identical to those of the water heater design used for the spiral element water heater:

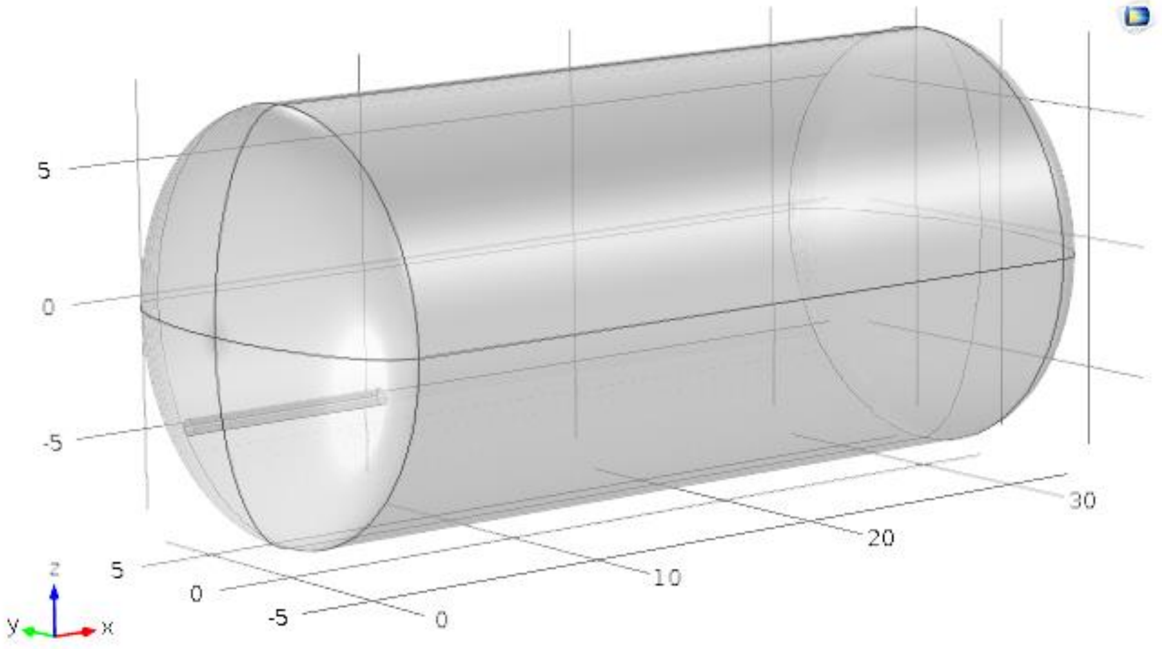


Figure 7-2: COMSOL geometry: linear element water heater.

The expected temperature probe response is similar to that of the spiral element type. There may be Rayleigh-Taylor Instabilities that arise due to the element being off-centre which would influence the element probe.

7.3 Centre Spiral Heating Element – Horizontal Orientation

7.3.1 MathWorks MATLAB Simulation

A model built of a side view of spiral element type water heater is constructed and run in the modified code yields the image in Figure 7-3.

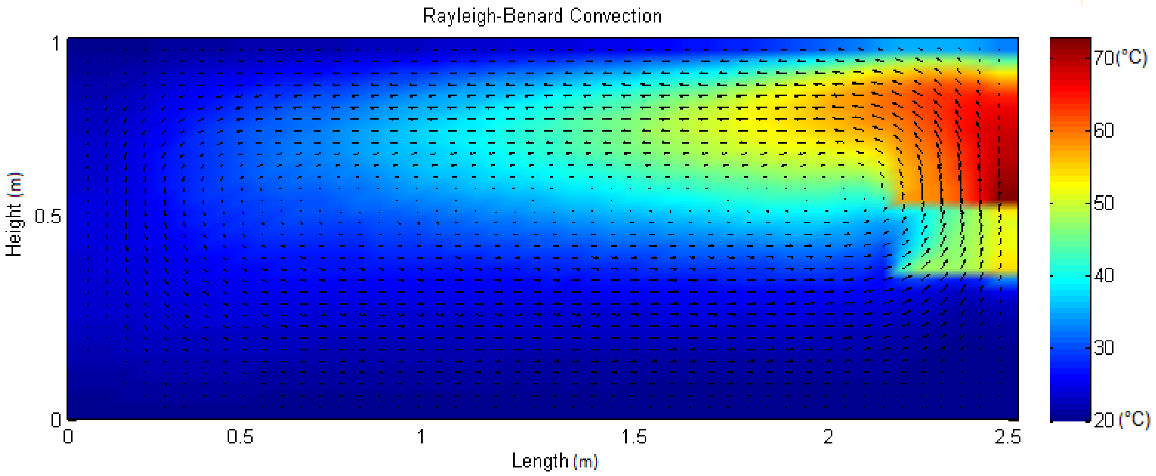


Figure 7-3: Spiral element water heater, 2D side view, horizontal orientation, thermal dissipation and fluid flow.

In Figure 7-3, the key on the right indicates the temperature of the water in the water heater. The black arrows in the figure are indicative of the flow of water. The image is taken a few seconds after a cold start condition but will also indicate where the hot areas will be while the element is on in a steady state condition. When a spiral element water heater is used, the hot areas appear to occur at the base of the element on the top of the spiral. The flow of water pushes the newly heated water up and against the body of the water heater, an area that was identified as a problem area previously in the practical part of the investigation in Chapter 4.

During the testing of the spiral element type water heaters, one of the hot zones discovered was on the mounting plate of the element. The majority of water heater manufacturers did not account for this exposed area, leaving it uninsulated and prone to heat losses. This gives insight into one of the areas that potentially shows the greatest heat loss but is also one with the most potential, being the easiest to correct.

The flow inside the water heater is circular throughout the water heater. The heat immediately accumulates at the top of the water heater, rising above the cold water due to the lower density of the warm water. At the start of the simulation, a Rayleigh-Taylor instability was seen as the hot plume of water, i.e. the less dense plume of water rising off the element, encountered the colder and denser water.

If viewed from the front or element side, the flow in the water heater around the element can be simulated. For the spiral element type water heaters, the geometry consists of a circular mesh representing the body of water with a smaller ring representing the element.

Figure 7-4 shows the cross sectional view of a spiral element type water heater. The colour gradient represents the thermal behaviour of the water heater and the arrows represent the flow of water inside the water heater. On either side of the water heater circular flow patterns are observed. This is an example of the patterns formed as described in Rayleigh-Bénard Convection.

Another hypothesis and observation made with the side view simulation is that the hot water accumulates at the top of the water heater. Figure 7-4 reinforces this hypothesis but still further research is needed to confirm.

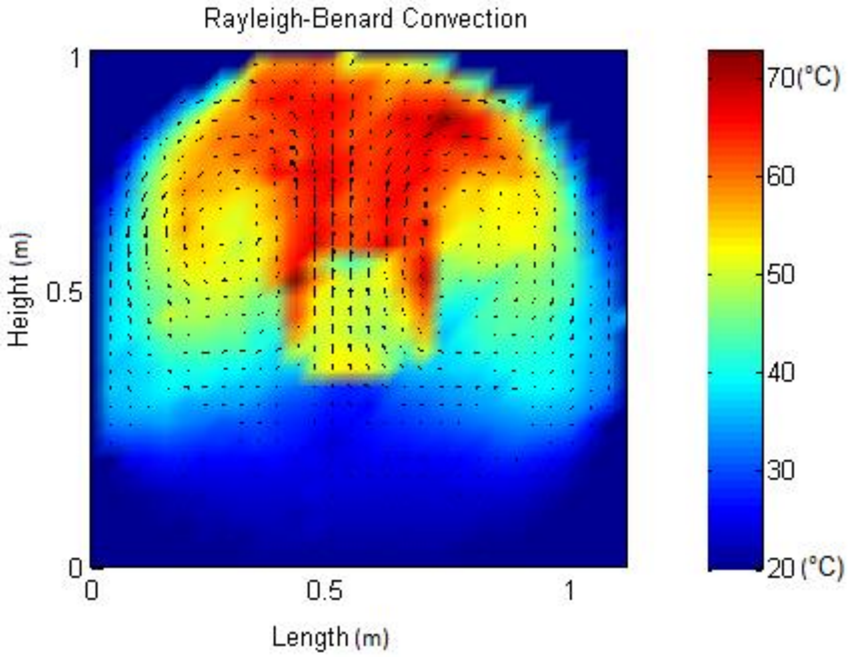


Figure 7-4: Spiral element water heater, 2D cross-sectional view, horizontal orientation, thermal dissipation and fluid flow.

7.3.2 COMSOL Simulation

Figure 7-5 shows the results from the sample point check inside the water barrel. The point investigation, as described earlier in the chapter, has points placed at the position of the thermostat, the cold water inlet pipe and the hot water outlet pipe. The sample point just ahead of the element is represented by the blue line and appears to approach the final value of 338 K or 65 °C. As is expected, the sample point taken at the perceived hot water outlet rises faster than the previous described one, as all the hot water accumulates at the top of the water heater. Lastly, the sample point, taken at the cold water inlet, rises with a delay in time when compared to the others.

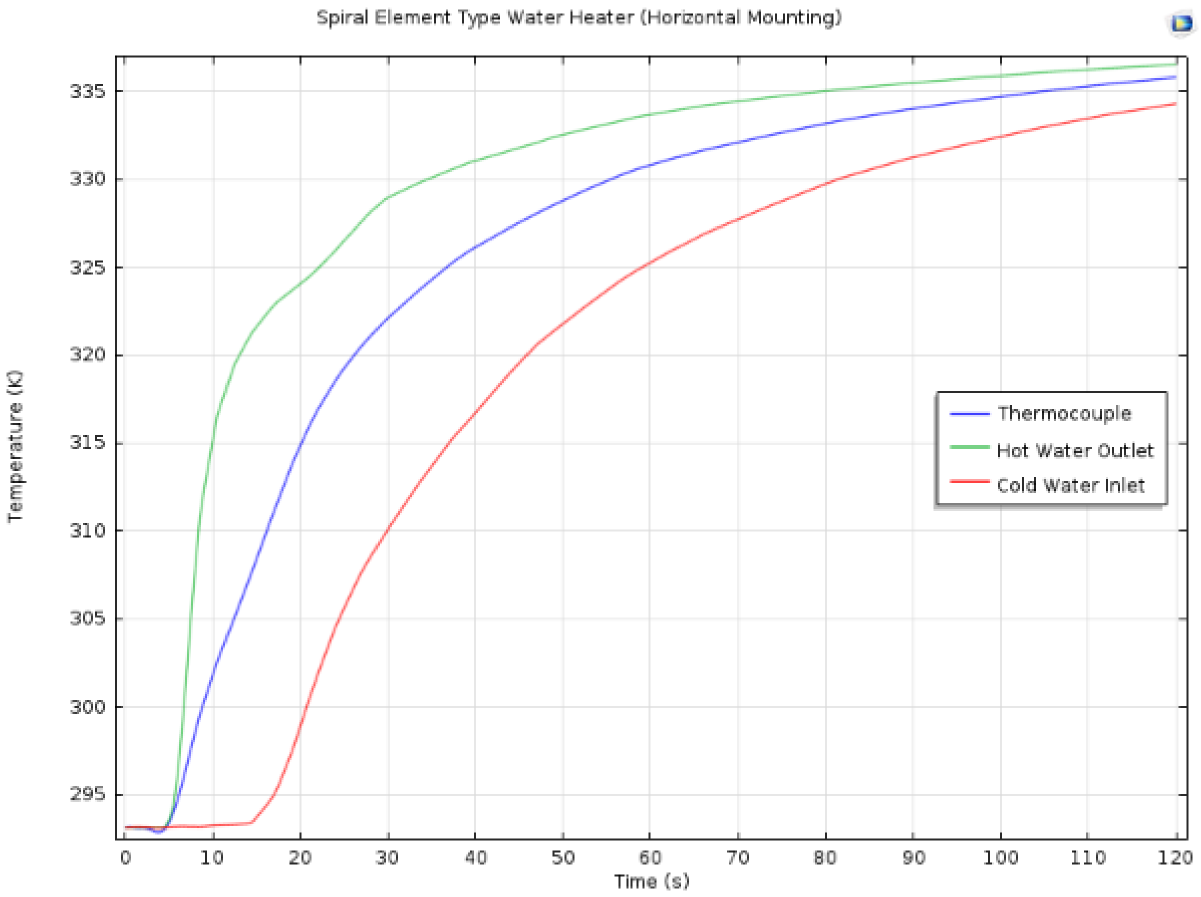


Figure 7-5: COMSOL spiral element water heater (horizontal) spot point temperature investigation.

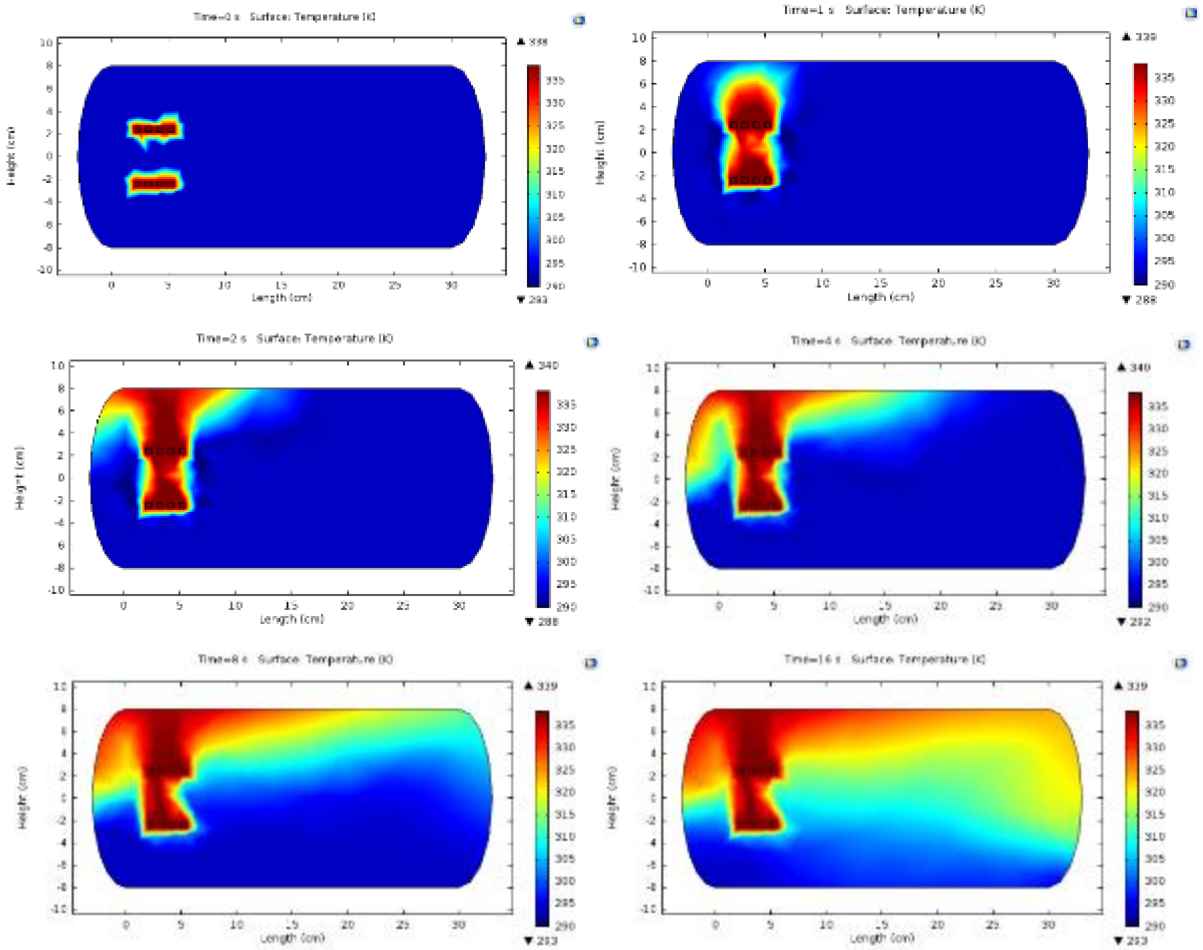
The hot water outlet temperature probe appears to have a slight cavity in the rising action. This could either be due to the convective effects in the water heater or due to an instability occurring in the water body. As explained in the literature study, Rayleigh-Bénard convection describes the principle of hot and cold water patterns starting to form once a certain state is reached. However, the water heater has not reached a state of equilibrium and the probability that it is an instability is higher, namely a Rayleigh-Taylor Instability. This is when fluids of different densities react in different ways inducing unexpected behaviour.

Due to the simplified ideal nature of this investigation, the temperature trends will all converge to one temperature, namely the temperature of the element. In the previous simulations as well as in those following, the final temperature all thermal trends will reach will is 338K. Nevertheless these results do coincide with those collected in the practical investigation with regards to the warm up of the water heaters.

To recapitulate, the purpose of this investigation is to gain a better understanding of the thermal behaviour of the water inside of a water heater. Thus the velocity and temperature fields need to be investigated. What follows is the 2D cross-section of the geometries representing the temperature and velocity inside the water heater at the intervals described previously.

Temperature (Horizontal)

The temperature range is fixed at between 290 K and 338 K as to observe the true temperature dissipation throughout the water heater. The temperature plots in Figure 7-6 reveal that the heated water rising off the element accumulates at the top of the water barrel, as was suspected. It also suggests that there is water flow behind the element. This is to an area with compromised thermal insulation. The water velocity plots would share more insight into that possible issue.



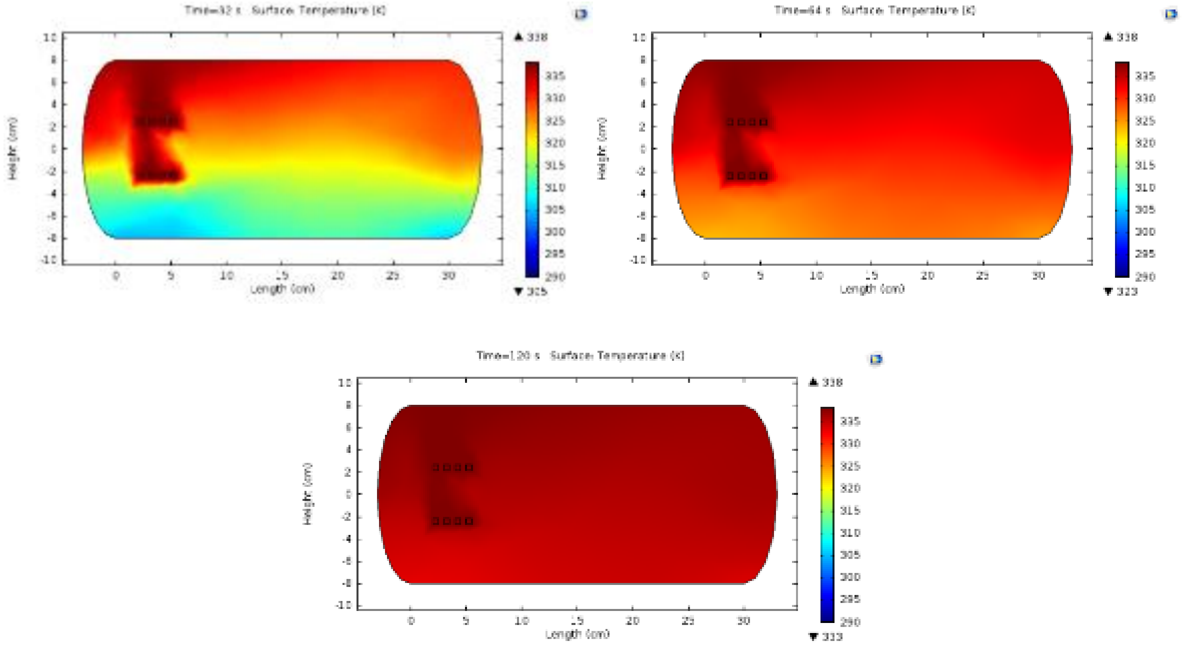
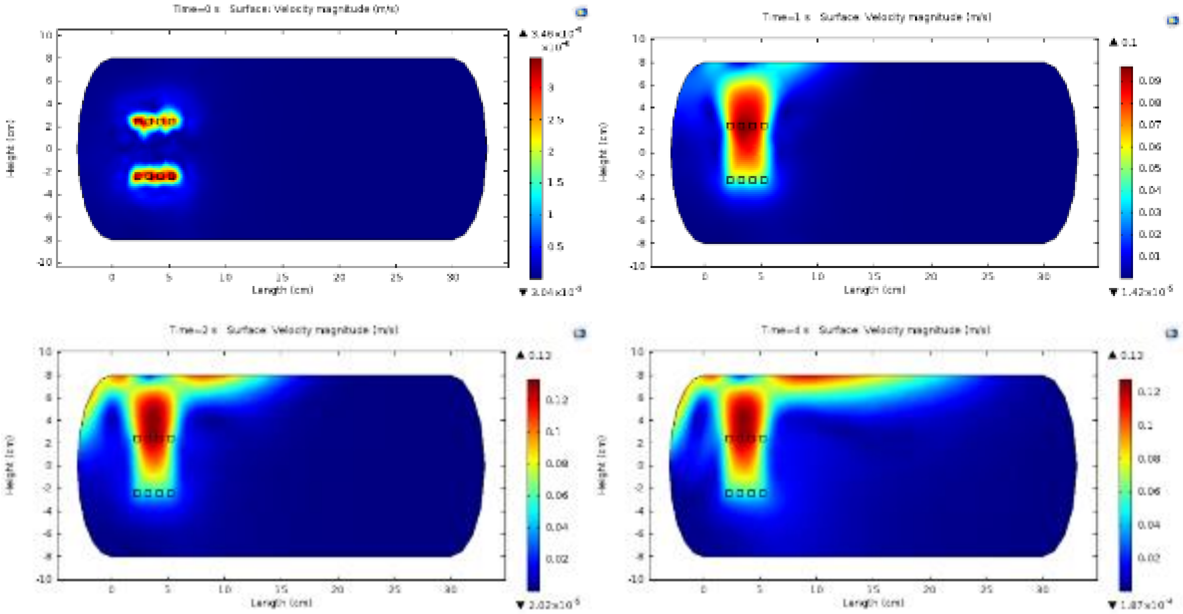


Figure 7-6: Spiral element water heater, horizontal orientation temperature progression.

Velocity (Horizontal)

The velocity range in Figure 7-7 is set at automatic scaling to get a feel of the movement of water throughout the water heater. As the temperature stabilizes the velocity decreases from the order of 0.12 to 3×10^{-2}.



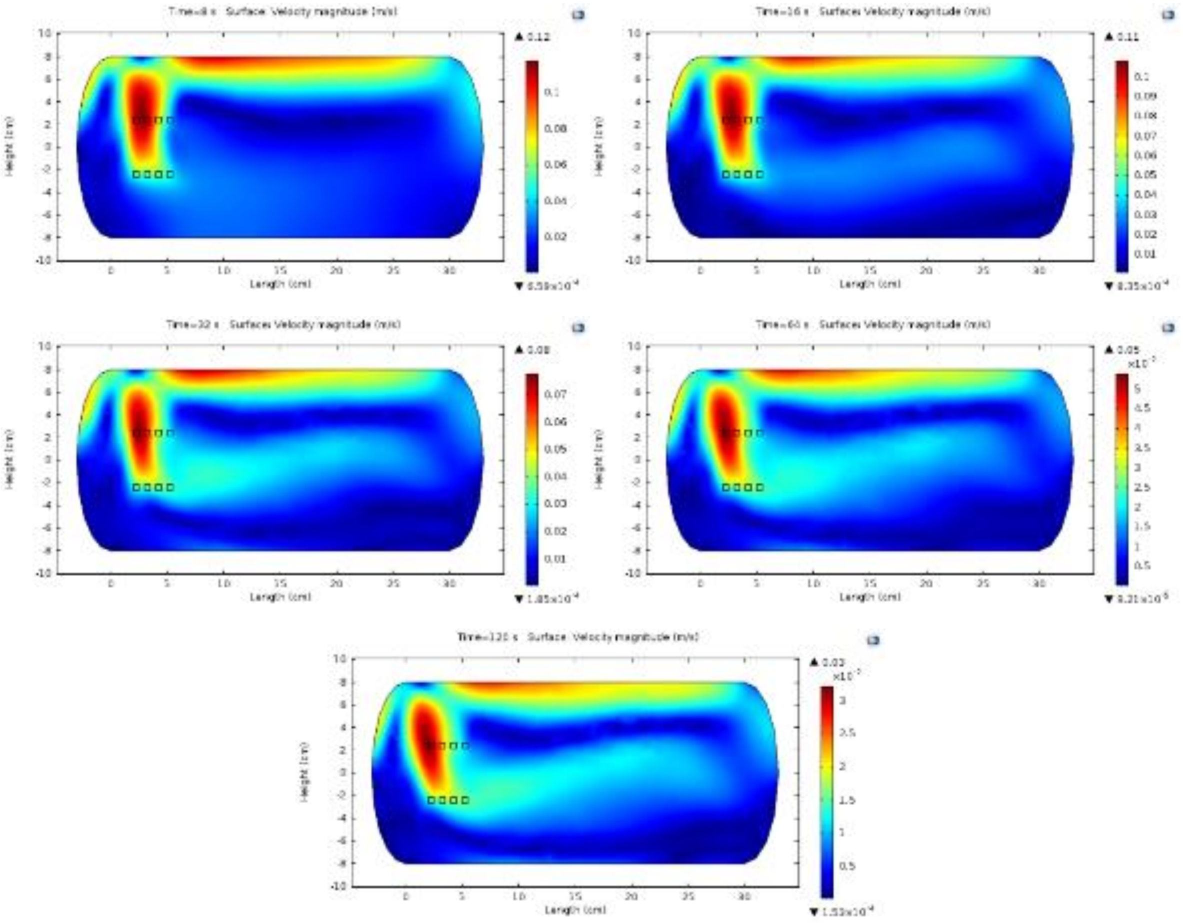


Figure 7-7: Spiral element water heater, horizontal orientation velocity progression.

The velocity fields show circulations into the larger part of the water barrel to the right as well as to the left of the element. From the moment the element is first switched on, circulation starts in both directions. However the circulation does not include the entire water body. Initially, at 8 seconds, the entire body is involved in the circulation as the water heater stabilizes. Then at 16 seconds a pattern emerges where a pocket of water remains isolated from the circulation opposite the element towards the bottom. This pattern in the circulation stabilizes as time progresses. To further investigate this trend, a streamline plot is done by defining a set number of points that are tracked over a time interval and plotted in the 3D geometry.

Flow (Horizontal)

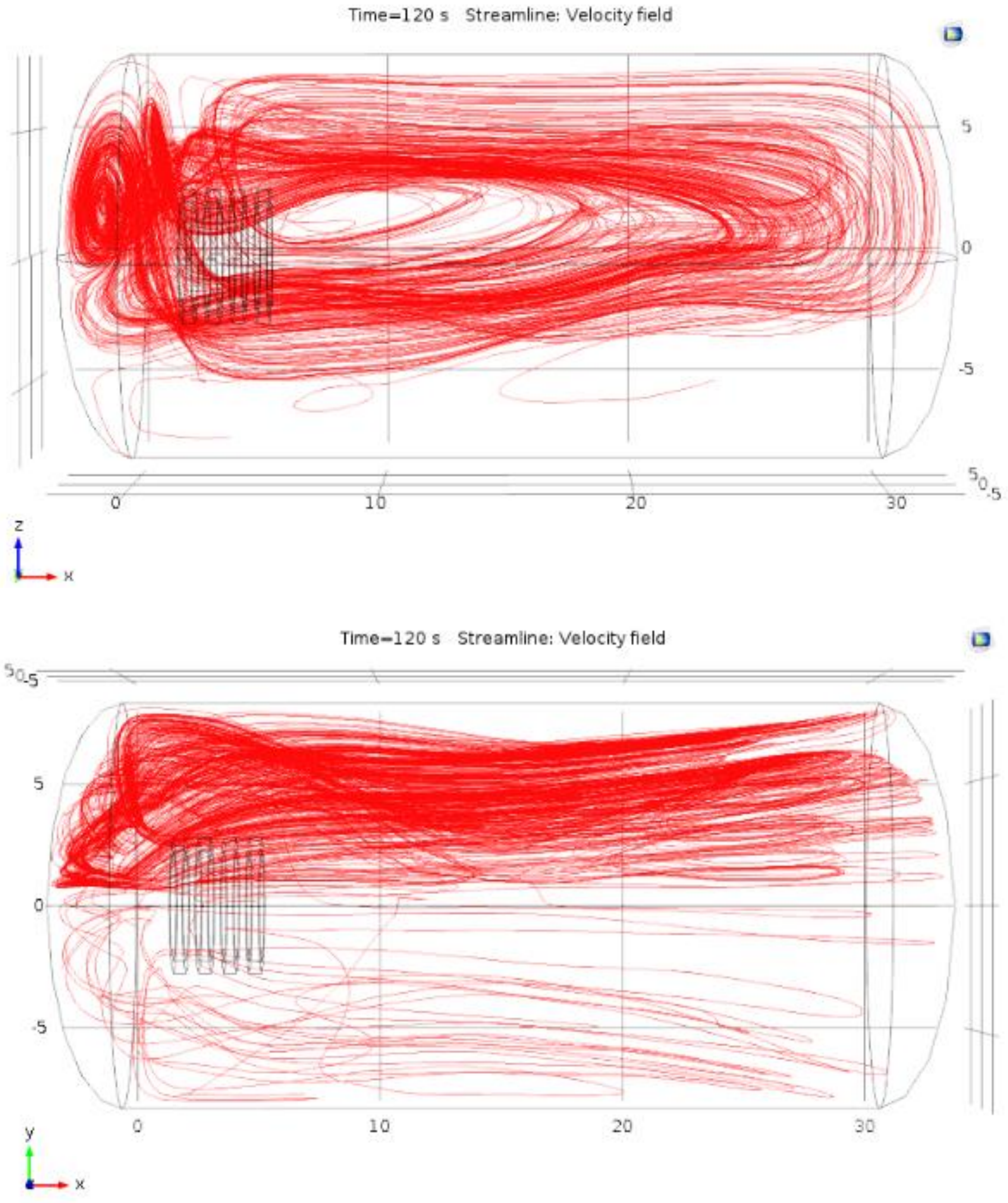


Figure 7-8: Spiral element water heater, horizontal orientation velocity streamline plot.

Further inspection of the water flow at steady state, reveal more about the observations made in the velocity and temperature plots. From the side view, presented first, it is observed that as the water flows through the barrel to the hot water outlet and circulates back to the element leaving the bottom section undisturbed. The circulating water induces a flow behind the element towards the mounting plate, causing the transportation of more heat to the compromised insulation.

The topographical view reveals that the water circulating behind the element pushes the colder and more dense water, that returns from the hot water outlet side, towards the side the of the water barrel as it is heated by the element inducing a flow there.

The reason that the topographical view looks one-sided is that the points are chosen at random and the majority of the points seem to have originated on that side of the water heater.

7.4 Centre Spiral Heating Element – Vertical Orientation

7.4.1 MathWorks MATLAB Simulation

If the water heater should be mounted vertically, it is expected that the hot water will rise to the top of the water heater from the element. Figure 7-9 confirms the above statement showing that the water does indeed rise to the top of the water heater and that the hottest point in the system is on the top end of the element as expected. This will minimize heat losses through the element mounting plate and reduce energy usage. However, with the design of the insulation on one side of the water heater being on average thinner, as seen in the tear down of the water heaters in Chapter 4, the heat losses will not be uniform around the sheeting of the water heater. It will severely impact the efficiency of the water heater if the insulation is substandard or compromised.

The water flow seen in the water heater is also as expected, with a central plume of hot water rising and pushing the colder water down the outside of the water heater. The circulation occurs along the entire wall of the water heater.

However the central hot area directly above the element is of concern as this would affect the temperature readings of the thermostat, making the behaviour of the water heater considerably more impulse driven. The consequences are that, every time the element would engage, the thermostat would see high temperature readings, shutting it off again. This behaviour was observed in some of the thermal run-ups of the water heaters, as well as when scrutinising the on-cycle in some of the tests.

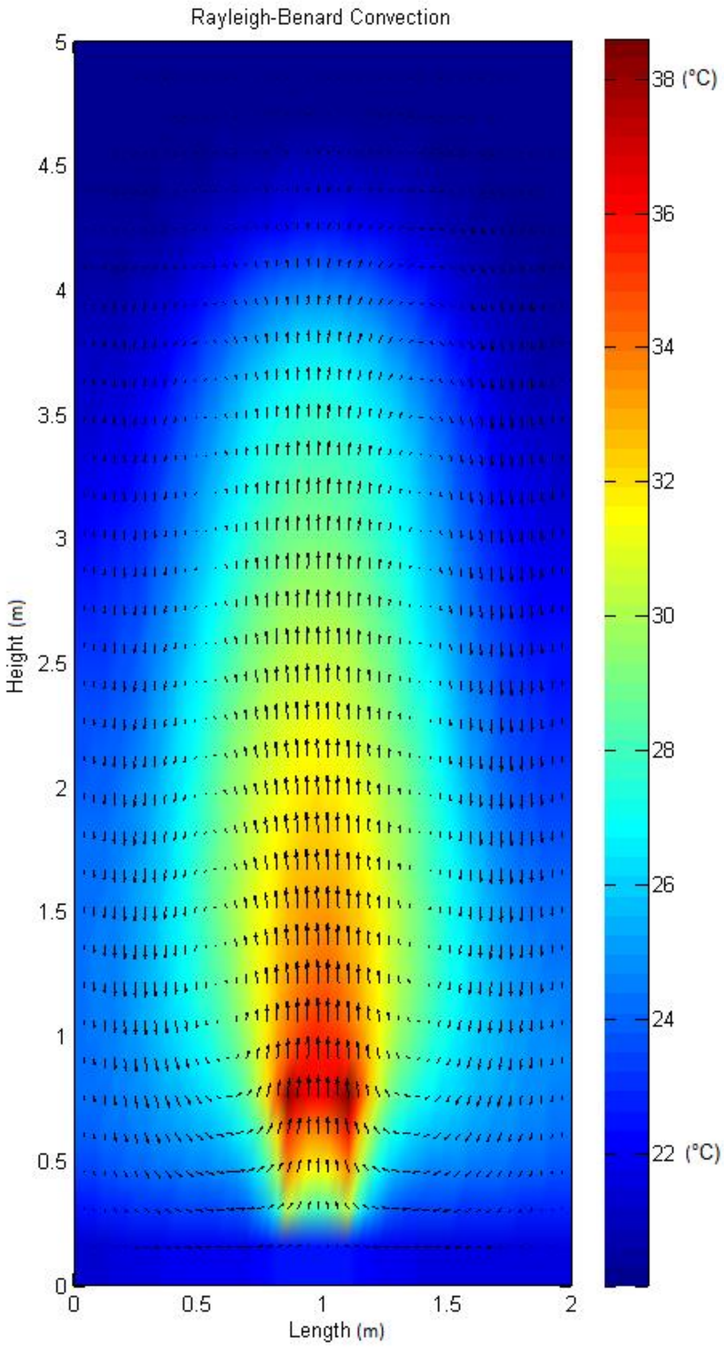


Figure 7-9: Spiral element water heater, 2D cross-sectional view, vertical orientation, thermal dissipation and fluid flow.

The simulation of the spiral element water heater shows an instability arising after some heating has occurred. The central hot plume would go out of alignment causing it to allow more water around one side of the plume. This would then cause a Rayleigh-Taylor instability causing a swirl to occur and finally causing the simulation to fail. This is presented in Figure 7-10.

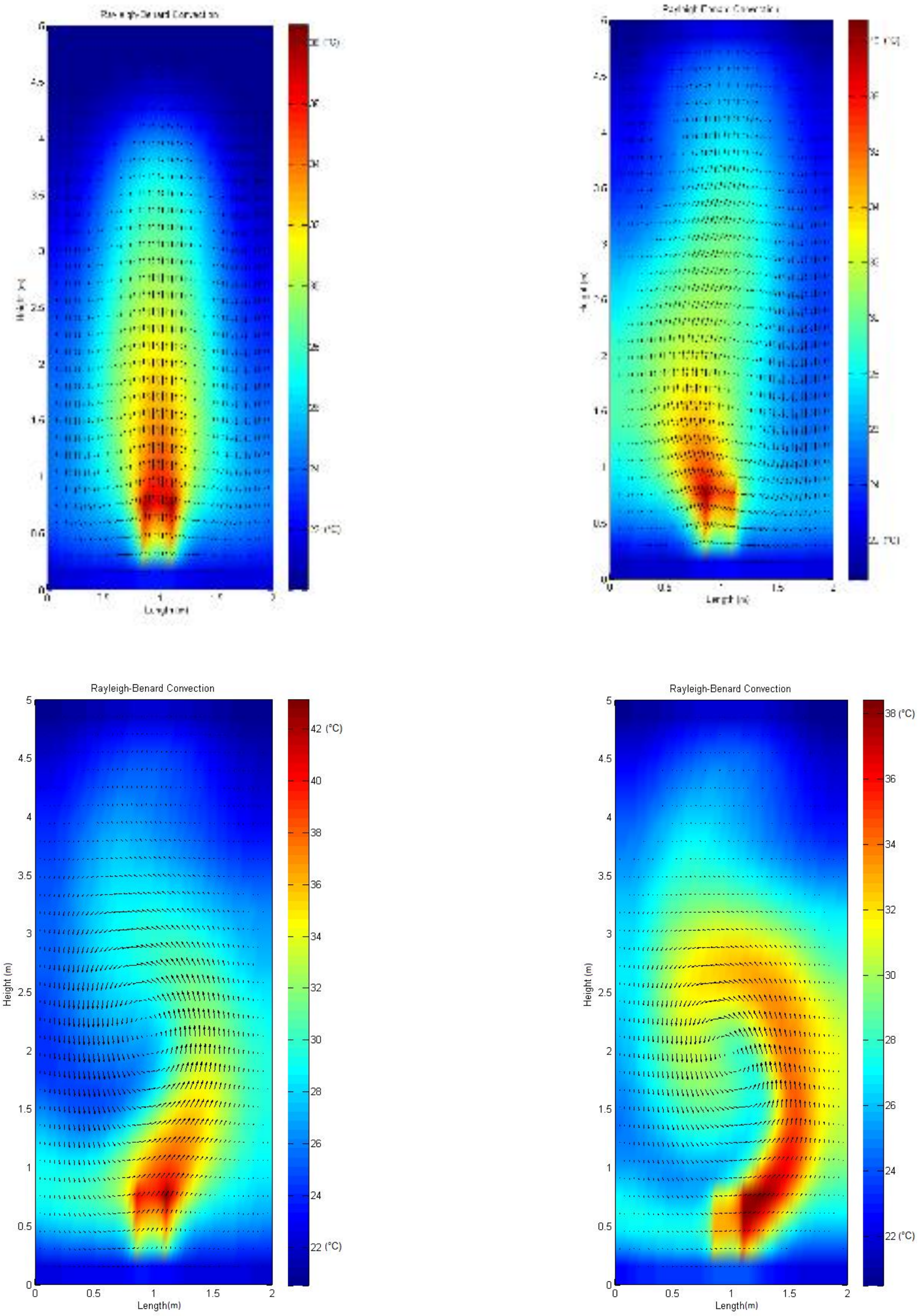


Figure 7-10: Spiral element water heater, 2D cross-sectional view, vertical orientation instability.

7.4.2 COMSOL Simulation

In the practical investigation in Chapter 4, the vertically mounted water heaters showed very different temperature trends and standing loss values when compared to the results of the horizontally mounted water heaters. Due to the insulation thickness varying around the circumference of the water heater, the heat losses through the insulation would be higher on one side of the water heater. What was seen in the MathWorks MATLAB simulation is an instability but the simulation was only able to shed very little light onto the issue. Should the instability arise in a 3D model, then the thermal behaviour could be tracked with a view to see if the thinner insulation should cause greater heat losses. The thermal behaviour of the water inside the water barrel is simulated in a 3D model. Below is the pointwise investigation from the simulation in COMSOL:

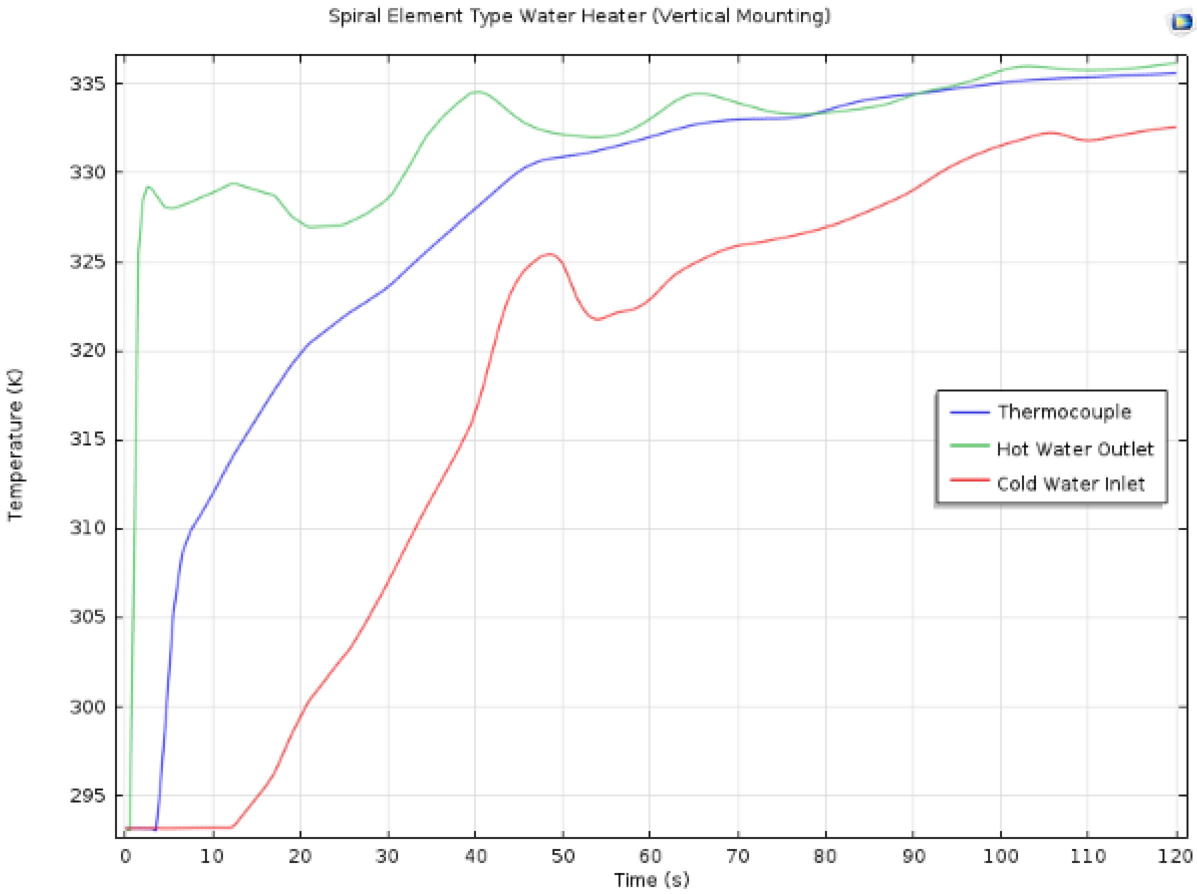


Figure 7-11: COMSOL vertical spiral element water heater spot point temperature investigation.

In Figure 7-11 the same points are placed in a vertical structure allowing for similar plots to be measured. The response however does differ drastically from those of the same model placed in the horizontal position. The rise in temperature is more unstable for all sample points. The hot water rises to the top of the water barrel off the element, influencing the temperature measurement there, thus the rise time of the hot water outlet temperature is shorter. The thermostat temperature does not respond in the same way, suggesting that the cold water in the rest of the water barrel still mixes with the hot water. After a time of 70 seconds however, the hot water outlet probe and thermostat probe trends converge. The cold water probe does however take much longer to respond and a large instability can be seen 50 seconds into the simulation. These results coincide with the plots seen in the MathWorks MATLAB simulation.

The slow rise time can be attributed to the bottom of the water heater not being influenced by the flow of water. The instability at 50 seconds could be caused by Rayleigh-Taylor Instability. To confirm this a further look into the thermal behaviour and velocity fields must be completed.

Temperature (Vertical)

The temperature progression plots reveal that the temperature dissipation is as expected, with the hot water collecting at the top of the water heater and the bottom being left undisturbed. This would lead to a more concrete conclusion that the varying insulation thickness is a factor in the heat loss problem. The lack of insulation on the element mounting plate is not as great a problem when the water heater is mounted vertically, as this is where the water mass is at its coldest.

At 16 seconds an instability is observed when the hot water plume suddenly veers to the left. This could be explained as follows:

- Initially the hot water rising off the element is too little to initiate the flow.
- As the flow increases, the volume of hot water rising off the element increases
- This in turn causes the hot water to push into the more dense cold water inducing a Rayleigh-Taylor Instability.
- As the descending hot water encounters the cold water well at the bottom of the water heater, cold water rises up through the element causing that part of the rising water to rise slower than the other part of the water body.
- This in turn causes the faster moving hot water to veer over on top of the slower moving water causing an instability that can be seen in Figure 7-12 from 16 seconds onwards.
- Once the instability is established, the rising hot water column starts to circulate around the water barrel causing a clockwise circulation of the upward flowing hot water plume.

The clockwise circulation is observed in the simulation after 16 seconds. Please note that the circulation could occur in either the clockwise direction or anticlockwise direction. The clockwise rotation merely describes what is observed in the simulation. Before that, the flow is too slow to induce the whole rising column of heated water to circulate. This means that before the instability is established, the heated water will rise off the element, rise through the centre of the water barrel, and circulate back downwards along the casing of the water heater.

The rotation will be better observed from the velocity plot rather than the temperature plots. In addition the rotating circulation will be better observed, as well as any instabilities that should arise during the simulation.

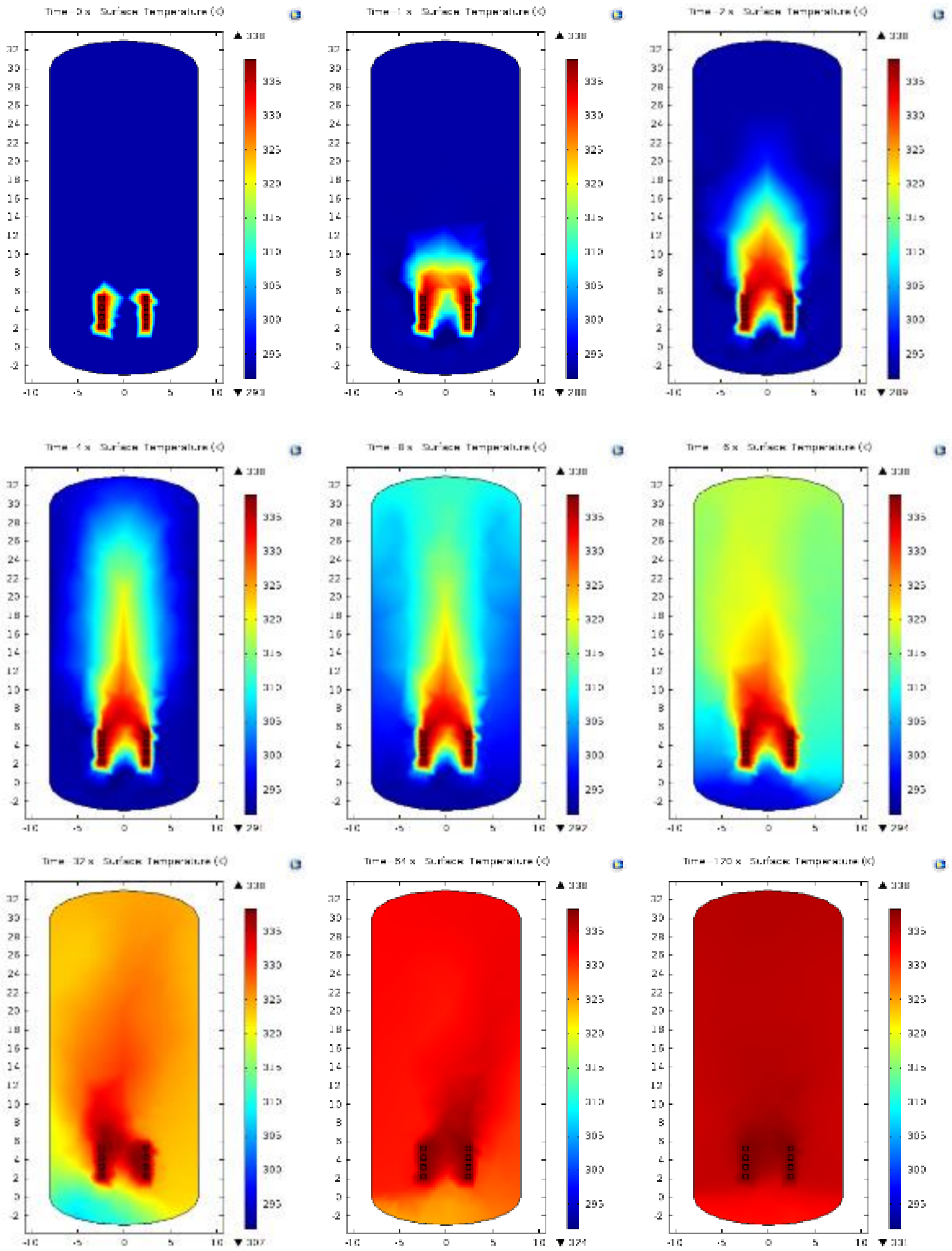
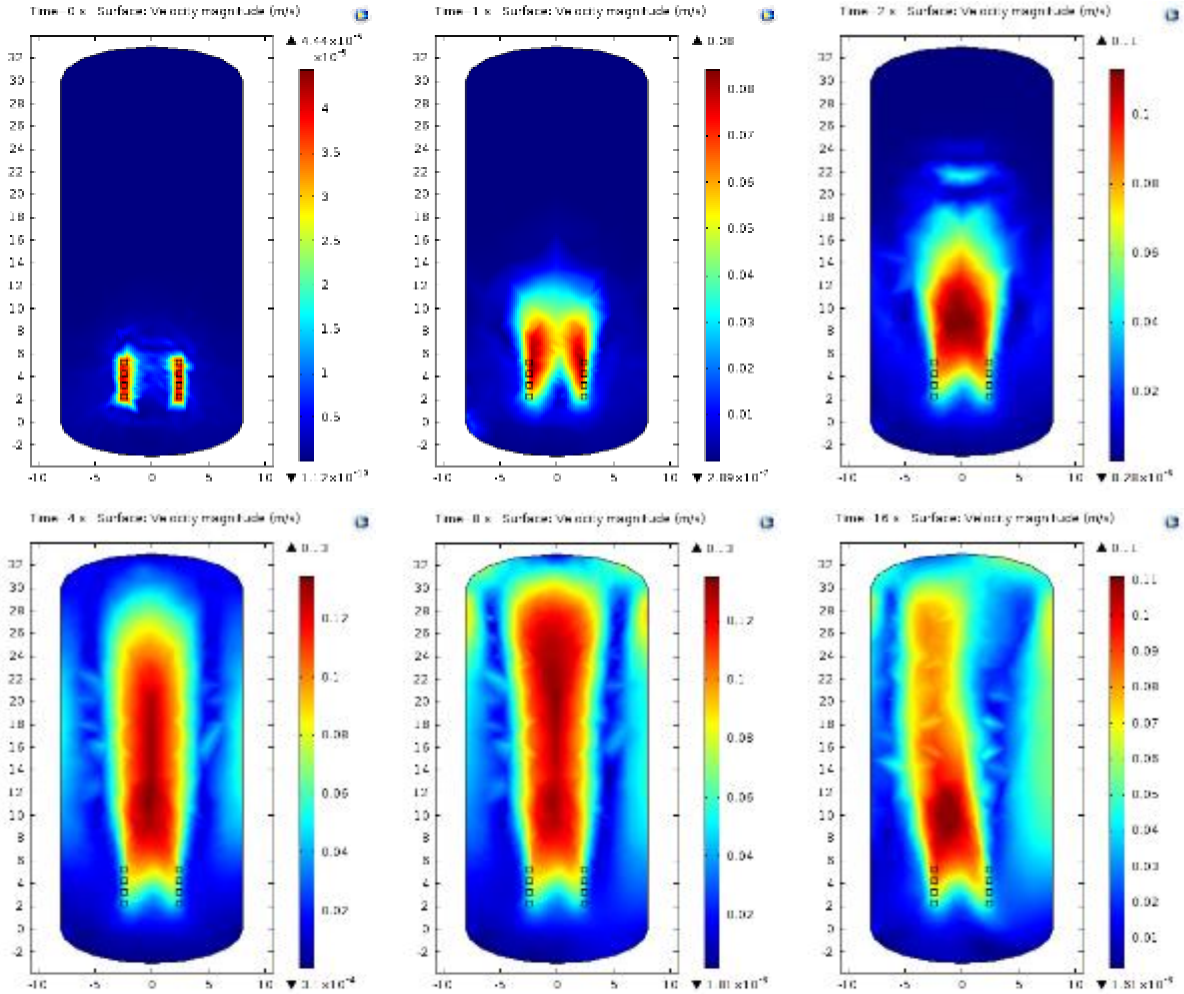


Figure 7-12: Spiral element water heater, vertical orientation, temperature progression.

Velocity (Vertical)

The velocity plots in **Figure 7-13** begin as expected with the velocity of the hot water rising as a column in the centre of the water heater. At 16 seconds the instability occurs with the plume veering to the left and then trending to the right. At 120 seconds the circulation seems to have rotated 90 degrees with the plume not showing in the plot.



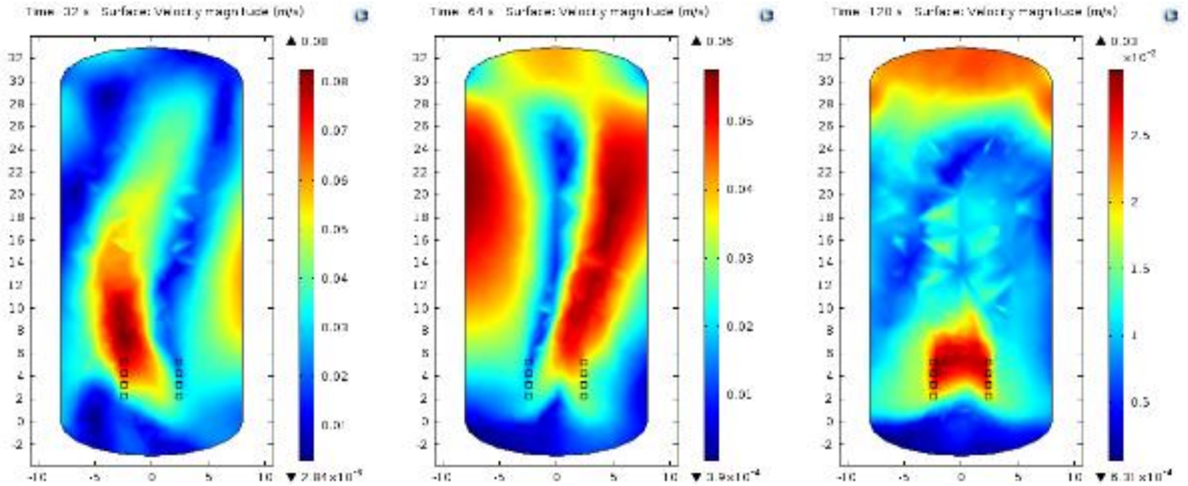


Figure 7-13: Spiral element water heater, vertical orientation, velocity gradient.

Flow (Vertical)

The circulation of water in Figure 7-14 shows the water circulating through the element, rising on the one side of the water barrel and returning on the other side of the water barrel. This can be problematic. If the hot plume is rising on the side of the water heater with the thinner insulation the heat losses would increase.

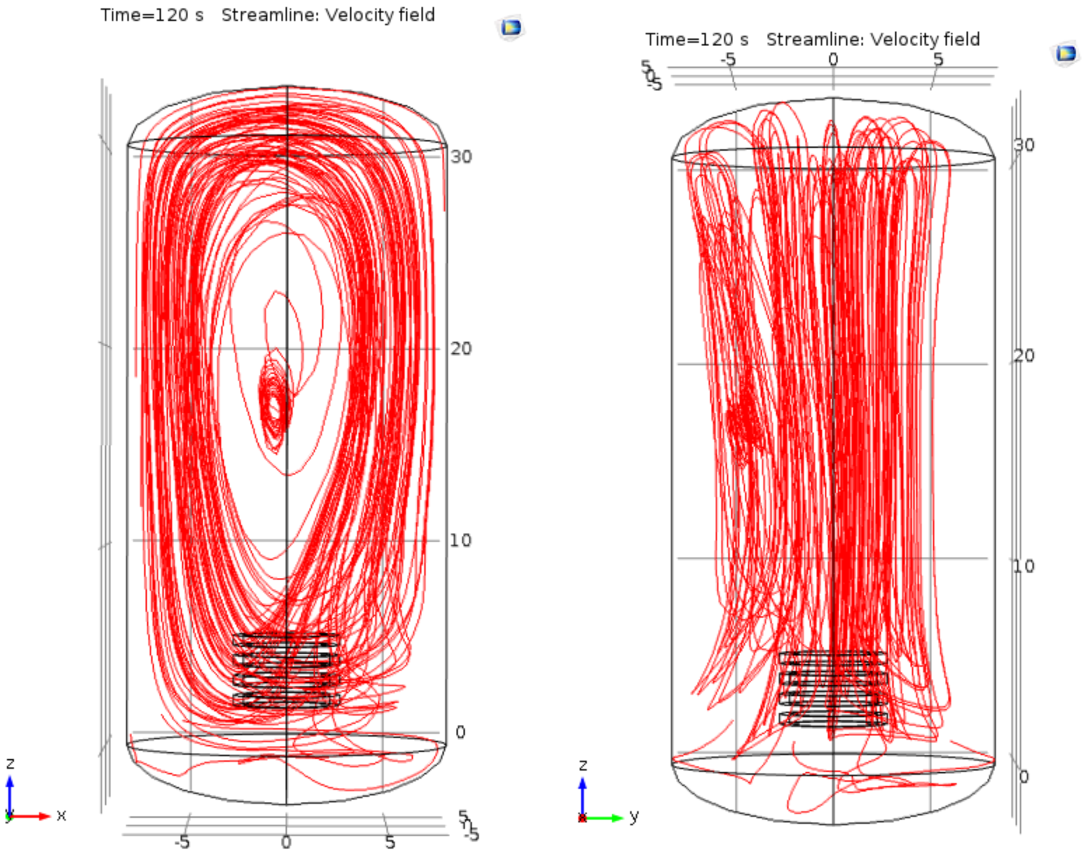


Figure 7-14: Spiral element water heater, vertical orientation, velocity streamline plot.

On start up or on the reheat cycle, the hot water plume would however rise in the centre as shown in Figure 7-15:

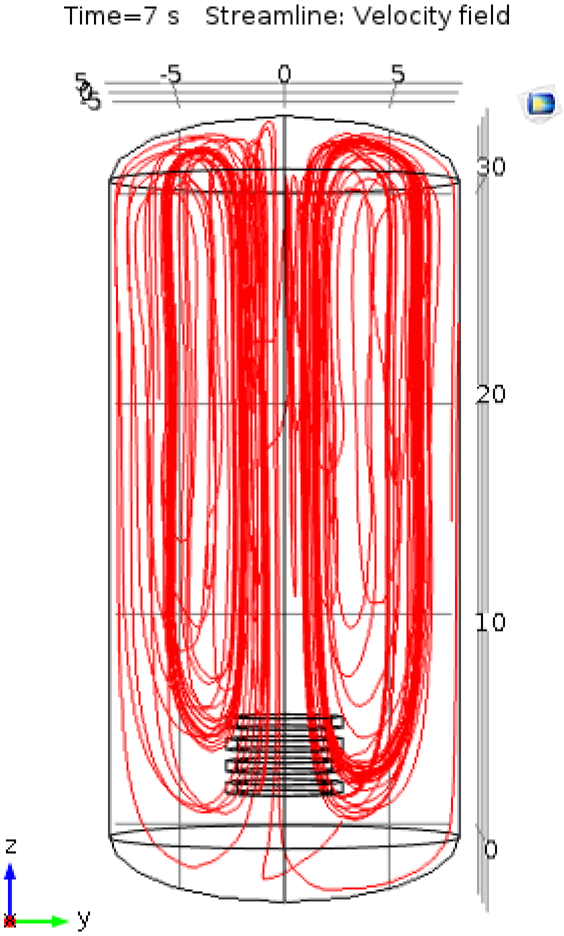


Figure 7-15: Spiral element water heater; vertical orientation, velocity streamline plot reheat cycle.

This gives rise to the belief that on a reheat cycle, the initial plume of hot water rises through the centre of the water body. The heat distribution would be even and gradual apart from the collection of hot water at the top of the barrel. The design of the insulation doesn’t lend itself to this type of heat distribution.

7.5 Off-centre Linear Element – Horizontal Orientation

7.5.1 MathWorks MATLAB Simulation

The linear element water heater simulation will present its own set of complexities. The water barrel will still be symmetrical about its centre but the element is not central, so symmetry about the centre axis is not possible. The consequences of this are that the water heater cannot be simulated as an axisymmetrical model. Nevertheless a 2 dimensional model can be built in MathWorks MATLAB to further understand the thermodynamic behaviour of the water around the element.

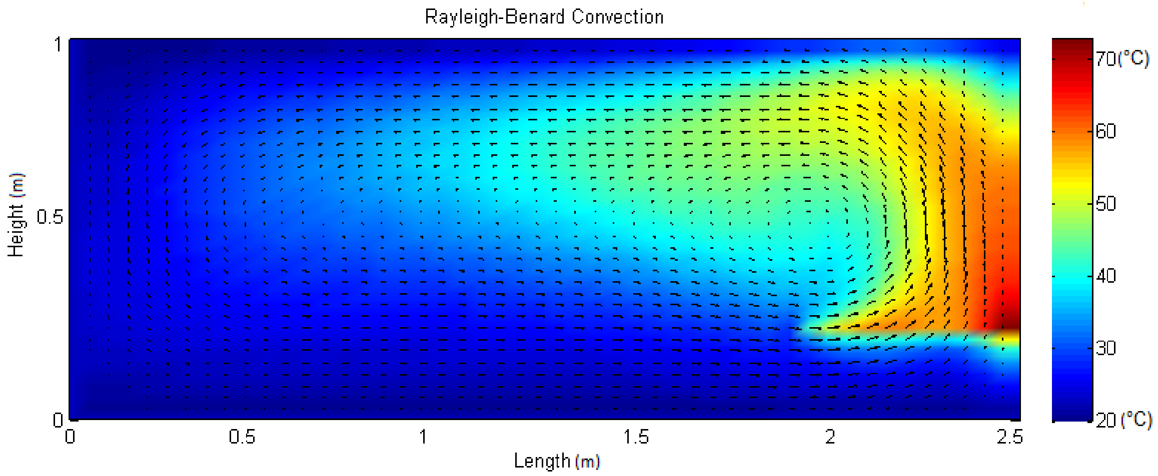


Figure 7-16: Linear element water heater, 2D side view, horizontal orientation, thermal dissipation and fluid flow.

Figure 7-16 shows the temperature dissipation within the water heater as well as the flow. As discussed before, the flow will be a false representation of the actual flow as the linear element is displaced to the side and not in the centre. To display this, the cross-sectional or front view simulation is done. Due to the lack of symmetry, all simulations in MathWorks MATLAB are only run for a short interval after a cold start-up. This is done to minimise any complexities that might arise later in the simulations due to convective effects or vortices.

Figure 7-17 gives insight into the fluid flow and thermal dissipation inside the water heater with a view to observe the turbulences involved with a linear element. The flow rises from the element and moves in a circular fashion around the perimeter pushing the colder water around under the element. One observation is that there is a circular flow to the left of the hot water plume leading to the conclusion that further simulations are needed to understand the behaviour in 3 dimensions rather than just two.

The temperature does not rise as much as is observed in other simulations. That is because the thermal point is much smaller and does not reflect the amount of energy being introduced into the water heater.

One last observation in Figure 7-16 and Figure 7-17 is that the hot water once again accumulates at the top of the water heater. This result is important as it shows that the flow of water is not symmetrical and the heat dissipation is not uniform throughout the water heater.

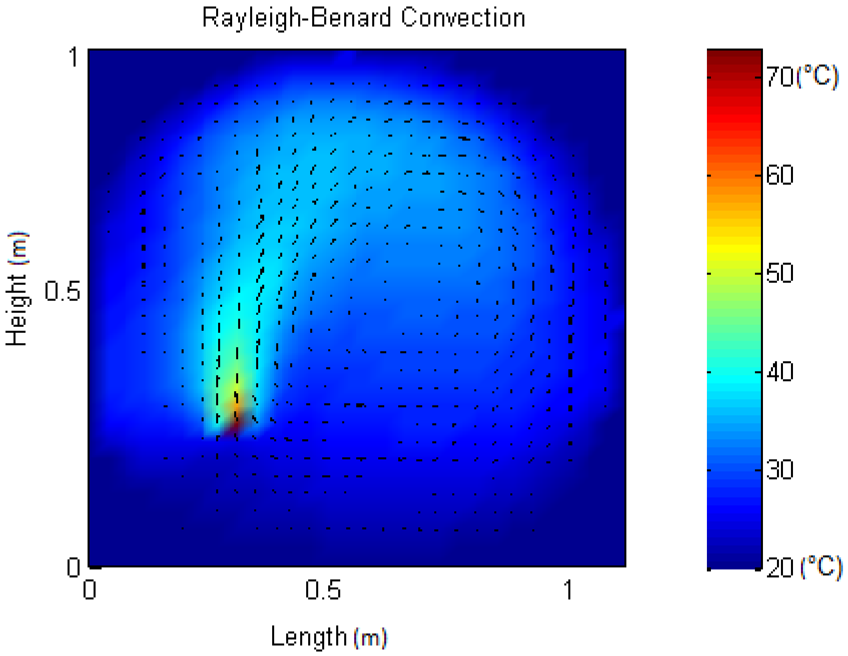


Figure 7-17: Linear element water heater, 2D cross-sectional view, horizontal orientation, thermal dissipation and fluid flow.

7.5.2 COMSOL Simulation

The initial conditions in the water heater start much the same as the other simulations. The starting temperature is set at room temperature of 293 K. From this, data is extracted to give the best possible picture of what occurs inside the water body.

The initial response, seen in Figure 7-18, shows that the Thermostat probe as well as the cold water inlet probe are first to respond. After reviewing the data it is seen that circulation first occurs in a circular fashion around the circumference of the barrel on the element side. However as the water starts heating up, it transfers the heat to the rest of the barrel allowing for a less dense path to emerge along the top side of the barrel opposite the element.

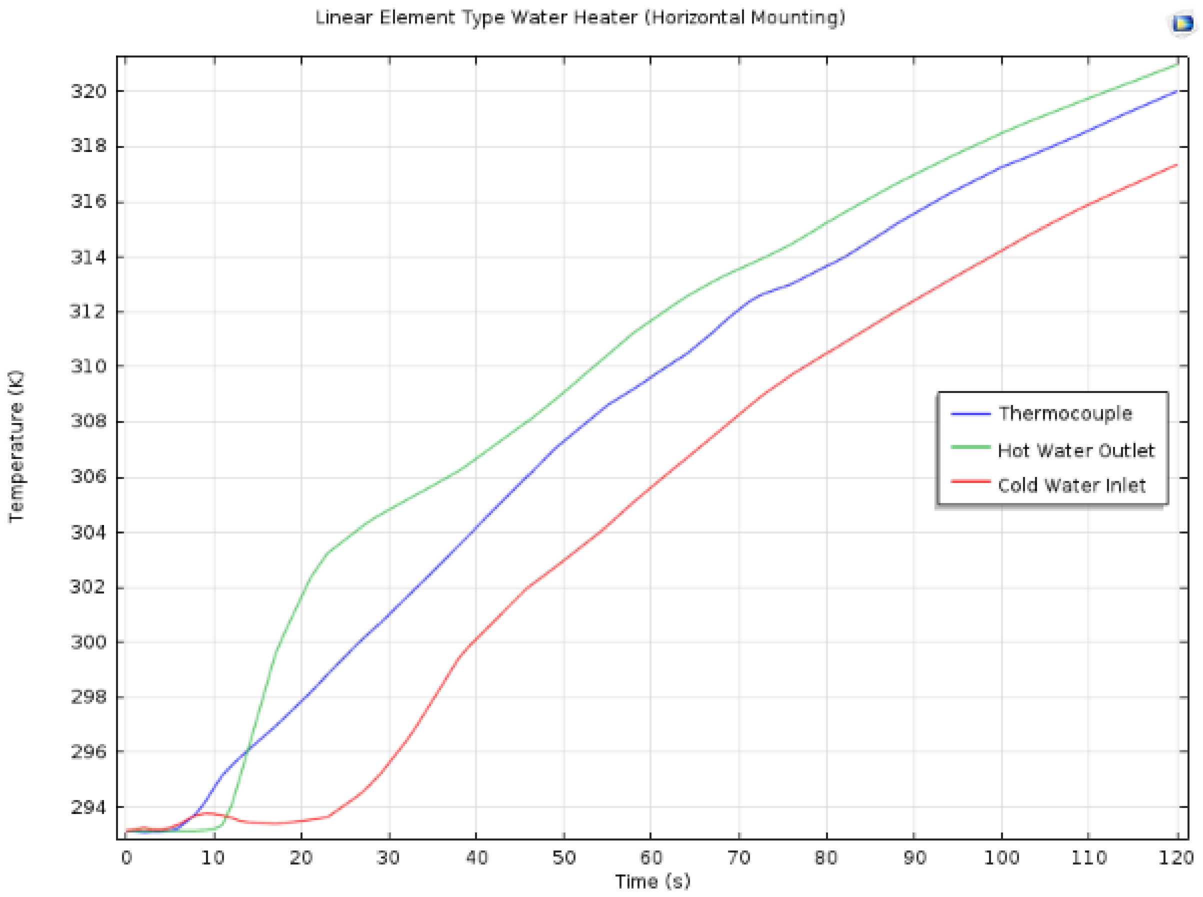


Figure 7-18: COMSOL horizontal linear element water heater, spot point temperature investigation.

The simulation doesn't reach steady state after the time frame used by in the spiral element water heater simulation. When the time frame is extended to 300 seconds the simulation still doesn't achieve steady state. During the practical part of the investigation a similar behaviour was observed. The linear element water heater took much longer to achieve steady state conditions. This could be due to the lower flow rate around the element due to it being positioned at the outer side of the water heater. Another potential cause is that the flow could occur in line with the element, meaning that, at the boundary of the element, the flow is too fast over a smaller effective surface area. This would lead to a less effective heat transfer. However this will only be revealed in the simulations.

Temperature (Horizontal)

Figure 7-18 shows that the water heater does not reach steady state after 120 seconds. Thus what is expected is that the temperature should rise but not achieve complete mixing or heat dissipation.

Figure 7-19, starting at 1 second, shows that the temperature does indeed rise and collect at the top of the water barrel. The flow is not as clear on the images but there is an indication that the hot water flows along the top of the water heater from the element to the opposite side. The image set also shows that the flow seems to flow from the element against the area where the thermostat mounting plate is positioned. This would assist in heat losses in the real world scenario and would lead to higher standing losses.

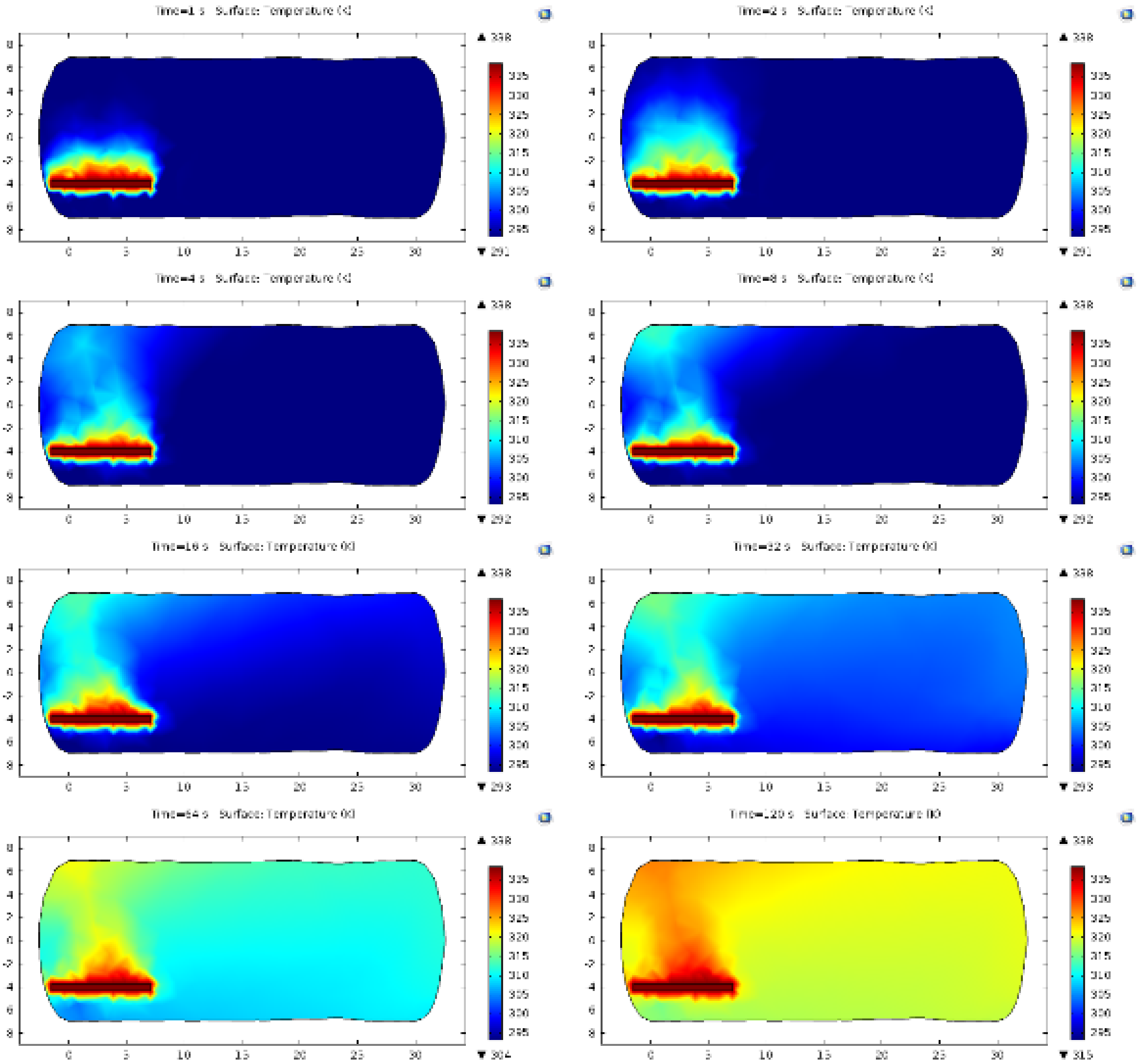


Figure 7-19: Linear element water heater, horizontal orientation, temperature progression.

Velocity (Horizontal)

The velocity plots in Figure 7-20 do not help to shed light on the issue. The plots need to be looked at in conjunction with the flow diagrams which show a much clearer picture. The initial flow of water is in a rotating manner from the element around the circumference of the water heater. Once the water heats up, it starts to disperse the heat to the rest of the water body inducing flow there. From this it can be deduced that, on a reheat cycle, the initial flow will be of a rotary fashion. From there, depending on how much heat is lost or how much cold water is introduced, the cycles will differ.

However, with the hot water rotating on the element side of the water heater only, it would suggest that, on a reheat cycle, the thermostat would be exposed to the hot water first before sufficient mixing has taken place. Once the water mixes however, the temperature decreases, causing the element to switch on again. In conjunction with the heat losses through the insulation, the switching frequency would be much higher than the spiral element type counterpart.

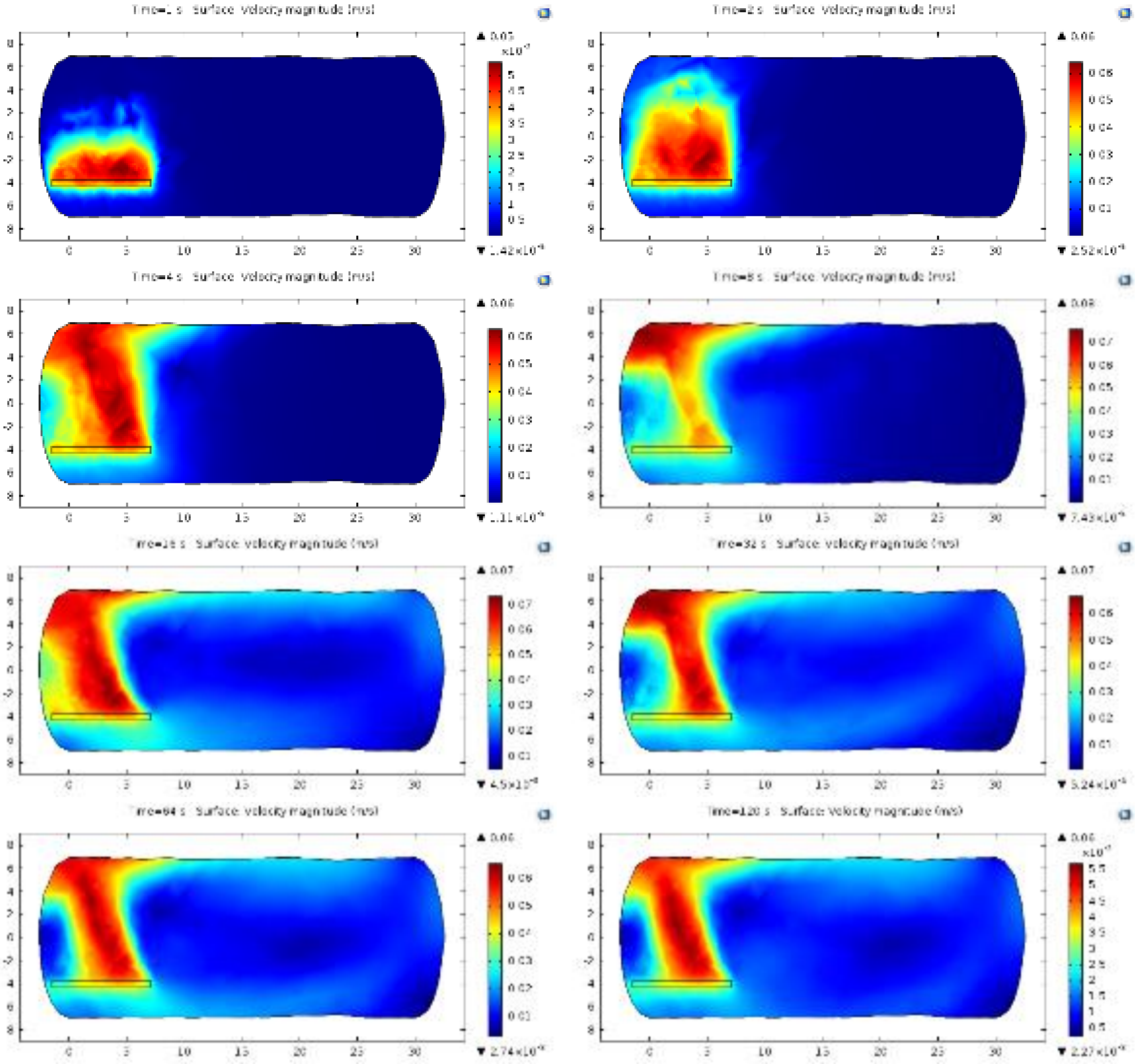


Figure 7-20: Linear element water heater, horizontal orientation, velocity progression.

The flow however cannot be discerned from the velocity plots as the view is in two dimensions and omits most of the data from each iteration in the rest of the mesh. To get a better grasp of the flow, a streamline plot can be implemented.

Flow (Horizontal)

Figure 7-21 is a side view of the water heater with the linear element on the left bottom hand side. In steady state, the water rising off the element approaches the element on the bottom of the water body. There is a section of water at the bottom that seems to be largely excluded from the circulation. Once the water passes the element, it rises to the top, circulating around above the element to the top of the water heater and flowing to the other side of the water heater via the top of the barrel.

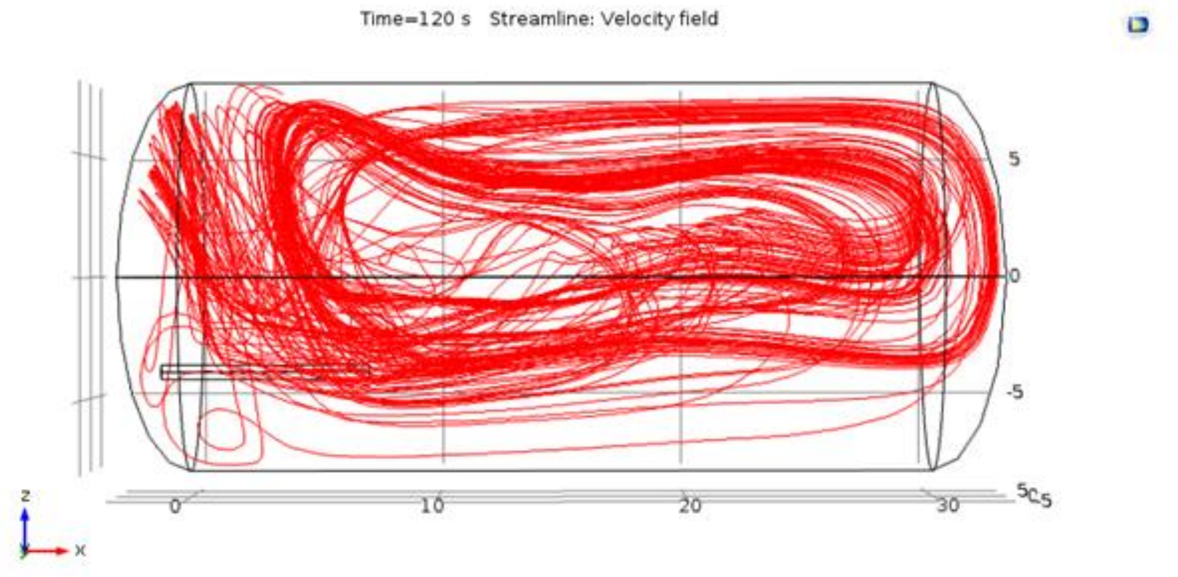


Figure 7-21: Linear element water heater, horizontal orientation, velocity streamline plot.

A front view of the water heater would shed more light as to the return path of the water as well as the cross flows and induced currents.

The hot water appears to rise straight off the element as shown in Figure 7-22. From there the flow splits. The largest body of water appears to flow to the other end of the water barrel via the top of the water barrel on the side opposite to where the element is mounted. The insulation on that side of the water heater was not compromised in the majority of the tear down analyses that were performed.

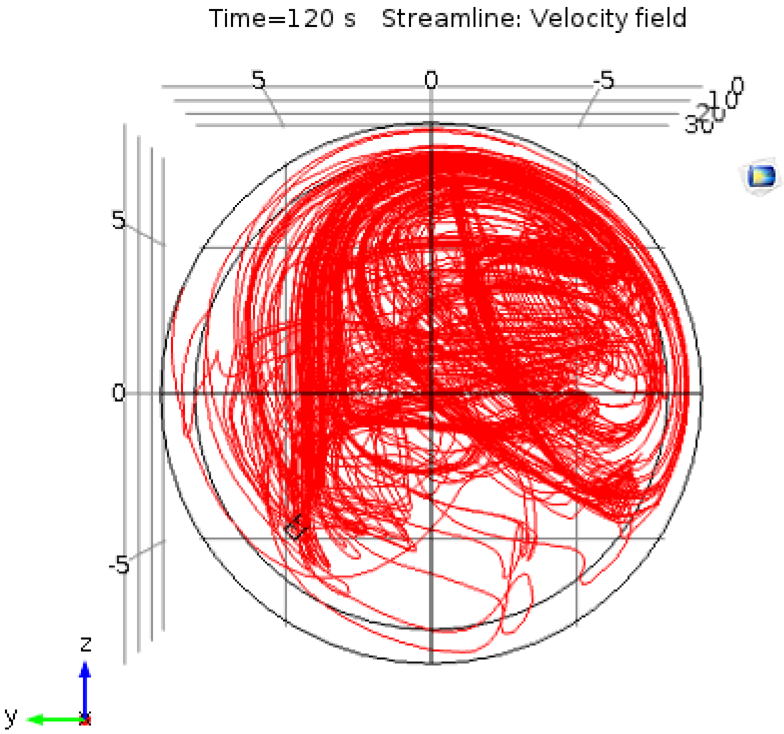


Figure 7-22: Linear element water heater, horizontal orientation, velocity streamline plot: front view.

In addition, a few streamlines do appear to flow clockwise around the element side of the water heater when looking at Figure 7-22. This would allow some of the cold water at the bottom of the water heater to circulate and heat up with the rest of the water body.

The return path, the last part of the path, of the large warm water body appears to return on the element side of the water barrel. This is not a good sign because less mixing and thus less heat transfer will occur. With the water flow travelling along the element, the reheated water will continue along and absorb more of the heat from the element and eventually flow upwards due to convection effects. Thus a smaller effective heater area is exposed to the water explaining the time taken for the water heater to stabilize.

7.6 Off-centre Linear Element – Vertical Mounting

7.6.1 MathWorks MATLAB Simulation

If the linear type water heater is mounted in the vertical position, the simulation is more conclusive. If a cross-section of the water heater is taken it can be done in order to fit in the element while giving a more reliable result. Expected is that the water will rise from the element and accumulate at the top of the water heater. The hot water rising would push the colder water down alongside the hot plume inducing circulation in the water heater.

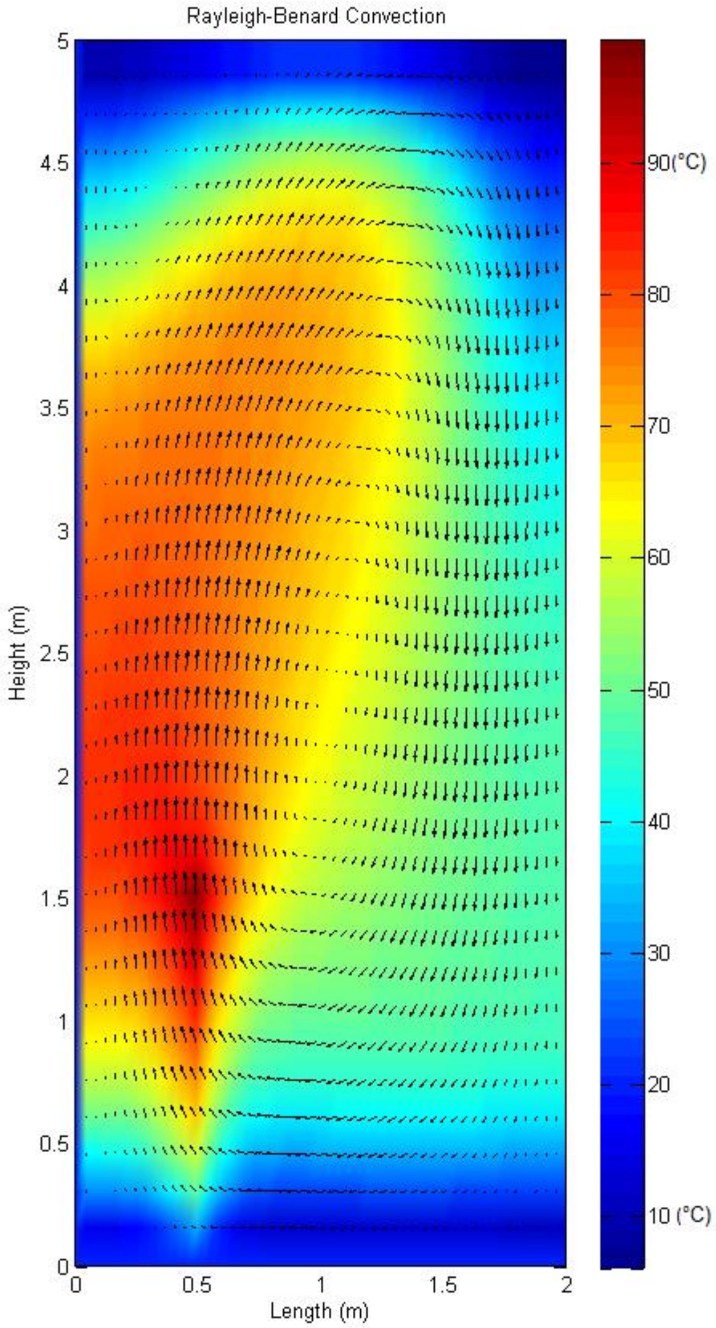


Figure 7-23: Linear element water heater, 2D , vertical orientation, thermal dissipation and fluid flow.

Figure 7-23 shows a linear element water heater with the linear element on the bottom left hand side, extending upwards. Hot water rises from the element and pushes the colder water down on the opposite side of the water heater inducing circulation. The black arrows show the flow of water throughout the water heater.

The temperature profile is taken just after the water heater element engages so the collection of hot water cannot be observed yet.

The results from the MathWorks MATLAB simulations are not as conclusive or precise as needed for this investigation. That is why COMSOL is used to simulate the water heater in 3 dimensions. This is done with a view to get a better understanding of the thermal behaviour in the water heaters.

7.6.2 COMSOL Simulation

Figure 7-24 shows the final simulation which is run for a 300 second interval rather than the previously used 120 second interval. This is largely due to the fact that the final temperature of the thermostat after 120 seconds is 310 K whereas the previous configuration reached a temperature of 320 K. This is still not the desired 338 K but such a simulation would take much more time and computing power.

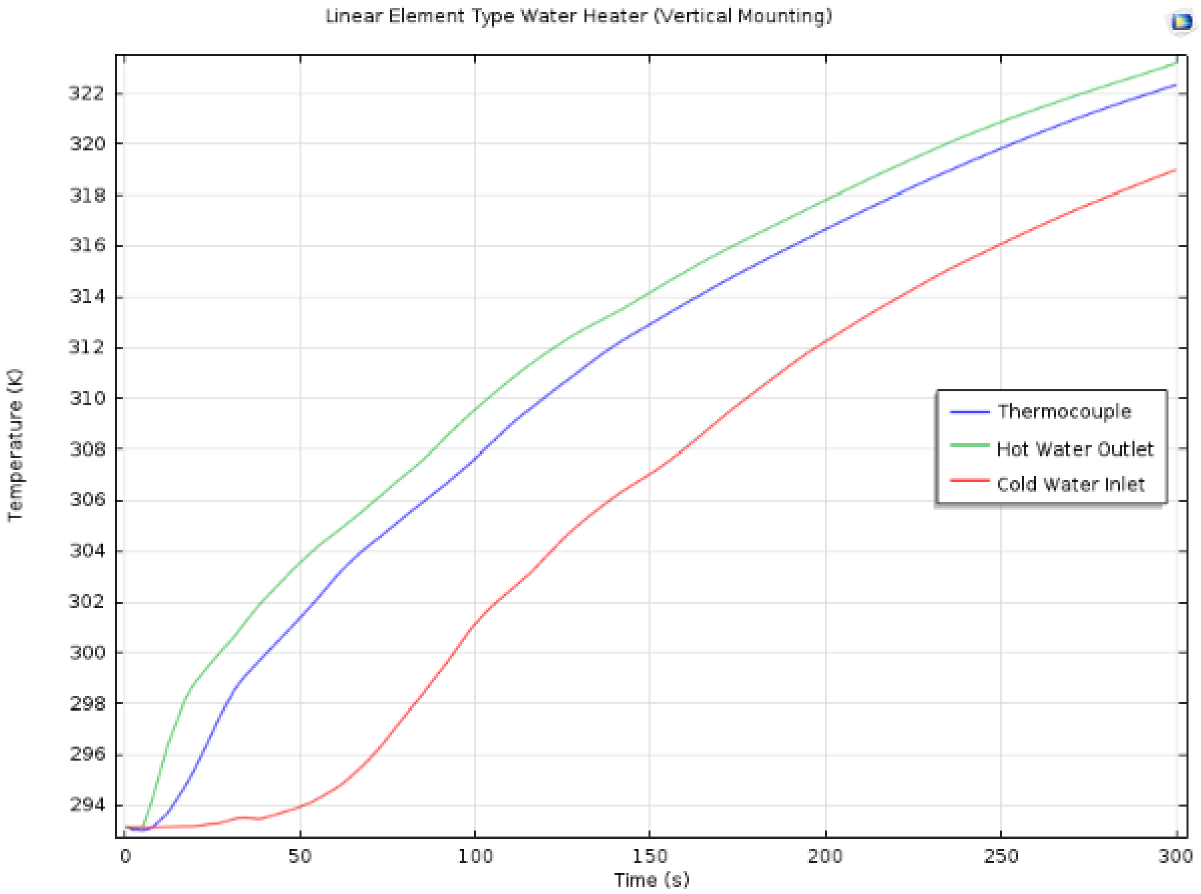


Figure 7-24: COMSOL vertical linear element water heater: Spot point temperature investigation.

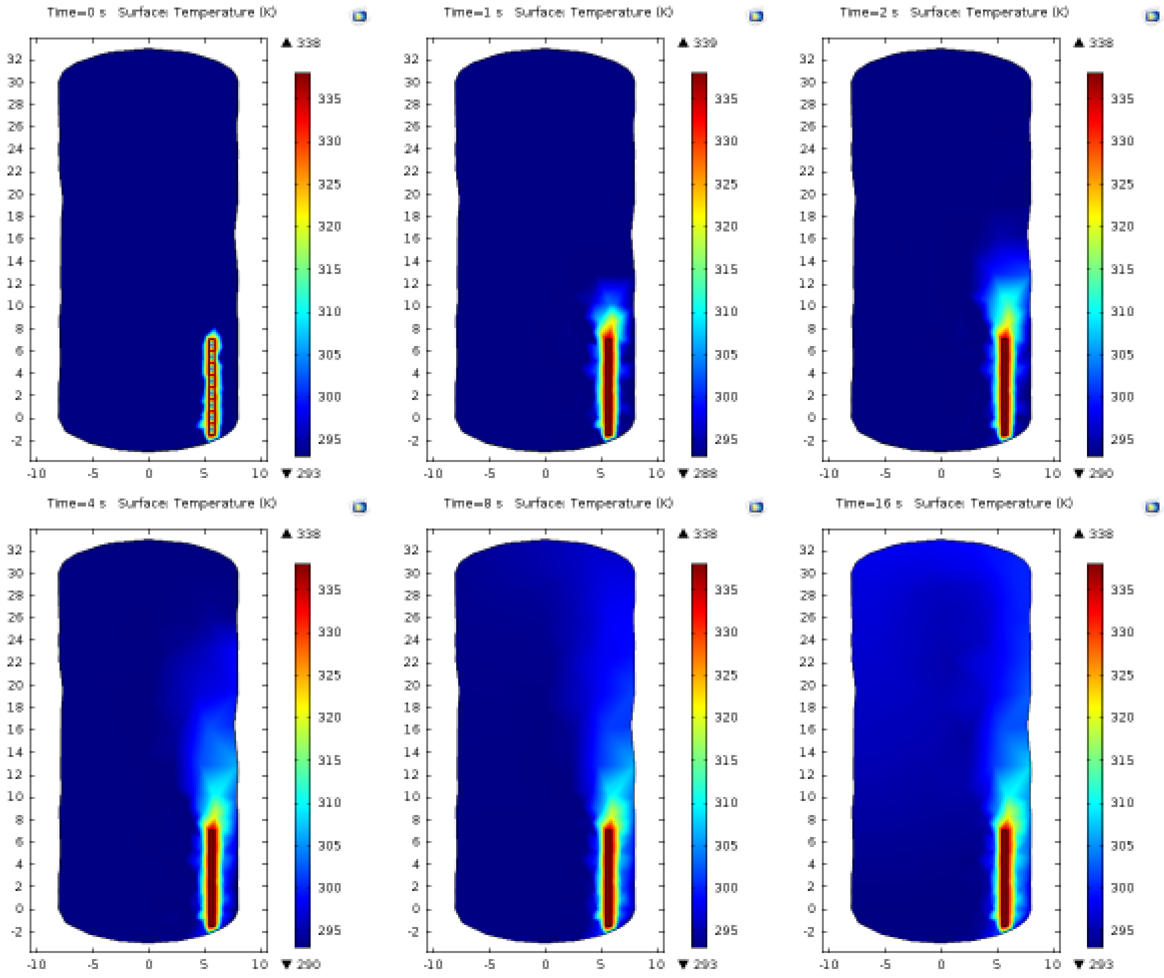
The temperature response seen in Figure 7-24 is what is expected from a conventional water heater. The hot water temperature is first to respond, followed by the thermostat temperature.

Lastly, the cold water temperature responds although in this case the response is somewhat subdued and continues to lag behind for the duration of the simulation.

Temperature (Vertical)

The temperature flow and distribution are as expected with the hot water rising off the element and collecting at the top. As the simulation progresses, a clear colder area is seen at the bottom of the water body suggesting that the flow only occurs in the top three quarters of the water barrel.

Another observation is that the temperature dissipation is again very slow. In the previous section it was observed that any flow along the element reduces the effective heating area. In this instance the flow occurs up and around the element rendering it very ineffective. The velocity plots as well as the streamline plots should reveal more.



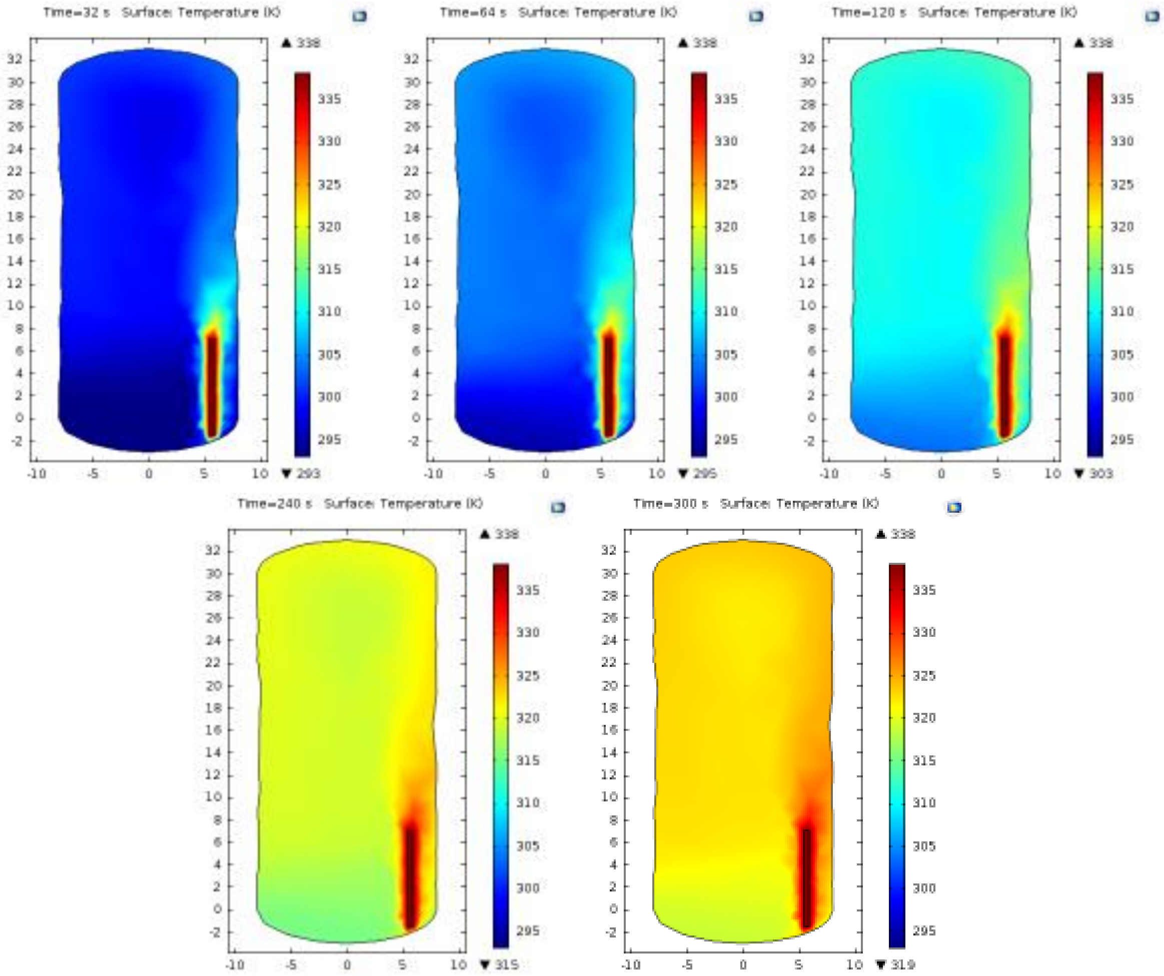


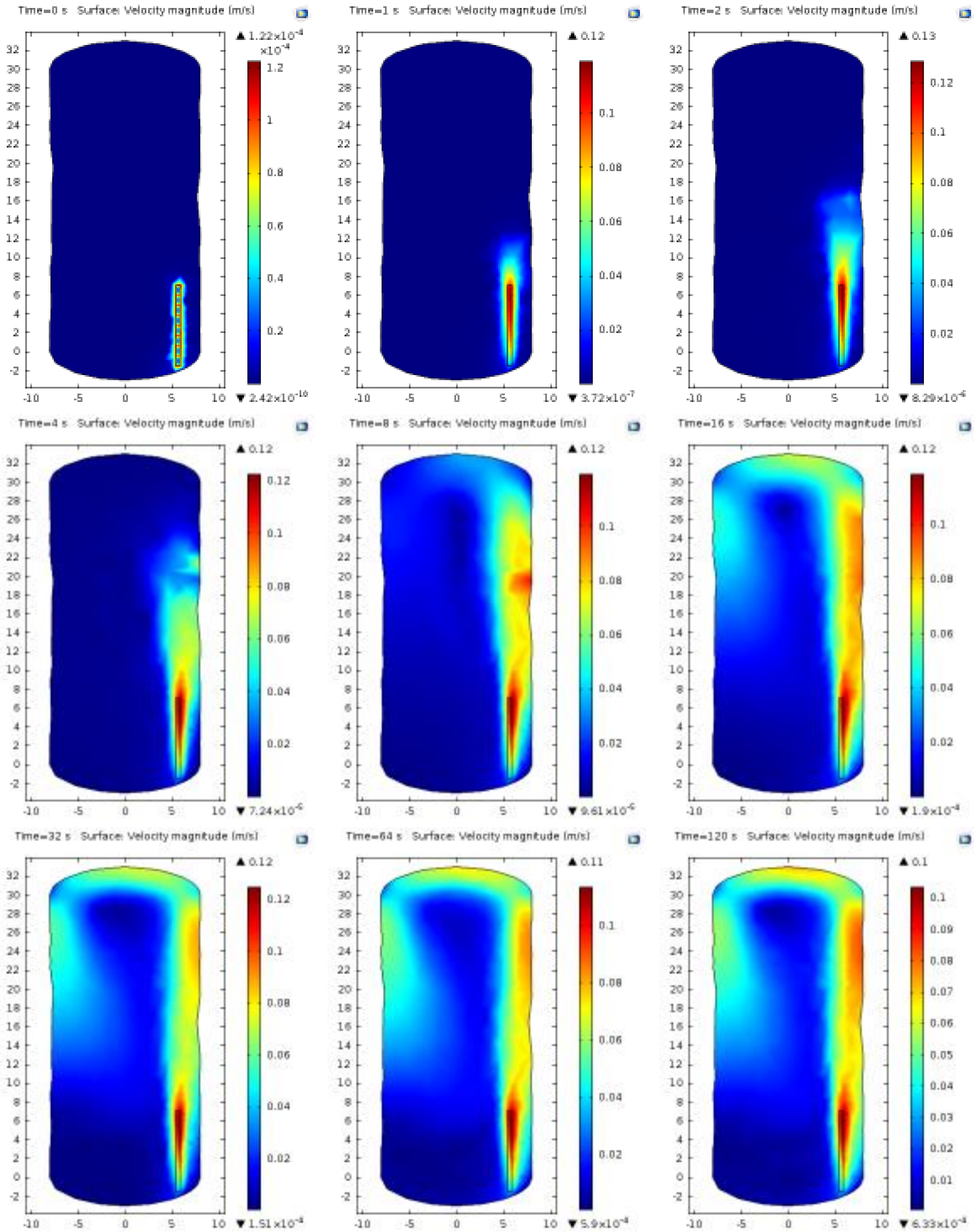
Figure 7-25: Linear element water heater, vertical orientation temperature progression.

Velocity (Vertical)

The suspicions are further reinforced with Figure 7-26. As surmised, the velocity around the element rises and stabilizes resulting in the effective heating area being very small. The water flows up due to its lower density. The result of this upwards flow is Rayleigh-Bénard Convection.

Small Rayleigh – Taylor Instabilities can be seen on the upwards plume where the differential in temperature between hot and cold water is at its highest.

To confirm the suspicions, a streamline plot must be completed. This will allow for conclusions to be drawn on whether the water heater is viable.


Time=0 s Surface: Velocity magnitude (m/s)
▲ 1.22×10⁻⁴
×10⁻⁴
▼ 2.42×10⁻¹⁰
Time=1 s Surface: Velocity magnitude (m/s)
▲ 0.12
▼ 3.72×10⁻⁷
Time=2 s Surface: Velocity magnitude (m/s)
▲ 0.13
▼ 8.29×10⁻⁶
Time=4 s Surface: Velocity magnitude (m/s)
▲ 0.12
▼ 7.24×10⁻⁶
Time=8 s Surface: Velocity magnitude (m/s)
▲ 0.12
▼ 9.61×10⁻⁶
Time=16 s Surface: Velocity magnitude (m/s)
▲ 0.12
▼ 1.9×10⁻⁴
Time=32 s Surface: Velocity magnitude (m/s)
▲ 0.12
▼ 1.51×10⁻⁴
Time=64 s Surface: Velocity magnitude (m/s)
▲ 0.11
▼ 5.9×10⁻⁴
Time=120 s Surface: Velocity magnitude (m/s)
▲ 0.1
▼ 6.33×10⁻⁴
-10
-5
0
5
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-2
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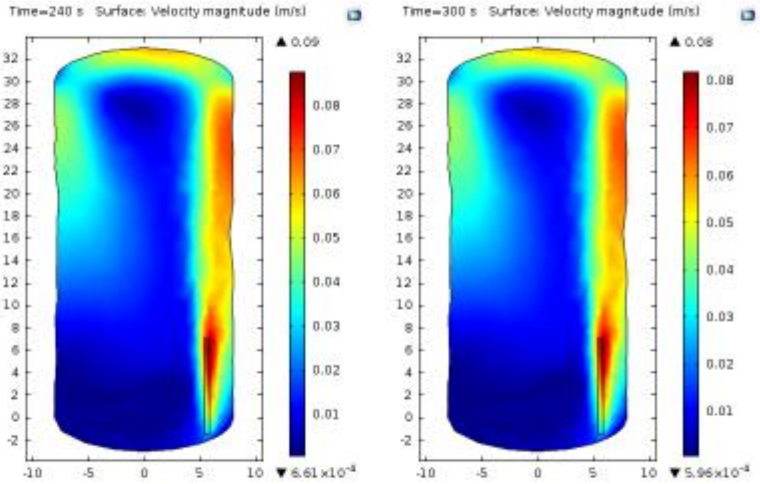

Figure 7-26: Linear element water heater, vertical orientation velocity progression.

Flow (Vertical)

The suspicions are confirmed in Figure 7-27 with regards to the flow. However most of the water seems to only come into contact with the top third of the element. A few of the streamlines in the figure make an interesting detour from the normal flow diverting to the bottom of the element excluding the pocket of water at the bottom of the water heater.

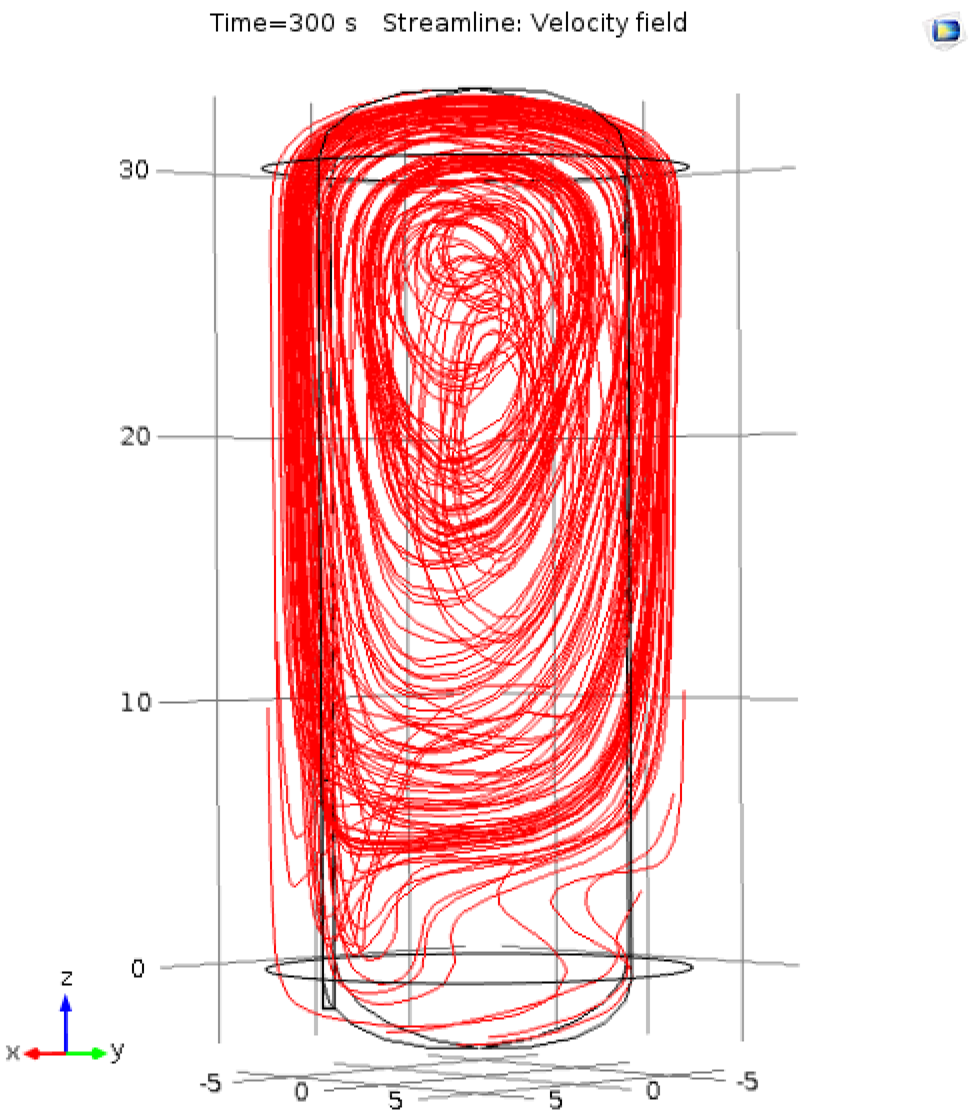

Figure 7-27: Linear element water heater, vertical orientation streamline plot.

In contrast to the previous simulations, more of the water body seems to be involved in the flow dynamics of the water body. This would lead to better mixing of the hot and colder water if it were not for the flow across the element.

The Circulation of water appears to be fixed by the rising hot water coming off the element. This is an issue as the element is placed at the bottom of the water heater barrel where the insulation is the thinnest. This would translate into heat loss, more energy consumption and higher standing losses.

7.7 Conclusion

The most successful simulations were conducted in COMSOL Multiphysics and led to a much better understanding of the heat dissipation and flow within the water barrel. These results should assist in future designs concepts and the manufacture of water heaters.

The MathWorks MATLAB simulations were also insightful although the complex flows increased the complexity of the program considerably. The investigative capabilities of COMSOL outshined any of the other competing programs.

Table XL shows the final temperatures after 120 seconds but does not reflect the rate of change of temperature. It can however be seen that the spiral element type water heaters achieve a greater stability at 120 seconds and the linear element type counterpart approaches the 120 seconds with a much greater gradient.

Table XL: Thermostat temperature at 120s.

Water heater element	Orientations	Temperature [K]
Spiral	**Horizontal**	336
	Vertical	336
Linear	**Horizontal**	320
	Vertical	310

Reviewing the data with regards to the spiral element type water heaters, they reached the operating temperature in a much shorter time frame. The water behaviour was as expected, with the exception of the circulation between the element and the element mounting plate in the spiral element water heater. This would of course not aid with heat losses. During the practical investigation, one of the manufacturers supplied a polystyrene cylinder with a view to insulate the element mounting plate. The water heater did rate amongst one of the best performing in the investigation although the plug didn’t completely insulate the area.

The instability observed in the vertically orientated spiral element water heater affected the measurement considerably but assisted with the mixing of the hot and cold water within the barrel. This test arrangement seemed to be the fastest to respond, leading to the conclusion that this is the best possible mounted orientation.

The linear element water heater took much longer than its counterpart. Even when the time frame was extended, a steady state was not reached. The cause of this is possibly the fact that the flow of water across the element causes the effective heating surface to be much smaller resulting in less heat making it into the water body.

It appears that the Spiral element type water heater is the best performing design and should be the preferred choice when installing a water heater.

From the results of this chapter, it can be seen that the set objectives, mentioned at the start of the chapter, have been met:

- COMSOL proved to be a powerful tool at analysing the fluid flow dynamics inside the water barrel for different water heater topologies, shining light on certain phenomena that were previously unexplored.
- Different trends in the flow of water were discovered, including stabilized flows that continued throughout the rest of each simulation. These phenomena helped in creating recommendations for future work.
- The quality of the simulations exceeded the expected outcomes of the chapter.

Most of the complexities of the test were successfully eliminated without influencing the results. The simplifications implemented on the model still allowed for trends to be identified in each simulation, allowing for a greater understanding as to the heat loss areas that cause most of the energy loss.

8 Conclusion

8.1 Achievements of set objectives

The purpose of energy management is to ensure the stability of energy resources and assist in ensuring the sustainability of the natural environment. The evaluation of the efficiency of energy consumers is at the heart of energy management [74]. Initiatives, such as DSM, were introduced in South Africa to help with the increased stress on the electricity grid. This, in conjunction with the DME energy efficiency policy, attempts to ensure proper growth of electrical sources as well as helping with the load on the grid in times when demand outweighs supply.

In Europe, the Green Paper, published by the European Commission, proposes strategies to ensure energy security within the next few years. This included minimizing the dependency on external sources of energy or electricity. The Kyoto protocol, which makes mention of the Green Paper, aims at reducing emissions using strategies such as labelling residential appliances to keep the consumer informed. The papers and protocols have led to numerous studies being done to find where power can be saved. Zpryme Smart Grid Insights completed a study that established water heaters to be the main power consumer in residential households. Numerous other studies also concluded that the water heaters were the main culprit in residential power consumption.

The introduction stipulated a set of objectives, key questions and research tasks that were to be reached by the end of the investigation. The conclusions are discussed according to the set research objectives but can initially be summarised as follows:

- The South African MEPS standard was compared with other international MEPS standards.
- The South African MEPS standard was further explored with a view to gain comprehensive knowledge on the testing methodology.
- A set of water heaters was chosen. They were tested successfully using the SANS 151 testing methodology, and the standing losses of each of the water heaters was calculated to be within the MAPS levels of South Africa. This was done using LabView.
- The sources of heat loss on the construction of the water heaters were identified and the causes of them were explored with the use of thermal imaging.
- The effects of different water heater orientations was experimentally investigated.

- An alternative testing methodology was explored with a view to make the test less dependent on uncontrollable variables. Better guidelines for a test were also stipulated with a view to minimise confusion and allow for the tests to yield more repeatable results.
- The dynamic thermal behaviour of the water inside the water barrel was simulated with a view to explore additional heat loss sources on the water barrel.

Comprehensive knowledge about the test methodologies and standards is required to conduct an investigation into water heaters. The literature review established the importance of evaluating the water heaters on the South African market as well as comparing it to international standards of the same subject. A comparison revealed the poor nature of the South African Standard. The SANS documents contained outdated and unrefined testing methodologies as well as allowing for higher standing loss values for the respective volumes. The aim of the study was to evaluate where improvements could potentially be made to the standing loss test and if any improvements could be done in the design and manufacture of the water heaters.

A more detailed review of the test methodology was done to establish and define a test hierarchy that could be implemented in a detailed and repeatable manner on various water heaters. The SANS 151 document also supplied a formula that uses the measured power usage profiles as variables in the calculation of the standing loss figures.

Once a comprehensive understanding of the test methodology was established, and a test hierarchy defined, testing of the water heaters could finally commence. The water heaters were chosen based on the manufacturer’s market share. Once the standing loss tests were completed for all orientations of all the water heaters, the standing loss values were calculated. In addition IR images of the water heater were taken during the test to determine possible heat loss sources. This was done in conjunction with a tear-down analysis to complete the water heater investigation. A direct correlation was found between thinner insulation and more heat loss through that insulation. One of the water heaters also had compromised insulation leading to the conclusion that the manufacturing process is not up to standard. Considering that the water heater in question has one of the larger market shares, this is of some concern.

Water heater C, with a standing loss of 1.77kW/24h in the horizontal orientation and a standing loss of 1.86 kW/24h mounted vertically, performed the best for each orientation class. Upon further investigation, it was found to have better insulation as well as a more uniform insulation coating covering the entire water barrel. If these figures are compared with the MEPS levels of other countries, it can be seen that it is out of bounds for certain countries. An international investigation would need to be conducted to ascertain the difference between the designs of the water heaters.

The compromised insulation in water heater A and the thinner insulation on water heater A and B were both identified in the tear down analysis. The analysis was completed, in conjunction with the IR images, to gain a more comprehensive understanding where the heat losses occurred. The IR images revealed that the feet of the water heater were a source of heat loss. Suggestions to mitigate these were to either increase the thickness of the insulation or change the mounting design or material. In addition, the element mounting plate was found to be transmitting heat and causing heat losses. One of the manufacturers supplied a polystyrene cylinder to cover the element mounting plate in order to achieve better results. This was done in a very rudimentary manner but could still prove effective if designed so as to cover more of the element mounting plate and surrounds.

The last source of heat loss identified was the inlet and outlet water pipes. One of the water heaters came with a plastic conduit from the water barrel, through the insulation, to the pipe connector. It broke during the installation of the water heater, but its function is not to be ignored. It would not however be able to prevent all heat loss through the pipes. This is where the heat wells on either side of the water heater come into effect. These are normally not insulated and cause a substantial amount of heat loss.

Upon completion of the practical tests, the collected data could be used in furthering the investigation.

One of the methods of grading water heaters is through grading the insulation. In order to ensure that the customer is informed, an R value should be given with each water heater. However, no such value was found in any of the documentation supplied with the water heaters. Thus a new calculation was developed using the available data collected during the testing. It was found that, even though water heater C performed better in the standing loss category, water heater D seemed to have the best insulation rating. Upon re-evaluation, water heater D had thicker insulation than water heater C on either end of the water barrel, but thinner insulation at the top and bottom of the water barrel. This would either lead to the conclusion that the insulation was of a higher grade, or that the faceplates play an even greater role in preventing heat loss than what was previously thought.

In light of the testing methodology depending on a host of different variables, and allowing so easily for errors to occur, an alternative testing methodology was proposed. The testing methodology was to raise the temperature of the water heater to a set point above the temperature used in the SANS 151 document, switch the power off and record the temperature regression of the water inside the water heater. Using the temperature data, a regression formula was developed, independent of ambient temperature control, which was one of the more volatile variables in the test. Two types of regression curves where superimposed onto the data. The most promising of those was the exponential regression curve. When compared to the measured standing losses, the calculated values were lower. The new methodology shows promise, but is very rudimentary and would have to be refined in future studies.

To round off the investigation, a final theoretical investigation was completed with a view to fully understand the dynamics of the hot water inside the water heater. The programs chosen to complete the study were MathWorks MATLAB and COMSOL Multiphysics. MATLAB showed promise when a model of both water heaters was built into an existing Rayleigh-Bénard Convection Example. But COMSOL was found to give the best output for 3 dimensional models. The results of the simulations showed data that correlated closely with the data recorded in the practical tests. In addition it showed the heat distribution in the water heater throughout a run up as well as the flow of water.

Problem areas observed in the simulations were inter alia, that heat loss areas needed to be continuously observed. The heat loss areas, which were already identified in the practical investigation, were the element mounting plate and the feet of the water heater.

In the water heater where a spiral element was simulated, hot water circulation between the element and its mounting plate was observed. This would allow for great heat loss to occur. This was only observed when the water heater was mounted horizontally. When mounted vertically, a Rayleigh-Taylor Instability was observed where the upwards hot water flow, rising off the element, started to divert to the side of the water barrel and start rotating around the rising wall of the barrel. This would assist in mixing the hot and cold water but played havoc with the temperature measurements. The drawbacks are that, should the hot water column rise on the side with the thin or compromised insulation, then the heat loss would be greater. Lastly, the flow of heated water bypassed the lower part of the water barrel, where the colder water resided. This occurred on both orientations. This would indicate that, under steady state conditions, a portion of the cold water in the geyser does not mix with the heated water, forcing more on cycles. This configuration however performed the best in terms of time taken to reach steady state.

In the water heater where the linear element was simulated, stability was reached much later. The hot water rising off the element bypassed the thermocouple faceplate but caused turbulence on the opposite side of the water barrel. Better mixing occurred during the heat up cycle but caused the water heater to take much longer to heat up. One of the major contributors to this is that the flow over the element reduced the effective heating area.

The results of the investigation indicated that there are possible improvements to be made on water heater design. One simple suggestion would be to remove the cold water dispersion inlet fitting when the water heaters are mounted vertically to prevent cold water reducing the mean temperature at a faster rate. Complex suggestions included adding plates to divert flow to allow for better mixing and preventing heat loss on certain areas, and increasing the grade of the insulation, or the thickness.

8.2 Design Improvement Suggestions

During testing of the water heaters, many different designs were encountered. The designs can be placed into two separate categories. One category consists of water heaters where the element is designed in a spiral form, and another where it is designed linearly. These designs are standard but there are other minor variations within this sample group that are considered inconsequential. However after looking at the collected data as well as the results collected from the simulations, some patterns are observed that could potentially lend themselves to help make the water heaters be more efficient.

In previous chapters water heaters available on the market were investigated, studied and tested. Simulations were also run to comprehend what occurred inside the water heater.

This chapter separates the two classes of water heaters by the element type used and based on the observations and data collected makes certain deductions and recommendations that could improve the overall efficiency in the design, manufacture and implementation of water heaters.

8.2.1 Spiral Element

In the case where the element has a spiral design, the temperature reading is measured using a thermocouple and a sealed metal tube that extends beyond the element into the water heaters centre and is attached to the baseplate of the element.

The design is made as one unit so that the element and thermocouple, when removed, come out as a complete unit. In case of a leak or break, this design makes for easier replacement.

The cold water inlet is situated off-centre below the element unit. Most designs incorporate a plastic housing at the end of the inlet that extends into the water heater dispersing the incoming cold water to improve mixing.

The hot water outlet is situated at the top of the water barrel on the opposite side to the element. The design ensures sufficient heat is distributed to the colder water to save energy.

The power usage profiles from the water heaters that use the spiral element design are consistent and stable. The temperature readings are likewise more stable and regular due to this. This may be attributed to the hot water being allowed to mix more completely before the thermocouple reads any significant changes.

No draw off of hot water was completed during the practical investigation. However when consulting the data collected during the simulations, any introduction of cold water would affect the thermostat reading. If the current would carry the colder water along the streamlines established in the previous chapter, the cold water would travel over the thermostat and influence the reading. Should this occur, the element would switch on.

If the water heater is mounted horizontally then there is no real problem due to the fact that the lower part of the water barrel is largely excluded from the main circulating body. However if the water heater were to be mounted vertically, the extension on the cold water inlet pipe would ensure cold water introduction into the main current flow. Depending on the main circulation inside the water barrel, the cold water could either be introduced to the up-draught, causing the end user to suddenly freeze in the shower. Should the cold water be introduced in the opposite flow, the element would switch on again due to cold water detection on the thermostat.

For stabilization purposes, the water heater should be mounted horizontally to avoid instabilities and rogue currents as well as serious heat losses through the thin insulation.

For the vertical orientation, the extension should be removed to prevent the incoming colder water to join the main flow. Alternatively the thermocouple could be extended further into the water barrel to minimize interference from the introduction of the colder water and for a better mean temperature measurement. Notwithstanding that, the water heater is designed for horizontal orientation and the insulation should still be improved in the lower half of the water heater. And staying with insulation, it was observed in the simulations that small currents of heated water circulated between the element and the mounting plate. This should indicate that the plate should be adequately insulated yet on all the water heaters no such insulation was encountered. The area acts as a very efficient heat conductor resulting in higher standing losses that could be mitigated using a simple insulating plug. It does pose a fire hazard due to the electrical wiring in the area. This could be combated with proper installation techniques or with an isolated unit with a plug build in at the manufacturing stage.

For the horizontal orientation, the cold water inlet extension could be extended further towards the centre of the water heater. As seen in Figure 7-8 the lower part of the water body is isolated from the flow. Following the principles of Rayleigh-Bénard Convection, the cold water should rest at the bottom of the barrel. The problem this introduces is that once the water starts circulating, the mean temperature in the water heater decreases, potentially increasing the amount of power used in the long term.

On the tear down investigation it was discovered that the inlet and outlet pipes were directly mounted on the barrel in the majority of the water heaters. This also allows for better heat conduction from the barrel to the external environment. Better insulation is needed on these to further minimize heat losses. These improvements could take the form of thicker glazing on the inside of the water heater or pipe foam mounted onto the incoming and outgoing water pipes up to the point of the heat wells. A select few of the water heaters had plastic conduits from the barrel to the incoming and outgoing pipes. In theory this should work but upon implementation it was found that the plastic was too brittle to ensure proper sealing when installing the pipes. A more resilient material would have to be used.

The thermal investigation revealed some of the mounting feet radiating at a high temperature. Upon teardown, the reason seemed to be the supporting structure inside the foam in place to support the water barrel in the foam. Some water heaters seemed to use a type of polystyrene whereas others opted for a metal skeletal structure. This would not assist in heat insulation. If the insulation were increased, this problem of heat conduction would be decreased, however not alleviated. Different methods could be explored where rubber balls are used to either lift the barrel or secure it.

8.2.2 Linear Element

The design of the water heater with a linear element usually had the design aspects of element at the bottom and thermocouple above it. Other than that the designs are fundamentally the same. However, these linear element designs lead to erratic power readings and turbulent temperature readings due to the instabilities and flow patterns as seen in the simulations in the previous chapter.

Many of the changes mentioned for the spiral element type water heater are also valid for the linear element type, namely all those pertaining to the barrel design. Notwithstanding that, some design improvements could still be made.

The issue faced when mounting the water heater vertically is that all the rising hot water travels over an area of the barrel that has a very low insulation thickness allowing for greater heat losses. This poses a problem with regard to efficiency and trying to minimize power usage. Should the insulating foam thickness be increased, the heat loss should decrease.

Another issue is the flow over the element causing a reduced effective heating area. Any changes to the design such as dispersion panels or flow diversion plates would only add to the complexity of the design. Changes to the element design itself would be less costly but still labour intensive. Instead of bending the element back on itself it could potentially be bent at 90 degrees to intercept the flow patterns. This should be investigated further.

The placement of the element is also a cause for concern. Being placed so close to the side wall of the water heater, opens the design up to greater heat losses and less heat being introduced to the water body. There was a marked difference in heating times in the simulations as well as the practical investigations. Should the element be placed in the middle of the water heater, the heat would be transferred to the water much more efficiently. The problem with this suggestion is that the temperature reading would be immediately affected if the element were to switch on.

This leads to the next suggestion, the same made in the previous sub-chapter. The thermostat should be extended into the middle of the water heater. The element is approximately the same length as the thermostat sleeve. This poses a causative correlation between the element and the thermocouple. When the element switches on, it directly affects the temperature reading, leading to erratic power readings and switching profiles. Placing the element in the centre would delay this effect and allow for better mixing of hot and cold water.

Another improvement that could be made to the water heaters, would be to decrease the running temperature. The settings on the thermocouple allow for temperature variations from 30 to 80 degrees Celsius. Decreasing the maximum temperature would prevent accidental high temperature operation of the water heater.

As mentioned before, there are companies offering products to monitor, track and control power consumption of water heaters, such as Geyserwise. These products are able to limit the number of hours in a day that the water heater operates. This in turn makes the amount of power used more stable, but does not necessarily decrease the amount of power used. As the water heater is only on for a few hours every day there is a certain amount of power it will use. However, even when not used, the water heater will still switch on and make up for the heat losses incurred during the power off period. With no control unit in place, the water heater will only need small bursts of power to keep the temperature up. If the water heater is not used at all, it could potentially use less power than the Geyserwise power controlled water heaters.

8.3 Recommendations for future work

During the pre-test setup of the water heater and the installation of the relevant piping, there were questions as to how the incoming and outgoing pipes should be arranged. Longer piping without heat wells would cause further heat loss and influence the measurements. Other elusive information included whether the piping should be insulated. All these would easily be answered with a more in-depth description in the standard. The standard also did not specify how the temperatures of the hot and cold water inlets should be measured. Upon carrying out the practical investigation, two thermocouples were placed at either conduit, namely one inside the incoming copper pipe and one soldered onto a steel plug sealing off the outgoing hot water pipe. The measurements varied widely, with the thermocouples inside the pipes reading the most reliably. The thermocouples attached to the outside of the incoming and outgoing pipes read temperatures with a difference of between 10 and 30 K when the values were compared to the internal measured temperatures.

The importance of recording accurate data that is reliable, is paramount in any investigation. The quality and reliability of data collected is determined by the type of thermocouples used to collect the Data. This is an area where, in future studies, it is worth investing resources in acquiring robust measuring equipment. Research in acquiring accurate and reliable thermocouples is essential, as was done in Chapter 2.

Further research is necessary to fully understand where all the heat is lost, in and around the water heater. During the investigation it was found that with the IR images, the temperature of the water heater body could not be read. However, the reflection of the author could sometimes be seen on the barrel. Should the barrel be coated in a thin film of paint, the temperature could be read and further deductions be made as to the quality and effectiveness of the insulation. A select few feet could also not be captured on the IR camera, thus they would also need to be painted or coated in a material that does not affect the heat losses.

The derived regression curves showed potential, but a more in depth investigation would have to be carried out in order to gain more data and refine the equations presented. In addition, if the test, as described in this paper, were to be repeated successfully, more variables could easily be incorporated to give more accurate standing loss values.

The theoretical thermal investigation revealed more than was anticipated, but further studies could possibly indicate the effects of different thicknesses of insulation, as well as the effects of insulating the element mounting plate. Further investigation into the effects of insulating the element mounting plate is required. This is probably the most reasonable test to implement.

Does an insulating cover for the element mounting plate affect the standing loss value, and if so, by how much?

In addition, any physical design changes to the internals of the water heater, as suggested earlier in this chapter, could be simulated in COMSOL to gauge the effects thereof.

All this is imperative in implementing DSM policies to minimise emission and maximise efficiency. This field of study has shown great promise. The potential of reducing power consumption on the consumer side of the energy cycle is immense.

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