A Water Flow Meter for Smart Metering Applications

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ABSTRACT

The availability and depletion of natural resources is increasingly punted as the limiting factor for sustainability. A lot of focus, especially in drought-stricken countries, is placed on water conservation. One way to affect prudence with this scarce resource is to generally create timely awareness of consumption thereof, and also the related cost for the consumers. Existing metering solutions are often manually read by officials, and the information difficult to digest. Moreover, billing information, which serves as feedback, lags consumption by several weeks. Smart meters address many of these challenges by enabling electronic and real-time metering, but are still prohibitively expensive. In this paper, a novel low-cost water flow meter is developed for use in household smart metering solutions. The design is based on an orifice plate, to leverage the Venturi effect, which causes a measurable pressure drop. The results demonstrate that the meter provides accurate and repeatable results, mostly indistinguishable from the results of a much more expensive meter. Further improvements are also suggested.

KEYWORDS

smart meter, orifice, water flow meter, obstruction, differential pressure

INTRODUCTION

The preservation of natural resources in general, and water in particular, is a vital requirement for sustainable survival of the human species. Various approaches have been proposed to improve the management of water supplies, including awareness campaigns, leak management, specialised equipment (such as aerating shower spouts, low-flush or composting toilets and high-efficiency clothes washers), the passing of proposed water management laws, rain water harvesting and waste water reuse [1, 2].

One approach that offers various fringe benefits is that of smart metering. Driven mostly by the recent emergence of ubiquitous wireless networking, smart metering enables autonomous metering of utilities (e.g. electricity and water usage). Two key benefits of smart metering, both of which affect savings, are the low-latency and highly visualised method of data reporting. These two factors ensure that the consumer of the utility, who is usually also the payer thereof, is aware of consumption patterns, which leads to more responsible behaviour [3, 4]. The main enabler behind the reduction in latency with smart metering, is that utility suppliers do not need to manually read the meters for billing purposes, but can autonomously capture and process all the data centrally, without having to send an official to every household to read the meter readings.

Significant inroads have been made towards achieving smart metering in the energy sector [5]. Progress in smart metering of water supplies has, however, been much slower. A key challenge faced by smart water metering is the prohibitive cost and complexities associated with electronic water flow meters [6, 7].

Contribution

In this paper, a novel low-cost water flow meter is developed for use in household smart metering solutions. The design is based on an orifice plate, to leverage the Venturi effect, which causes a measurable pressure drop. The meter is tested using representative flow rates, and compared with an existing solution. The results clearly demonstrate that the water flow meter matches the more complex and expensive product, providing a viable solution for household smart metering.

The rest of this paper is organised as follows:

Section 2 discusses related work done in this field, Section 3 describes the design of the smart flow meter and Section 4 discusses the testing of the meter. Section 5 concludes the paper.

RELATED WORK

A flow meter is an instrument used to measure the volumetric flow rate (m^3/s) of the substance (water) flowing through it.

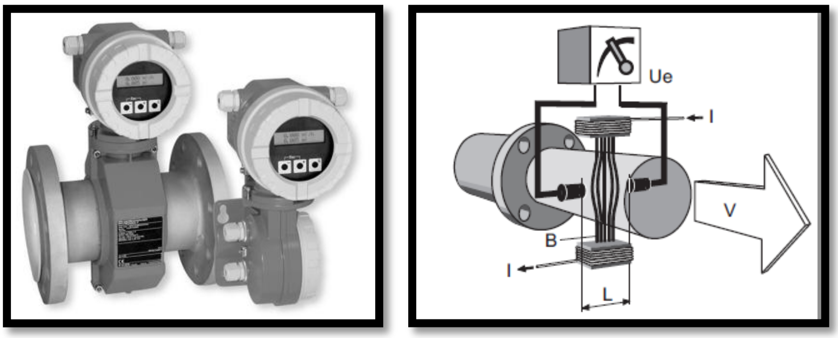
Off-the-shelf products in the range of this study are too expensive and seldom adhere to all of the requirements simultaneously such as the flow medium, size, measurement range, ability to integrate with a microcontroller etc. For example, one suitable off-the-shelf product can be seen in Figure 1, the EH Promag 10P. This product functions as an electromagnetic flow measuring system, often used in chemical or process applications, to very accurately measure flow rates with little to no effect on the water flow. Its measuring principle can be seen in Figure 1b and is further explained in its datasheet [8]. However, its price of approximately R 25 000 (US$ 2 500) eliminates it as an option for large scale household deployment, based on the criterion of affordability.

An alternative approach is to use an obstruction flow meter. Although obstruction flow meters provide an intrusive form of measurement, they are generally easier to manufacture and more affordable. For this type of flow meter, an obstruction is inserted into the line of flow, which causes a measurable pressure drop over the obstruction. The pressure drop is used to determine the flow rate by applying Bernoulli's equation, where the pressure drop is a function of the square of the flow speed.

Three common types of obstruction flow meter designs are the orifice, Venturi and, nozzle flow meter. According to the Engineering Toolbox [**Error! Reference source not found.**], the nozzle flow meter is more readily used for air and gas flow in industrial applications, where much larger flow rates are to be expected. The actual nozzle is difficult to machine and therefore more expensive. The functioning of the orifice and Venturi meter is shown in Figure 2. Both are relatively simple to design, are suited for water applications and have good accuracy. The Venturi can have a higher turndown rate, which is a measure of the operating range of a flow meter, and can recover more of the pressure lost over the obstruction. The orifice can accommodate widely different flow rates by changing the orifice plate. It is also less expensive and easier to manufacture. The orifice is often used for development and testing, while the Venturi is a more permanent installation.

Due to the typical flow rates that are encountered within the scope of this study, litres per minute (l/min) is used as the unit of volumetric flow rate instead of the typical SI unit of cubic meters per second (m^3/s). The conversion rate is given below.

$$1\ m^3/s = 60000\ l/min \tag{1}$$



a) b)

Figure 1: Endress+Hauser Promag 10P. a) Physical appearance. b) Electromagnetic measuring principle. [8]

DESIGN

This section describes the design of an obstruction flow meter. Since the design is aimed at household installations, the local municipality was contacted to ascertain the pipe size, static pressure and approximate flow rates that are observed in local residential buildings. This information is summarised in Table 1. This information was used to choose an appropriate type of flow meter.

Table 1: Residential water use information

Feature	Value
Pipe size	22mm or 3/4''
Pipe material	Copper (cold and hot water, expensive) or Polycop (cold water, inexpensive)
Static water pressure from main	4 to 5 bar
Typical residential fixture flow rates	Faucet: 5 l/min Toilet: 7 l/min Shower: 9 l/min Washing machine: 15 l/min Average residence peak: 55 l/min

From the research done, it was decided to use an obstruction flow meter, also known as a differential pressure flow meter. In this paper, an orifice flow meter was designed as a prototype. The calculations associated with the orifice flow meter will now be explained.

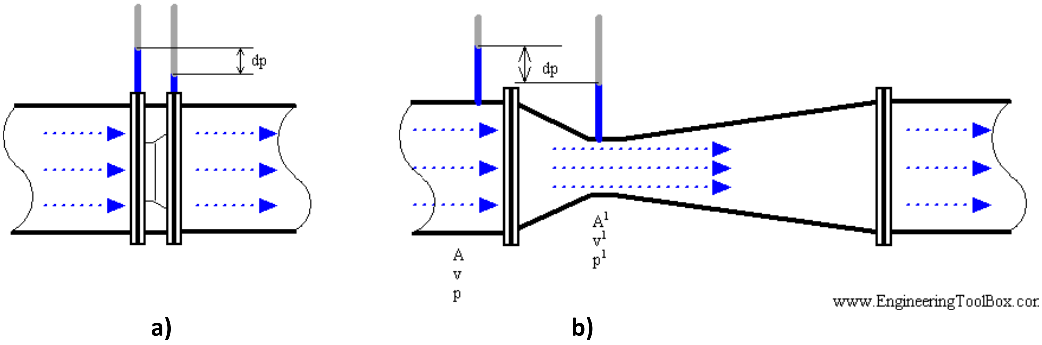


Figure 2: Obstruction flow meters. a) Orifice flow meter. b) Venturi flow meter [Error! Reference source not found.**]**

Flow meter calculations are based on ISO standards [9]. For these calculations both the flow rate and the Reynolds number of the fluid are unknown variables. The Reynolds number is a dimensionless quantity that describes different flow regimes within the fluid flow, of which the extreme cases are laminar and turbulent flow [**Error! Reference source not found.**]. A custom flow rate calculator was developed to perform the iterative calculations to get the flow rate while balancing the Reynolds number. The equations used in this calculator are summarised below.

A determining factor in orifice plate design is the β-ratio (defined in Equation (2)). A smaller ratio relates to a larger pressure drop across the plate for a given flow rate (thus easier detection), but also a larger permanent pressure loss down the line. The pipe inner diameter (D) is fixed at 22mm (see Table 1). To vary the β-ratio, the orifice diameter (d) must be varied. The above file was used to determine the final β-ratio and with it the orifice diameter.

$$\beta = \frac{d}{D} \tag{2}$$

Both the pipe and orifice (throat) cross-sectional area are determined respectively.

$$A = \frac{1}{4} \cdot \pi \cdot D^2 \tag{3}$$

The discharge coefficient is determined in Equation (4).

$$\begin{aligned} C_{ISO} &= 0.5961 + 0.0261\beta^2 - 0.216\beta^8 + 0.000521 \cdot \left(\frac{10^6\beta}{Re_{Dguess}}\right)^{0.7} \\ &+ \left(0.0188 + 0.0063\left(\frac{19000\beta}{Re_{Dguess}}\right)^{0.8}\right) \cdot \beta^{3.5} \cdot \left(\frac{10^6}{Re_{Dguess}}\right)^{0.3} \\ &+ (0.043 + 0.08e^{-10} - 0.123e^{-7}) \cdot \left(1 - 0.11\left(\frac{19000\beta}{Re_{Dguess}}\right)^{0.8}\right) \cdot \frac{\beta^4}{1 - \beta^4} \\ &- 0.031 \cdot \left(\frac{1}{1-\beta} - 0.8\left(\frac{1}{1-\beta}\right)^{1.1}\right) \cdot \beta^{1.3} + 0.011 \cdot (0.75 - \beta) \cdot \left(2.8 - \frac{D}{25.4}\right) \end{aligned} \tag{4}$$

The behaviour of C_{ISO} for different pressure values can be seen in Figure 3.

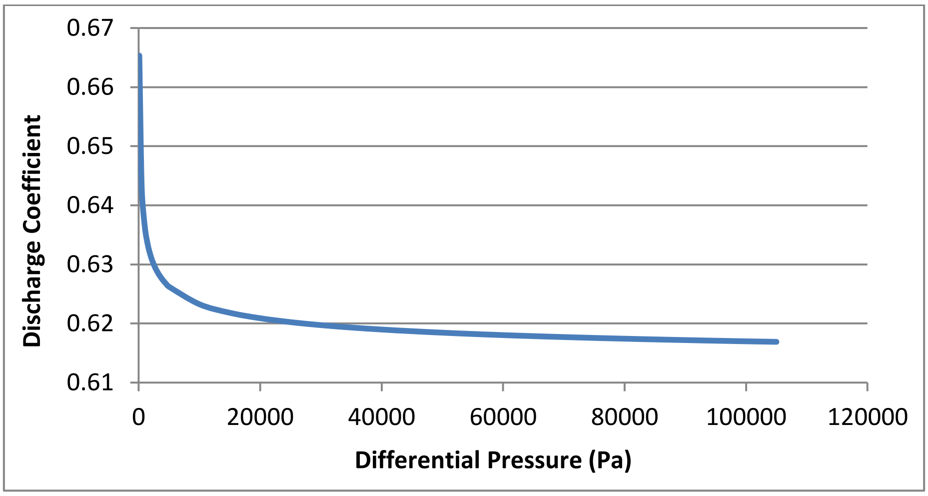


Figure 3: Discharge coefficient behaviour (ISO) and trend line fit

From this coefficient the volumetric flow rate can be calculated in litres per minute using Bernoulli's equation, given by

$$q_V = 60000 \cdot \varepsilon \cdot C_{ISO} \cdot A_d \cdot \sqrt{\frac{2\Delta p}{\rho(1-\beta^4)}} \quad (5)$$

In Equation (5), ε is the calibration error factored into the equation, A_d is the throat cross-sectional area, Δp is the differential pressure and ρ the fluid density. The flow velocity is determined in Equation (6), with A_D the pipe cross-sectional area.

$$u = \frac{q_V}{A_D} \quad (6)$$

The Reynolds number for this velocity is calculated as

$$Re_D = u \cdot D \cdot \frac{\rho}{\mu} \quad (7)$$

The average fluid velocity is indicated by u and its viscosity by μ. Equations (4) to (7) are now repeated with $Re_{Dguess} = Re_D$. This process is repeated until the error between Re_{Dguess} and Re_D is sufficiently small.

To determine the final β-ratio, it is required to know the approximate operating range of the differential pressure sensor that will be used in the flow meter. The selection of this sensor is discussed on page 6. By varying the differential pressure in the flow rate calculator between the minimum detectable pressures of the sensors available on the market as well as varying the orifice diameter, an acceptable combination was found. For this combination to work, the orifice diameter had to be chosen as small as possible, which is 12.5 mm according to the standards [9]. This diameter relates to a β-ratio of 0.57.

The focus of the study is to keep track of water usage. Therefore, the volume water that passes through a pipe can be calculated using Equation (8). A microcontroller would be used to perform this calculation and store the cumulative value, before sending it to a monitoring system such as a machine-to-machine (M2M) platform.

$$V_{water} = \int_0^t q_V(t)dt \quad (8)$$

Finally, the pressure sensor had to be selected. The difference in pressure between the two sides of the orifice plate acts as a proxy for the flow. A commercially available differential pressure sensor had to be selected.

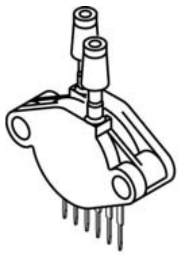
For an estimated maximum flow rate of $q_{max} = 70\ l/min$ for a residence, and for the parameters stated in Table 1, a maximum differential pressure of no more than $\Delta p_{max} = 110\ \text{kPa}$, or 1.1 bar, is expected. An open faucet running at $q_{min} = 5\ l/min$ would result in a differential pressure of at least $\Delta p_{min} = 0.5\ \text{kPa}$. This criterion was used to select a suitable, but also affordable differential pressure sensor with a high enough sensitivity to detect the minimum pressure difference and a suitable pressure range to accommodate the maximum expected pressure difference.

The Freescale MPX5100DP, seen in the illustration in Table 2, was selected. For a microcontroller with a 10-bit resolution, the minimum pressure difference is given by Equation (9).

$$\Delta p_{min} = \frac{5\ V_{DC}}{1024} \times \left(\frac{kPa}{45\ V_{DC}} \times \frac{1000\ mV_{DC}}{1\ V_{DC}} \times \frac{1000\ Pa}{1\ kPa}\right) = 108.51\ Pa \tag{9}$$

This value relates to volume flow rate of $2.41\ l/min$, which would enable the system to detect a sufficiently small change in water usage.

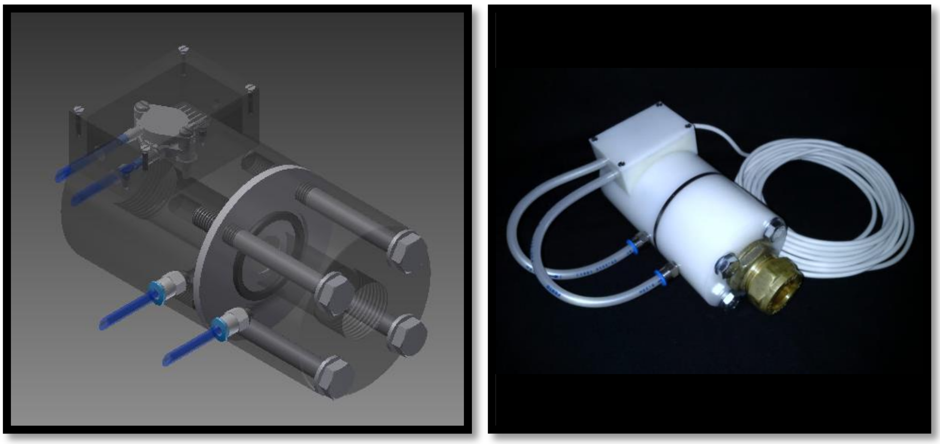
Table 2: Freescale MPX5100 selected characteristics [11]

Illustration	Characteristic	Symbol	Value	Unit
	Pressure range	P_{OP}	0 to 100	kPa
	Supply voltage	V_S	5	V_{DC}
	Minimum Pressure Offset	V_{OFF}	0.2	V_{DC}
	Full Scale Output	V_{FSO}	4.7	V_{DC}
	Full Scale Span	V_{FSS}	4.5	V_{DC}
	Accuracy	-	±2.5	$\%V_{FSS}$
	Sensitivity	V/P	45	mV/kPa

An isometric view of the design assembly in Inventor can be seen in Figure 4a. Designing the flow meter with the flanges, orifice plate and tubing all as separate parts makes this a highly modular design, and making it easy to replace the orifice plate for ones with different pressure drops. The price of this flexibility is the need for the visible tubing which also makes the flow meter more susceptible to damage. Therefore, the flow meter will need a protective housing if used outside.

It should be noted that this is only a prototype to help prove a concept and there is ample room for improvement on this design. Considerations for future designs should include removing more of the Acetal around the bolt heads to effectively decrease the bolt size and length and with it the diameter of the flanges, thereby decreasing material costs. Also, as the proper orifice properties were decided on after testing, future versions might have fewer parts by machining the orifice directly into the Acetal (or other material). This would mean having only one "flange" part instead of two flanges, an orifice plate, two O-ring seals and four bolts and washers, further lowering material and manufacturing costs. It would also open up new possibilities for the sensor casing shape and position, possibly removing the need for the visible tubing. Alternatively, as stated earlier, the Venturi should also be considered for its own advantages.

The completed flow meter can be seen in Figure 4b.



a) **b)**

Figure 4: Flow meter design in Inventor. a) Isometric view. b) Manufactured custom orifice flow meter.

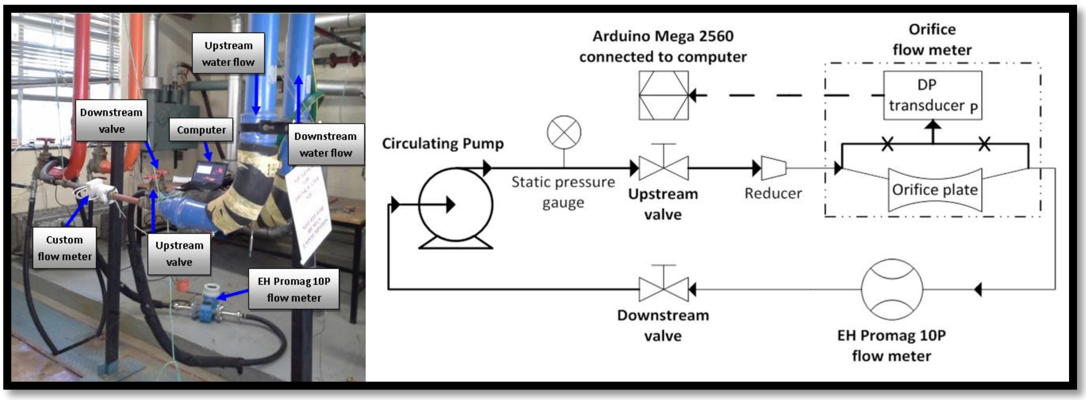
The unit cost of this design, assuming manufacture of 1 million units, is approximately R 3 000 (US$ 300) per unit, which is significantly lower than the comparative price of the Promag.

TEST SETUP AND RESULTS

This section describes the test setup and results. The purpose of the tests was twofold: to calibrate the flow meter against a trusted and accurate off-the-shelf flow meter, and to determine its accuracy and the limits of its use.

Test Setup

The setup and components can be observed in Figure 5. The orifice flow meter was installed with at least $30 \times D$ (pipe inside diameter) upstream and $7 \times D$ downstream straight length of Polycop pipe (see the left of Figure 5a) to ensure swirl-free, fully developed pipe flow at the orifice plate [9]. The valves upstream and downstream of the flow meters are used to remove any air between them before any readings are taken. A static pressure gauge, not visible in Figure 5a, is also included in the system, and is illustrated in Figure 5b.



a) **b)**

Figure 5: Flow meter test setup. a) Lab setup. b) Setup piping diagram.

The off-the-shelf flow meter that was used to calibrate the orifice flow meter is the Ender+Heuser Promag 10P. The Promag is accurate to $\pm 0.5\%$ for flow rates up to $9600\ m^3/h$

($160\ kl/min$), $130°C$ and a static pressure of $40\ bar$, which are all completely outside the boundary parameters of this test and thus more than sufficient. This flow meter has a signal output option as well as a digital display. The digital display of the Promag, together with digital display readings (on the computer) from the orifice flow meter were used to record results.

Results

Notable results are shown in the form of graphs in Figure 6 to Figure 8. The graph in Figure 6 is an illustration of the initially measured differential pressure for the known flow rates, with the Promag readings taken as the standard, as well as the offset corrected curve. This offset correction was achieved by adding the error (ε_V) measured at zero differential pressure and calculated in Equation (10), with V_{OFF} the offset voltage in Table 2, to V_{OUT} before calculating the differential pressure (Δp).

$$\varepsilon_V = V_{OFF} - V_{OUT} \tag{10}$$

Figure 8 shows the accuracy of flow rate readings, calculated as in Equations (11) to (13). Equation (11) calculates the range of measurable flow rates. The flow rate error (ε_q) calculated in Equation (12) was also used in the calibration process to adjust the error (ε) in Equation (5) to achieve the filtered flow rate curve shown in Figure 7.

$$\begin{aligned} q_{FSS} &= q_{max} - q_{min} \\ &= 65\ l/min \end{aligned} \tag{11}$$

$$\varepsilon_q = q_{Orifice} - q_{Promag} \tag{12}$$

$$Accuracy = \frac{\varepsilon_q}{q_{FSS}} \times 100 \tag{13}$$

A running average low-pass filter was applied to the measured flow rate to achieve the readings shown in Figure 7. The orifice flow meter performed better than expected. As seen in Figure 7, apart from minor inconsistencies in pressure readings, the considerably less expensive orifice flow meter, compared to the Promag, was able to achieve accurate readings. Also in Figure 7, when this graph is plotted for flow rates of 0 to $70\ l/min$, the two different lines become indistinguishable from each other.

The turndown ratio of a flow meter is an indication of its range of operation within a specified accuracy and repeatability. The typical orifice flow meter is expected to have a turndown ratio of less than 5:1 [**Error! Reference source not found.**]. Taking into account that flow rate readings can be detected accurately from $4\ l/min$ onwards, the use of $q_{min} = 5\ l/min$ can be considered as conservative. Also, $q_{max} = 70\ l/min$ is only the limit for this test and accurate higher flow rate readings may be achieved. Therefore the exceptional and conservative turndown ratio of 14:1 was calculated as in Equation (14).

$$\begin{aligned} TR &= \frac{q_{max}}{q_{min}} \\ &= 14 \end{aligned} \tag{14}$$

One unsolicited result of this test is the increasing variation between minimum and maximum differential pressure readings with increasing flow. This phenomenon can be contributed to the small orifice bore of 12.5 mm causing turbulent flow conditions at higher flow rates. It should once again be considered to use a Venturi flow meter in future applications, which should diminish this effect. Another possibility would be to design a scaled up flow meter.

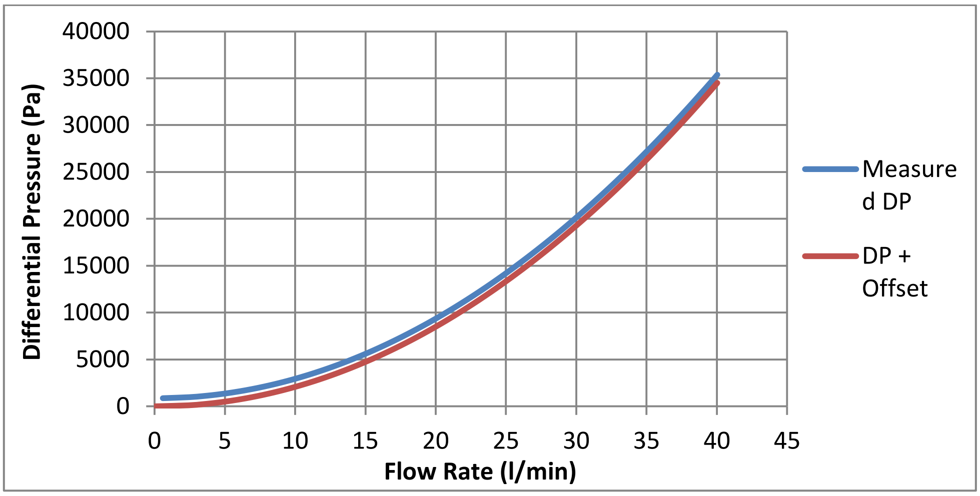


Figure 6: Differential pressure vs. flow rate

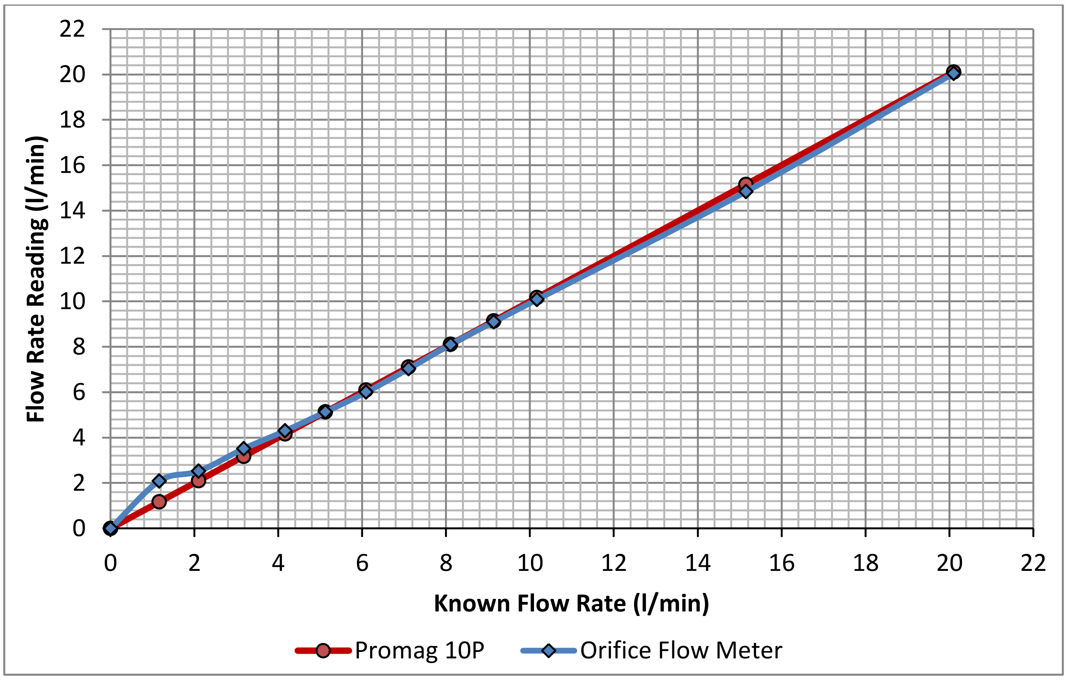


Figure 7: Promag & orifice flow rate vs. differential pressure

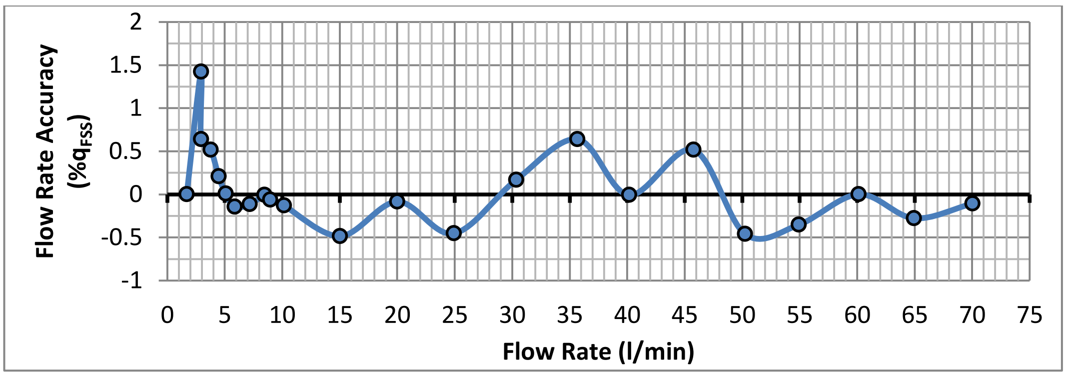


Figure 8: Flow rate reading accuracy

CONCLUSION

The work in this paper presents the design of a household orifice water flow meter for use in smart metering applications. The meter provides a low-cost alternative to existing solutions, with an estimated cost of 12% of the commercially available unit. The meter was manufactured and tested to measure flow rates to an accuracy of within 1% for flow rates between $4\ l/min$ and $70\ l/min$. It is advised that Venturi meter be considered should the product be taken into mass production, for which this design could easily be adjusted.

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