Experimental Evaluation of a Ranque-Hilsch Vortex Tube as a Particle Separator

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The Pebble Bed Modular Reactor (PBMR) is a Generation IV graphite-moderated helium cooled nuclear reactor developed in South Africa from the German Arbeitsgemeinschaft Versuchreaktor (AVR). After decommissioning of the AVR plant, radioactive isotopes of silver $_{44}Ag^{110}$ as well as graphite particles were found in the primary helium coolant loop of the reactor. Hence the main objective of this work was to evaluate the efficiency of the Ranque-Hilsch vortex tube (RHVT) as a separation device for removing graphite particles from a helium coolant stream. This objective was accomplished by designing and building an experimental test apparatus and measuring the particle separation efficiency of the RHVT under different operating conditions. It was found that the RHVT is a very efficient particle separator, which may, however, not easily be incorporated into the PBMR system.

Additional keywords: Dust, filtration

Nomenclature

Roman

c_p	specific heat at constant pressure [J/kgK]
d	diameter [m]
G	volumetric flow rate [L/min]
L	length [m]
m	mass [kg]
R	specific gas constant [J/kgk] , coefficient of determination

Greek

η	efficiency
μ	volume fraction

Subscripts

c	cold
h	hot
p	particle
vg	vortex generator

1. Introduction

The Pebble Bed Modular Reactor (PBMR) is a generation IV graphite-moderated helium cooled nuclear reactor which was under development in South Africa. The PBMR design is based on the German *Arbeitsgemeinschaft Versuchreaktor* (AVR). The AVR was decommissioned in December 1988 due to operational and safety problems.

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One of the main focus points of the PBMR project is safety and therefore all safety issues inherent to the AVR have to be addressed before its technology can be used in the PBMR. In the AVR it has been found that the radioactive silver $_{44}Ag^{110}$ isotope diffuses through apparently intact tristructural-isotropic fuel particles and that these isotopes bond to graphite particles, generated when the fuel pebbles rub against each other or against the containment walls[1]. The silver $_{44}Ag^{110}$ is then transported by the graphite particles through the primary helium coolant loop of the reactor[2]. This contaminated graphite particles can potentially be harmful to equipment, personnel and the general public. It is desirable therefore to find a way to separate the graphite particles from the helium coolant stream.

The device chosen to be evaluated for this appliction is the Ranque-Hilsch vortex tube (RHVT). The RHVT is a simple device having no moving parts that produces a hot and cold air stream simultaneously at its two ends from a compressed air source[3]. RHVTs are commercially used for tool-cooling or cryogenic applications. There are generally two main types of RHVTs, the counter-flow (often referred to as the standard) type and the uni-flow type.

The basic layout of the counter-flow vortex tube is shown in figure 1(a) and the uni-flow vortex tube is shown in figure 1(b). The counter-flow RHVT consists of air inlet nozzles, a vortex tube, a cold air outlet and a hot air outlet. Compressed air enters the counter-flow RHVT through two tangential nozzles or through a single supply tube and a vortex generator. A vortex generator is an aerodynamic surface consisting of small vanes or inlet nozzles that generates the vortex flow in the RHVT. The inlet nozzles or vortex generator generates strongly rotating flow within the vortex tube which flows through the tube rather than passing through the cold outlet located next to the inlet because the outlet is of a much smaller diameter than the vortex tube. The amount of air that escapes at the furthest end of the tube is controlled by the cone-shaped valve. The remainder of the air returns along the centre of the tube to the cold outlet, as a counter-flowing stream, hence the name counter-flow RHVT.

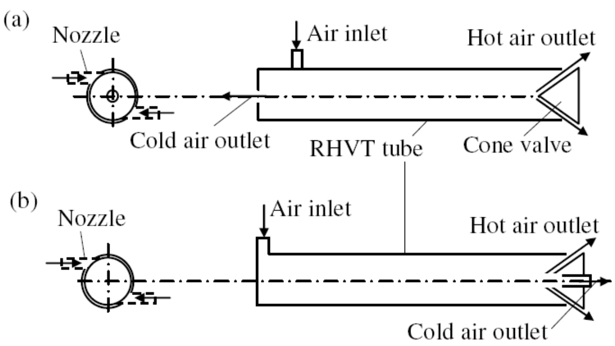

Figure 1: (a) Counter-flow and (b) Uni-flow vortex tube[4]

The vortex flow generated by the inlet nozzles or vortex generator located at the inlet of the RHVT is similar in speed to that of a gas centrifuge. The gas centrifuge is a very effective particle separation device generally used for isotope separation. The gas centrifuge's rotational speed determines its separation efficiency and since the air flow inside the RHVT is similar in speed to that of the centrifuge it can therefore, in theory, be used to separate the graphite particle from the helium coolant stream. The RHVT also has the added benefit of being able to either cool or heat the coolant and was thus selected as the separation technique to be tested experimentally.

In this evaluation the particle separation efficiency of the RHVT was tested experimentally using different grades of graphite particles, different fluids, various inlet volumetric flow rates, different cold to hot volumetric flow rate fractions and different RHVT geometries. A regression analysis was also done using the experimental data to obtain a correlation between the particle separation efficiency and the different operating conditions, that can be used to predict the separation efficiency under different operating and geometric conditions (such as the PBMR environment).

2. Literature Study on Ranque-Hilsch Vortex Tube

The possibility of using the RHVT as a particle separation device has intrigued many scientists and since the objective of this article is to use the RHVT as a particle separator, past experiments in this regard were investigated. Baker and Rathkamp[5] first investigated the possibility of using the RHVT as a particle separator, with specific application to isotope separation. They tested the separation of air, oxygen and nitrogen, isotopes of nitrogen and oxygen and a helium and argon mixture and found that the separation factor is so small that the deviance in their data could more likely be contributed to analytical errors rather than to actual separation. Although they did not entirely deny that the RHVT can be used as a particle separator, they claimed that it is highly unlikely on the basis of their findings.

After World War II Linderstrom-Lang[6] disproved the Baker and Rathkamp[5] theory when he showed that the RHVT can indeed be used as a gas mixture separation device. He put forth that centrifugation was the primary reason for the gas separation in the vortex tube. He conducted experiments using oxygen and nitrogen (air), oxygen and carbon dioxide, and oxygen and helium. It was found that the RHVT, acting like a centrifuge, transports the heavier molecules to the outside of the tube making it possible to separate the heavier and the lighter gas molecules. Marshall[7] also used several different gas mixtures in a variety of vortex tubes and confirmed that gas separation does occur as reported by Linderstrom-Lang[6].

Kap-Jong *et al.*[8] studied the particle separation characteristics of a counter-flow vortex tube using lime (CaO) powders with mean particle diameters of 5 μm and 14 μm. Using a RHVT of inner diameter 16 mm they found that more than 90 % of the lime powder was separated from the air stream when the cold volume fraction, $\mu_c = G_c / G_c(G_c + G_h)$ of the air was 0.9. They investigated the effects of varying cold volume fraction, inlet pressure and velocity and particle size on the separation efficiency. They found that varying the volume fraction did not change the separation efficiency significantly, until the volume fraction reached 0.5, and then the decrease in efficiency was only about 5 % at the most. Their results also showed that with an increase in inlet pressure and inlet velocity the separation efficiency decreased for the larger particle powder but increased for the smaller particle powder. Therefore, to obtain an efficient performance in particle separation for both particle sizes, they found that a separation efficiency of 93 % can be obtained with an inlet velocity of 14.52 m/s.

Kulkarni and Sardesai[9] did experiments to separate methane and nitrogen gasses using a vortex tube to enrich methane for mining applications. Their data showed that gas separation did occur, but only in small quantities which had to be measured with a gas chromatograph. They also determined that the gas separation is dependent on two parameters, the inlet pressure and the cold volume fraction. They found that the degree of molecular separation has a linear dependence on the inlet pressure; the higher the inlet pressure the higher the molecular separation capability of the RHVT.

The purpose of the experimental work was to measure the graphite particle separation capabilities of a RHVT and hence to determine its effectiveness as a particle separation device. Other than determining the particle separation efficiency, the influence of different operating conditions on its particle separation capabilities also have to be investigated. According to Kap-Jong *et al.*[8] the dimensions of the RHVT, such as tube length, cold volume fraction μ_c, inlet pressure and particle size have a considerable influence on the particle separation efficiency. The influence of these specific parameters was also reported by Yilmaz et al.[9]. Yilmaz et al.[9] also found that the inlet flow rate has a significant influence on the particle separation efficiency. Kulkarni and Sardesai[10] also reported the strong influence of the inlet pressure on the particle separation efficiency. Another parameter that can have a significant influence on the particle separation efficiency is the working fluid (air or helium). The commercially available RHVTs from the manufacturer Exair® are generally used in air whereas the primary coolant in the PBMR is helium. The effect of both these fluids on the particle separation efficiency will therefore have to be tested. Based on the above mentioned literature and the specified coolant used in the PBMR, the effect of varying operating variables on the particle separation efficiency η was determined and quantified in the experimental work. These variables included the volumetric flow rate G, cold volume fraction μ_c, working fluid, particle particle size and geometry of the RHVT.

3. Experimental Work

To evaluate the particle separation capabilities of the RHVT as well as to determine the influence of the operating variables discussed in the previous paragraph on the RHVT's particle separation efficiency, an experimental apparatus was designed that was capable of supplying compressed air/helium to the RHVT, injecting graphite particle upstream of the RHVT, collecting the graphite particle from the RHVT outlets and measuring the different operating conditions such as pressure and volumetric flow rate. Figure 2 shows a flow circuit diagram of the experimental test apparatus where the smaller numbers refer to the pipe inner diameters in millimeters and the bold numbers refer to the major components as listed below:

1 compressed air/helium cylinder
2 pressure regulator – FESTO LR (air) and Saffire OGM-5 (helium)[11]
3 air filter - FESTO Micro 1 µm[11]
4 shut-off valve
5 flow control valve – FESTO QS[11]
6 flow sensor – FESTO SFE1-LF (10 – 200 L/min) and FESTO MS6-SFE (200 – 5000 L/min)[11]
7 pressure sensors – FESTO SDE3[11]
8 reducer
9 particle particle mixing chamber
10 RHVT
11 particle collectors
12 T-type thermocouples

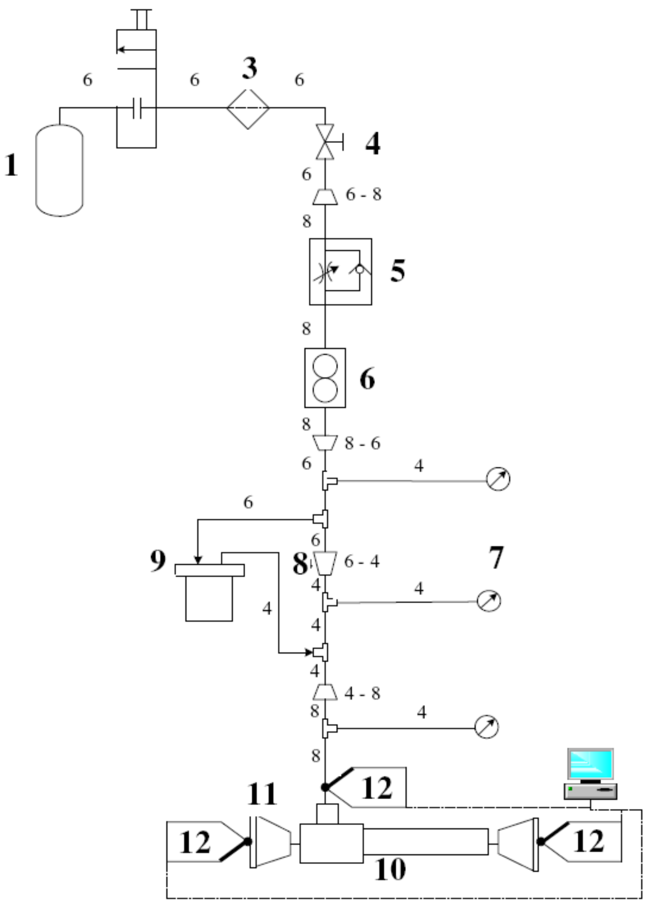

Figure 2: Flow circuit and major components of the experimental setup

A small and a medium sized commercially available vortex tubes (item 10 in figure 2) were used to test the effect of RHVT geometry on the particle separation efficiency. The RHVT models used in the experiment are the 3202 and 3210 from the Exair® Corporation[12]. These models were chosen for their difference in size and inlet flow rate requirements. The basic layout of the RHVT models are shown in Figure 3. The main components of the RHVT, as seen in figure 3, are the vortex generator (which consists of small inlet nozzles), the tube, hot outlet valve and cold orifice.

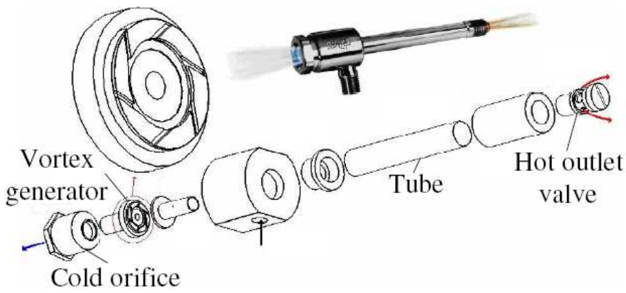

Figure 3: Exair® RHVT components[12]

Each RHVT model has a rated inlet volumetric flow rate (at an inlet pressure of 6.9 bar) and rated maximum cooling power. The specifications for each model are summarized in table 1.

Model	Size	Maximum cooling power [kJ/hr]	Rated volumetric flow rate [L/min]
3202	Small	142.4	57
3210	Medium	686.6	283

Table 1: RHVT model specifications (at 6.9 bar supply pressure)[12]

This experimental apparatus contains two items which had to be specifically designed for this application. These items are the particle mixing chamber (number 9 in figure 2) and the particle collectors (item 11 in figure 2). The particle mixing chamber was designed to inject graphite particles in small quantities into the main fluid stream. The chamber (figure 4) is essentially a pressure vessel with an inlet and an outlet and contains a predetermined amount of graphite particles. The chamber outlet is at a lower pressure than the inlet due to a drop in pressure caused by the reducer (item 8 in figure 2). This difference in pressure results in the particles to be ejected from the lower pressure outlet into the main fluid stream.

Figure 4: Particle mixing chamber

The purpose of the particle collectors is to collect the particles coming out of the RHVT. A particle collector will be attached to the hot and another to the cold outlet of the RHVT. The particle collectors were made from aluminium because they were designed to have a mass less than 200 g so that they could be weighed using a Precisa 405M-200A scale, with a maximum mass allowance of 200 g.

The particle collector consists of a perforated base and a cone distributor, as shown in figure 5. A fine metal mesh and a collection filter paper are also fitted securely between the cone distributor and the base. The base is perforated to allow air to pass through as well as provide a stable base for the filter paper to rest against, while the cone distributor ensures an even distribution of particles onto the filter paper. The metal mesh is added for extra stability of the filter paper on the base and the filter paper is used to collect the graphite particles.

Graphite particle with nominal particle diameters of 1.5 μm (fine particle) and 6.0 μm (coarse particle) were used in the experimental work. The filter paper had to therefore have the proper filtration grade to effectively collect the particle from the RHVT. Ordinary laboratory filter paper (Munktell Filter AB) with a filtration grade of 1 – 2 μm was used to capture the coarse particle but membrane filters (Sartorius Stedim Biotech, cellulose nitrate filters) with a filtration grade of 0.65 μm had to be used with the fine particle to be able to collect the particles that are smaller than 1 μm in diameter (at least 10 % of the fine particle has particles with diameters smaller than 1 μm)

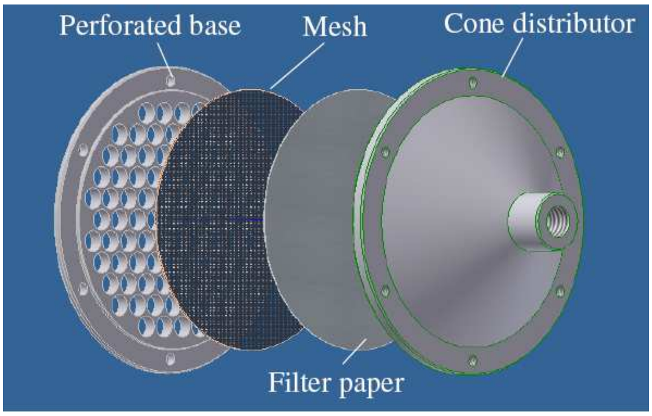

Figure 5: Particle collector

4. Experimental Results

The particle collectors were used to determine the particle separation efficiency of the RHVT by collecting the graphite particle from the respective outlets. The amount of particle captured by the particle collectors can be determined either visually or experimentally.

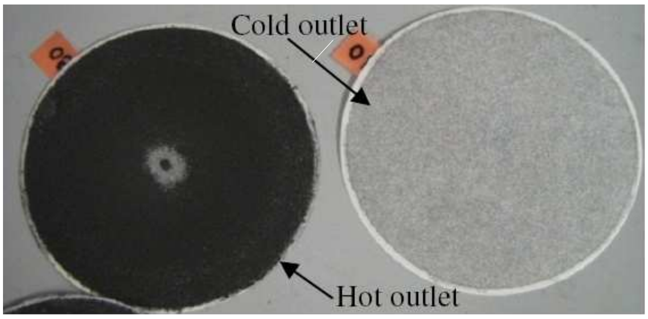

Figure 6: Particle collector filterpapers showing the difference in graphite particle collected on the hot outlet and cold outlet sides

For the visual method the filter papers are removed from the collectors and the amount of particle deposited on each filter paper are compared visually to determine from which outlet of the RHVT the most particle was collected. This method, however, only gives a qualitative indication of the particle separation efficiency but the difference in particle collected on the hot outlet and cold outlet filter papers is clearly visible, as seen in Figure 6.

In the experimental method the mass of the particle collectors were determined before and after an experiment and these measured masses were then subtracted from each other to determine the amount of particle collected by each particle collector. From these measurements the particle separation efficiency was determined as the ratio of the mass of particle collected by the hot outlet particle collector m_h to the total mass of particle collected by both particle collectors $m_h + m_c$, as seen in equation 1.

$$\eta = \frac{m_h}{m_c + m_h} \tag{1}$$

Table 2 summarises the experimental results of the measured particle separation efficiency for different values of the operating variables. The table shows the average particle separation efficiency results calculated after a statistical analysis was done on the raw data. The statistical analysis included calculating the standard deviation of all the measured efficiency values for each set of tests and then excluding the values which had a large standard deviation from the average value calculation. Due to systematic errors, a minimum of 5 tests were done for each variable configuration, shown in table 2, to obtain a better average value for the efficiency.

η [%]	G [L/min]	μ_c	Working fluid	Geometry	Nominal particle particle size [μm]
94.4	77	0.73	Air	Small	6
92.4	77	0.36	Air	Small	6
89.5	77	0.15	Air	Small	6
86.4	64	0.73	Air	Small	6
93.0	90	0.73	Air	Small	6
89.0	280	0.77	Air	Medium	6
93.0	280	0.54	Air	Medium	6
96.0	280	0.92	Air	Medium	6
92.0	290	0.77	Air	Medium	6
94.0	250	0.77	Air	Medium	6
91.5	40	0.73	Helium	Small	6
92.3	40	0.36	Helium	Small	6
85.1	40	0.73	Helium	Small	1.5
88.9	77	0.73	Air	Small	1.5
96.0	280	0.77	Air	Medium	1.5

Table 2: Experimental results

To find a correlation between the particle separation efficiency and the independent variables (measured variables), the dependant variable, a data regression analysis was done. To be able to do the regression all independent variables had to be quantified. The two variables not quantified are working fluid and geometry. The geometry was then quantified as the ratio of the outer vortex generator diameter d_{vg} to the length of the RHVT L, which is 0.133 for the small Exair® RHVT and 0.163 for the medium Exair® RHVT. The working fluid was quantified as the dimensionless quantity R/c_p, where R is the specific gas constant and c_p is the specific heat capacity taken at constant pressure. The values of the specific gas constant R and the specific heat capacity c_p at the average operating temperature of the experiments for both air and helium,are shown in table 3.

Material	R [J/kgK]	c_p [J/kgK]	$\frac{R}{c_p}$
Air	287	1007	0.2855
Helium	2079	5165	0.4025

Table 3: Specific gas constant R and specific heat capacity c_p values at 20 °C[13]

The first step in regression is to choose a curve fit that best suits the data. It was decided to test a linear, polynomial, power and exponential regression curve fit. The equations of these curves are:

Linear $$y = a + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5 \quad (2)$$

Polynomial $$y = a + b_1x_1^5 + b_2x_2^1 + b_3x_3^3 + b_4x_4^4 + b_5x_5^2 \quad (3)$$

Power $$y = ax_1^{b_1}x_2^{b_2}x_3^{b_3}x_4^{b_4}x_5^{b_5} \quad (4)$$

Exponential $$y = e^{(a+b_1x_1+b_2x_2+b_3x_3+b_4x_4+b_5x_5)} \quad (5)$$

The variables were assigned as shown in table 4:

Variable	Symbol	Assignment	Weight
Particle separation efficiency	η	y	
Volume flow rate	G	x_1	1
Volume fraction	μ_c	x_2	5
Working fluid	$\frac{R}{c_p}$	x_3	3
Geometry	$\frac{d_{vg}}{L}$	x_4	2
Particle particle diameter	d_p	x_5	4

Table 4: Regression variable assignment

The polynomial equation was determined after calculating the weight of each independent variable's influence on the particle separation efficiency and then assigning the variables with the most weight to the higher order polynomial values. The weights of the independent variables were determined by doing a regression analysis on each variable and then comparing their coefficient of determination (R^2-value). The variable with the highest R^2-value was assigned the most weight. In table 4 the different variables are assigned a number from 1 – 5 with 1 being the variable with the most weight and 5 being the least.

The regression analysis was done with 58 different data points which were taken from the processed experimental results. The processed experimental results exclude all values that were determined to be outliers after the statistical analysis was done. The regression analysis calculated the values of the constants for each curve fit, as well as the curve fits' coefficient of determination and the percentage error between the particle separation efficiency value predicted by the curve fit and the actual measured efficiency as shown in table 5.

	Linear	Polynomial	Power	Exponential
Constant	Value	Value	Value	Value
a	98.600	88.484	4.067	0.0003
b_1	0.029	497×10^{-15}	0.062	-0.013
b_2	-1.259	-0.809	-0.004	0.034
b_3	3.510	-18.900	0.097	-0.985
b_4	-95.008	4744.208	-0.240	4524.315
b_5	421407	59.1×10^{9}	0.016	4.588
R^2-value	0.254	0.219	0.290	0.250
% error	2.811	2.877	2.770	2.817

Table 5: Regression results

Although the R^2-values for all of the curve fits are poor with an approximate value of 0.2 the curve fits gave a reasonably good percentage error between the predicted and actual values of the particle separation efficiency of approximately 2.8 %. All the curve fits showed very similar results but from table 5 it is seen that the power curve fit gave the best results with an R^2-value of 0.290.

5. Discussion, Conclusions and Recommendations

The particle separation efficiency of the RHVT was tested using the experimental apparatus for various operating and geometric conditions. The experimental results showed a particle separation efficiency of more than 85 % and a maximum of 96 % which makes the RHVT a relatively good particle separator in comparison with other well known particle separators such as the gas centrifuge. The experimental results also showed that the inlet volumetric flow rate and RHVT geometry operating conditions had the largest influence on the particle separation efficiency. It was also shown that the efficiency decreased when the smaller particle particles were used, but not significantly. The results also showed that there was not a significant change in the efficiency between the air and helium tests.

Although the experimental results showed that the RHVT is a very efficient particle separator, a way still has to be devised to implement it into the PBMR. The RHVT cannot be inserted into the primary coolant loop as it would cause too much resistance to the flow and therefore it would have to be inserted in parallel. Some of the helium from the primary coolant loop can be tapped off into a smaller parallel loop that contains a RHVT or cascade of RHVTs. The helium would then pass through the RHVTs and the purified helium would then be injected back into the primary coolant loop. The effect of this parallel loop on the helium coolant flow and plant efficiency would have to be investigated further and other possible ways to implement the RHVT into the PBMR should also be explored. Another factor that has to be taken into consideration is the size of the RHVT, which would have to be rather large to accommodate the very high pressure and velocity of the helium coolant. Also the structural material used to manufacture the RHVT has to be considered due to the very high temperatures of the helium flow in the primary loop of the reactor.

References

1. *MacLean HJ and Ballinger RG*, Silver ion implantation and annealing in CVD silicon carbide: The effect of temperature on silver migration, *2nd International Topical Meeting on High Temperature Reactor Technology*, Beijing, 2004.
2. *Bäumer R, AVR: Experimental High Temperature Reactor; 21 Years of Successful Operation for a Future Energy Technology*, Dϋsseldorf: Association of German Engineers (VDI), 1990.
3. *Singh, PK, Tatghir RG, Gangacharyulu D and Grewal GS*, An experimental performance evaluation of a vortex tube, *IE Journal - MC*, 2004, 1, 149-50.
4. *Promvonge P and Eiamsa-ard S*, Review of Ranque-Hilsch Effects in Vortex Tubes, *Renewable and Sustainable Energy Reviews*, 2008, 12(7), 1822-42.
5. *Baker PS and Rathkamp WR*, Investigations on the Ranque-Hilsch (Vortex) Tube, Technical. Tennessee: Oak Ridge National Laboratory 1954.
6. *Linderstrom-Lang CU*, Gas separation in the Ranque-Hilsch vortex tube, *International Journal of Heat and Mass Transfer*, 1964, 7, 1195-206.
7. *Marshall J*, Effect of Operating Conditions, Physical Size and Fluid Characteristics on the Gas Separation Performance of the Linderstrom-Lang Vortex Tube, *International Journal of Heat and Mass Transfer*, 1977, 20, 227-31.
8. *Kap-Jong R, Jung-soo K and In-Su, C*, Experimental investigation on particle separation characteristics of a vortex tube. *JSME International Journal*, 2004, 47(1), 29-36.
9. *Yilmaz M, Kaya M, Karagoz S and Erdogan S*, A Review on design criteria for vortex tubes, *International Journal of Heat and Mass Transfer*, 2009, 45(5), 613-632.
10. *Kulkarni MR and Sardesai CR*, Enrichment of methane concentration via separation of gases using vortex tubes, *Journal of Energy Engineering*, 2002, 128(1), 1-12.
11. FESTO, Product Catalogue, 2008, http://www.festo.com/pnf/en-us_us/products/catalog , 15 September 2008.
12. Etest, Vortex Tubes, 2008, http://etest.exair.com/spotcooling/vtpage.php, 31 July 2009.
13. *Çengel YA and Boles MA*, Thermodynamics: An Engineering Approach., New York: McGraw-Hill, New York, 2001.