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Experimental Investigation On The Effect Of Length To Diameter Ratio (L/D) On The Performance Of Vortex Tube

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ABSTRACT

Vortex tube is a simple device that produces cold and hot streams from the pressurized gases. The separation of air steams by using of vortex tube principles can be utilized in many industrial applications, such as cooling of work piece in machining processes. The implementation of vortex tube for cooling purposes would provide many benefits, including simplicity, light weight, quietness and no need for refrigerants. This study aims to investigate experimentally the effect of the length to diameter ratio (L/D) on the performance of the vortex tube. A simple vortex tube was fabricated and tested for different L/D ratios: 27.50, 22.94 and 18.34. Besides, different air pressures of 2, 3 and 4 bars were applied. The collected temperature results on the cold air stream showed an inverse relationship with the pressure. It was noticed that the cold stream temperature starts to decrease with the decrease of L/D ratio until it reached 22.94 where it starts to increase again. The lowest cold air temperature for the tested system was found to be 7.6°C, which was observed at L/D ratio of 22.94. A similar trend was observed for the isentropic efficiency of the system as it was found that the highest efficiency was 27.41% at the L/D ratio of 22.94.

Keywords: Vortex tube, temperature separation, cold stream temperature, isentropic efficiency, performance

INTRODUCTION

A vortex tube is simple device that produces cold and hot streams from the pressurized gases [1, 2]. The vortex tube was first invented by French physicist George Ranque in the early of 30th of the twenty century [3, 4]. A detailed report on the device was then made by Hilsch in the mid of 40th of the twenty century [4, 5]. The main advantages of vortex tube are that it runs without any moving parts and capable to generate cold and hot stream simultaneously by using compressed gases and without using of any kind of refrigerants [6-8]. The simplicity compactness, low cost, quietness and ease of maintenance of vortex tube make it as good choice for some industrial applications such as spot cooling of work piece in different machining processes [4, 5]. On the other hand, from a thermodynamic point of view, the vortex tube was considered highly inefficient system, making it abandoned for years [3, 5, 9]. In the counter flow type vortex tube shown in Figure 1 the two exits are located at opposite ends of the tube. The device is consisted mainly of vortex chamber, hot exit, cold exit and control valve. When the compressed air introduced inside the vortex chamber tangentially, it produces a high vertical flow that moves to the end of the tube as a part of it forced back by the control valve in the opposite direction. The peripheral part of the flow escapes with a higher temperature through the hot exit while the forced back flow passed through the cold exit at lower temperature [10, 11]. Vortex tube performance is affected by number of geometric parameters such as tube diameter, tube length, orifice diameter, number of nozzles, location of nozzles, valve shape and location and air pressure [3, 12]. Geometric parameters of vortex tube influence strongly the separation phenomenon occurring inside the tube and hence this would affect the performance of the device. The study of geometric parameters on vortex tube performance is very important because it will determine the best values for each parameter to achieve maximum efficiency [3, 13].

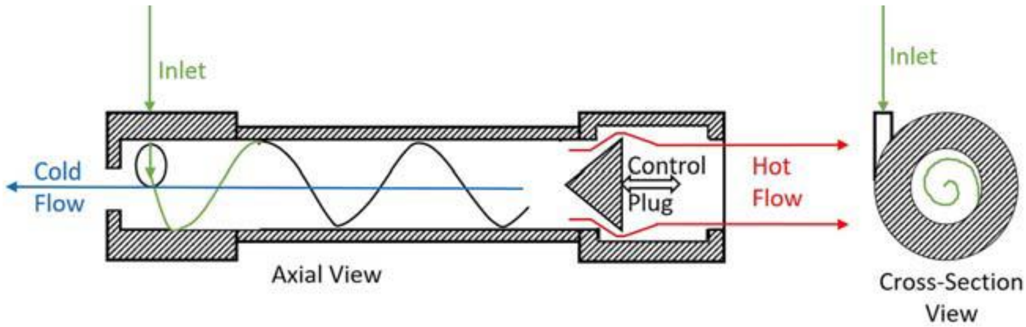

Figure 1. Flow structure in a counter-flow vortex tube [10]

Different researchers have carried out numerous studies on the effect of vortex tube geometry. Chaurasiya et al. [14] fabricated and tested experimentally the effect of length to diameter ratio (L/D) of a simple vortex tube. The results showed that the increase in L/D ratio made the temperature difference between cold and hot ends higher. Nouri-Borujerdia et al. [13] investigated the effect of L/D ratio, number of nozzles and cold orifice diameter/diameter ratio (β) on the performance of the vortex tube. The study proofed that for lower L/D ratio, the increase of the number of nozzles would increase the temperature difference between hot and cold ends. In addition, for the vortex tube with larger L/D ratio, the higher number of nozzles would result in more turbulence and hence lower energy separation. Kiran Devade and Ashok Pise [15] studied experimentally the effect of geometrical and operational parameters on the energy separation in a vortex tube. The studied parameters include length to diameter ratio L/D, nozzle geometry, valve angle, number of nozzles and cold orifice diameter. The collected results were then expressed in rise and drop and compared with literature. A numerical analysis on the energy separation at various numbers of nozzles was conducted by Fan Gaw et al. [11]. The study proved that the number of nozzles in vortex tube has great influence on the performance.

Although the advantages of using of vortex tube for cooling purposes no much studies were conducted in such systems. The in addition, the optimization of vortex tube geometric parameters would give a great opportunity for using of vortex tube in specific cooling applications. The present study investigates experimentally the effect of L/D ratio and operating pressure on the on the temperature separation of vortex tube. A simple vortex tube fabricated and tested at Faculty of Engineering and Technology of Nile valley University. The fabricated vortex tube system with specific geometry was characterized first for specific pressure and then the effect of L/D ratio on the achieved cold air temperature, hot air temperature and vortex tube isentropic efficiencies were investigated by verifying L/D ratio at different air pressure.

EXPERIMENTAL SETUP AND TESTING METHOD

In order to achieve the objectives of this work, a simple vortex tube made of PVC material was locally fabricated at College of Engineering and Technology of Nile Valley University. The fabricated vortex tube used in this study is shown in Figure 2. The system consisted of inlet valve, nozzles chamber, hot tube, cold tube and control valve, which located at the end of the hot tube. Table 1 shows a detailed specification of the system.

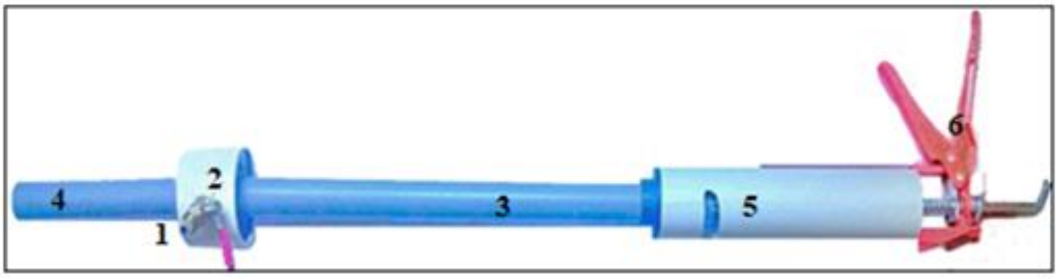

Figure 2. The locally fabricated vortex tube

(1) Inlet valve (2) Nozzles Chamber (3) Hot tube (4) Cold tube. (5) Control valve (6) Valve position controller

First, the system was placed in a horizontal position and the air from compressor is connected to the inlet valve. The compressed air pressure was set for a specific value by using pressure gauge. In this work, the vortex tube system was tested for different air pressures: 2, 3 and 4 bars. For each specific pressure, the temperature for air streams in the hot and cold tubes were instantaneously measured by using thermocouples and recorded manually. For each test, the control valve was adjusted at the position where the lowest temperature was reached. The experiments were repeated for different hot tube lengths of 500, 400, 300 mm and a fixed cold tube length of 100 mm which would give a variable length to diameter ratio of 27.52, 22.93 and 18.34, respectively.

Table 1. Vortex tube specifications

Parameter	Hot Pipe Length (mm)	Cold Pipe Length (mm)	Hot Pipe Diameters (mm)	Cold pipe Diameter (mm)	Number of Nozzles	Orifice diameter (mm)
Specifications	500	100	21.8	21.8	6	10

The performance of the vortex tube under study was calculated based on the isentropic efficiency of perfect gas principles. Since air expands adiabatically inside the vortex tube an isentropic expansion can be assumed and the isentropic efficiency was calculated by using the following equation [3]:

$$\eta_{is} = \frac{(T_i - T_c)}{T_i\left(1 - \left(\frac{P_a}{P_i}\right)^{\left(\frac{\gamma-1}{\gamma}\right)}\right)} \quad (1)$$

Where:

η_{is}: The isentropic efficiency
P_i: Inlet air pressure (Bar)
P_a: Atmosphere pressure (Bar)
T_i: Inlet air temperature (K)
T_c: Cold air temperature (K)
γ: Specific heat ratio (kJ/kgK)

RESULTS AND DISCUSSION

Figure 3 shows the variation of cold air stream temperature at different compressed air pressure of 2, 3 and 4 bars. It can be seen that for all length to diameter ratio (L/D), the temperature of cold air stream decreases as the compressed air pressure increases. The lowest achieved temperature was found to be 7.6°C, which was observed at the length to diameter ratio (L/D) of 22.94. This is because of the influence of the air pressure on the separation phenomenon. Sudden expansion is known to occur when compressed air is injected into the tube. Since the temperature drop is governed by the adiabatic expansion relations, a higher temperature drop will occur with the increase in the injected air pressure. Thus, for all tested L/D ratios, the higher temperature drops are associated with the higher pressures.

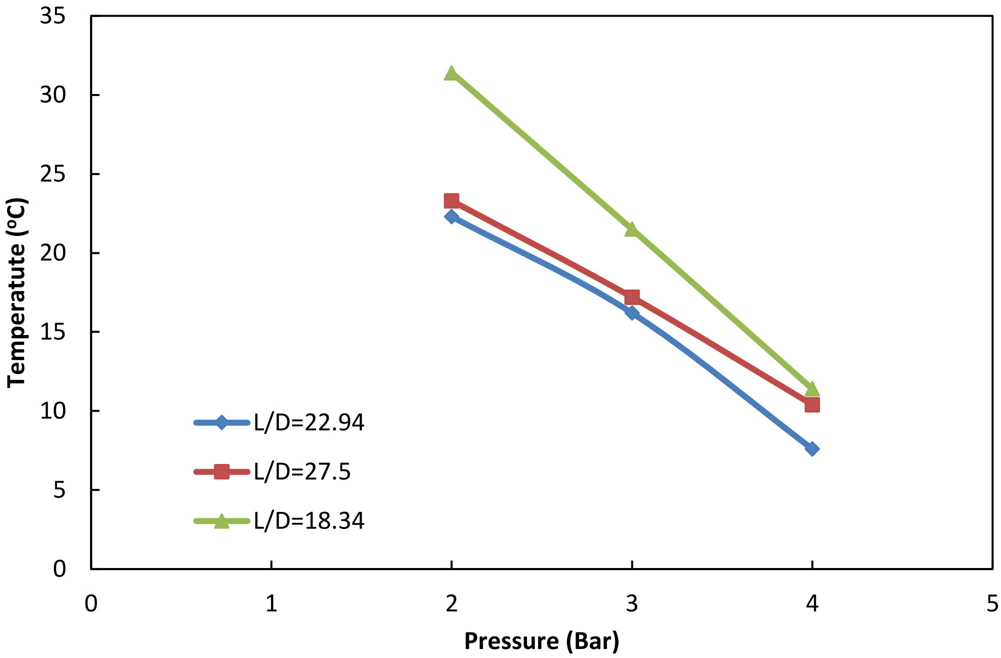

Figure 3. Variation of cold stream temperature with air pressure

For all tested pressures, the effects of L/D on temperature were very clear. As can be seen in Figure 4, for any specific pressure, the temperature starts to decrease with the increase of L/D ratio until it reaches its lowest value, then it starts to increase again. For this work, the lowest temperatures were found to be at L/D ratio of 22.94 which is expected to be the optimum L/D ratio. It was reported by many authors that the length of vortex tube should be longer than the critical length in order to achieve significant temperature drop. As mentioned by Yunpeng Xue et al. [16], when the vortex tube length is shorter than this critical length, this would effect on the separating vorticities which in term would effect on cold flow to be mixed with the hot flow and thus the temperature separation in short vortex tube will not be effective and resulted in higher temperature. Thus, from the previous discussion, in this work, for L/D of 18.34 the vortex tube length was less than the critical value while for L/D ratio the length of vortex tube under study was extremely higher than critical length. The investigation also showed that the higher pressure of compressed air the lower effect of L/D ratio on the temperature. The collected optimum L/D ratio in this study was found to be matching with other researcher findings where they found that in order to give significant reduction in temperature L/D ratio should be greater than 20 [17]. Another study showed that the L/D ratio should be in the range of $20 \leq {}^{L}/_{D} \leq 55$ [15] which is matching with the current results.

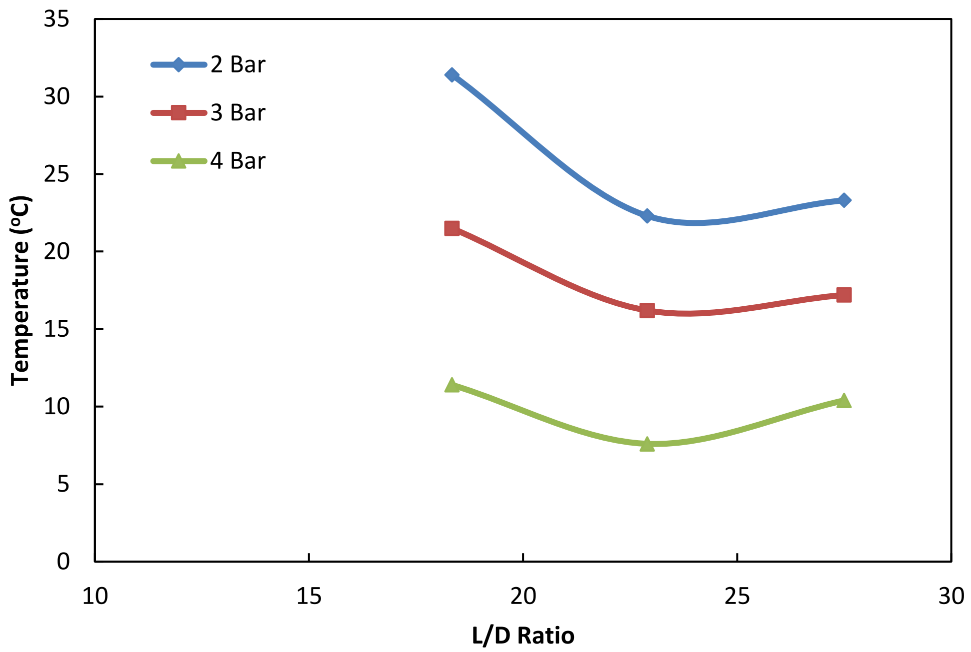

Figure 4. Variation of cold stream temperature with L/D ratio

Figure 5 shows the variation of hot air streams at the hot tube at different compressed air pressures and at different L/D ratios. It can be seen that, for all L/D ratios, the increase in compressed air pressure were affected in increase the temperature of hot air leaving the vortex tube. The increase in the temperature at the hot side was less affected by the compressed air pressure and L/D ratio as opposed to that of the decrease in temperature at the cold side.

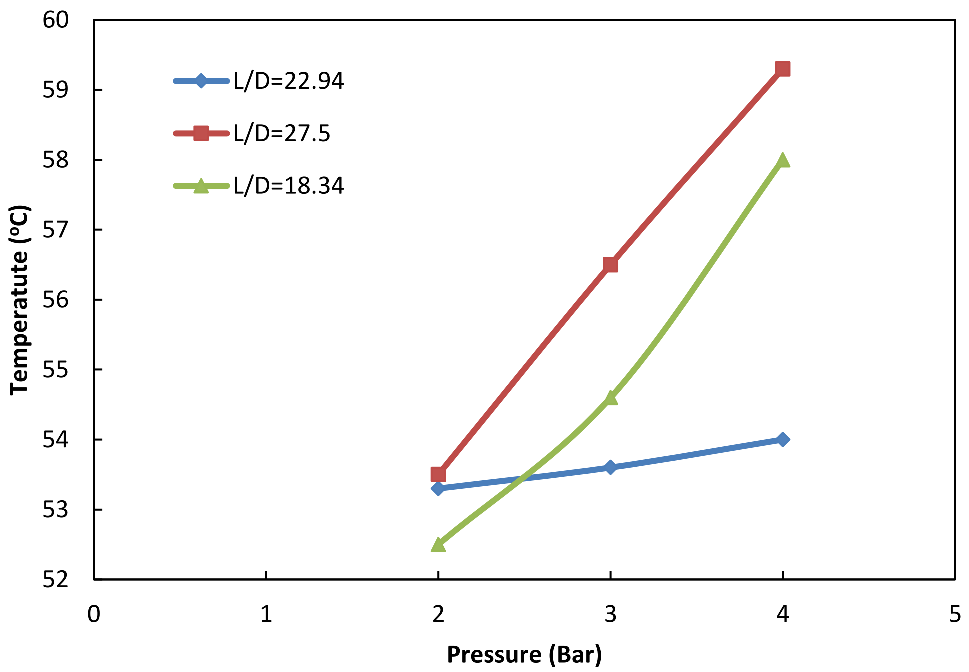

Figure 5. Variation of hot stream temperature with air pressure

As shown in Figure 6, for L/D ratio of 22.94, the temperature differences between ambient condition and cold air temperature ranges from 12.7 to 27.4°C for the cold side while at the same compressed air pressure the temperature differences with the ambient condition were between 8.3°C and 19°C for the hot air streams. Thus, the increase in the compressed air pressure from 2 bar to 4 bar increased the cold air temperature drop by 116% while for the same operating pressures, the increase of temperature difference for hot side was 4%. This is may be due to the location of control valve at the end of hot tube. The position of control valve affects strongly on the amount of airflow for both vortex tube sides. In addition, it affects the amount of reflected air at the central of the vortex tube and hence influences the temperature separation inside the tube. In this work, the location of the control valve was adjusted based on the lowest achieved temperature for each pressure and the mass air fraction for each side of the vortex tube was not measured. From the collected results on the temperature difference for each side of vortex tube, it is very clear that the cold mass fraction was extremely lower than the hot mass fraction which had influence on the collected results of temperatures difference at each side.

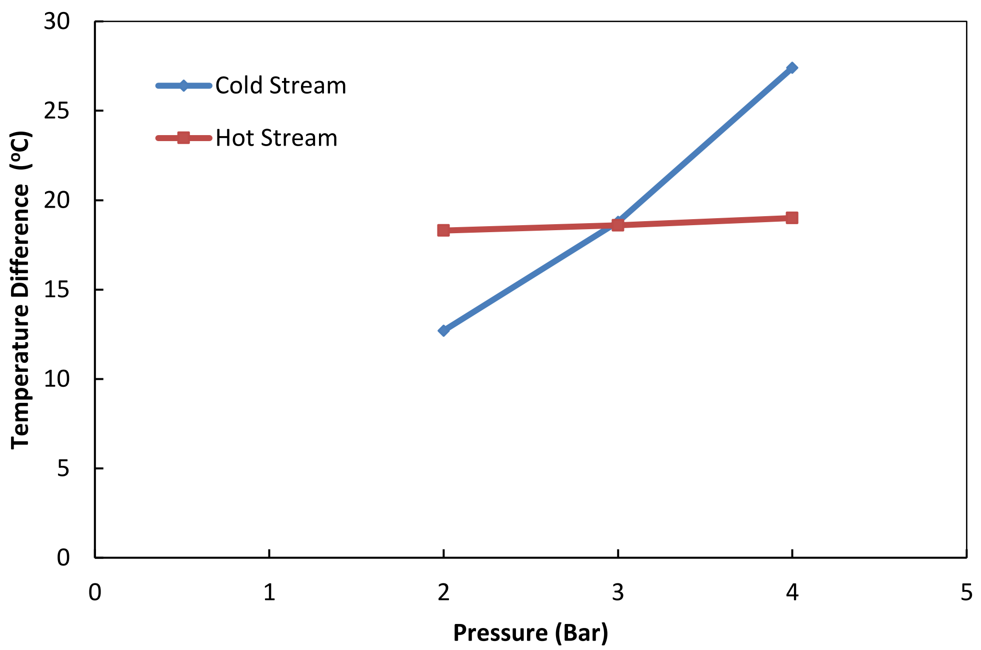

Figure 6. Comparison on temperature difference for hot and cold streams at L/D ratio of 22.94

Shown in Figure 7 is the variation of the isentropic efficiency with the compressed air pressure at different L/D ratios. The highest efficiency was found at L/D ratio of 22.94, followed by 27.5 and 18.34. It is clear that the isentropic efficiency for the system is affected by L/D ratio where the efficiency increases with the increase in L/D ratio till it reaches certain level then starts to decrease. This is due to the effect of cold stream temperatures on the isentropic efficiency. For same compressed air pressures, for higher L/D ratios, a higher back pressure which would lead to a lower diffusion of kinetic energy and thus lower temperature separation. On the other side, for low L/D ratio would result in low tangential velocities and also would affect in low temperature separation. In this work, for L/D ratio, the highest isentropic efficiency was found to be 27.41% which was collected at 4 bar pressure. It can be seen from the figure that the isentropic efficacy increases with the increase of compressed air pressure. This is due to the higher cold air temperatures drop which accrues at higher pressure ratios in an isentropic expansion.

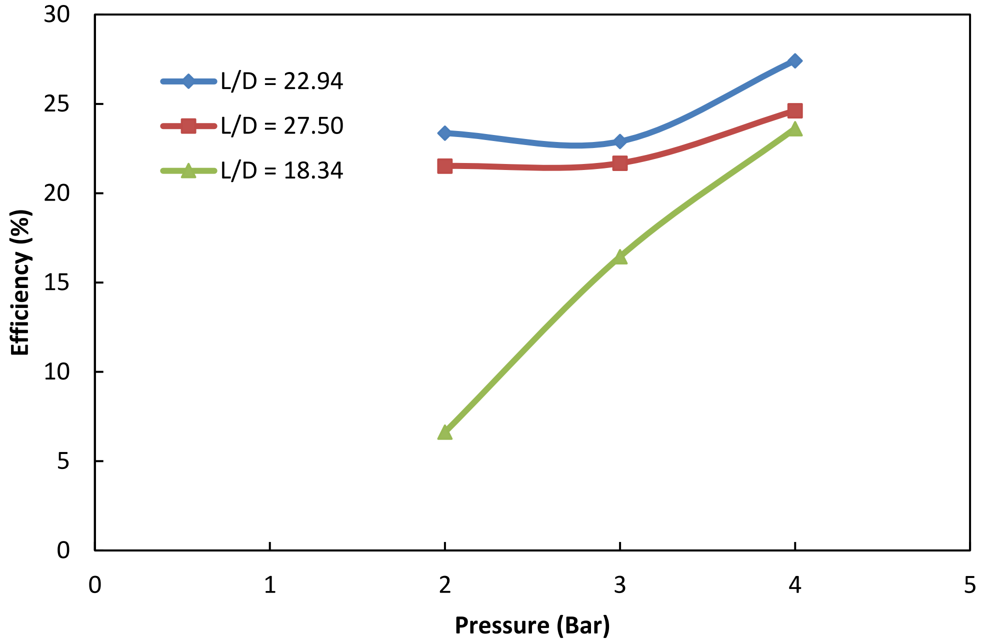

Figure 7. Variation of isentropic efficiency with pressure for L/D ratio

CONCLUSION

This paper presents the effect of L/D ratio on the cold and hot streams temperatures and isentropic efficiency of the system at different pressures. A small vortex tube was fabricated and tested at Faculty of Engineering and Technology of Nile Valley University. The collected results on the cold air stream showed an inverse proportionality with the pressure. It was noticed that the cold stream temperature starts to decrease with the decrease of L/D ratio until it reached 22.94 where it starts to increase again. The lowest cold air temperature for the tested system was found to be 7.6°C, which was observed at L/D ratio of 22.94. A similar trend was noticed for the isentropic efficiency of the system where the highest efficiency was found to be 27.41%, which was noticed at L/D ratio of 22.94.

Acknowledgements:

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References

[1] Y. Xue, J. R. Binns, M. Arjomandi, and H. Yan, "Experimental investigation of the flow characteristics within a vortex tube with different configurations," International Journal of Heat and Fluid Flow, vol. 75, pp. 195-208, 2019.

[2] K. I. Matveev and J. Leachman, "Numerical investigation of vortex tubes with extended vortex chambers," International Journal of Refrigeration, vol. 108, pp. 145-153, 2019.

[3] S. Eiamsa-ard and P. Promvonge, "Review of Ranque–Hilsch effects in vortex tubes," Renewable and sustainable energy reviews, vol. 12, pp. 1822-1842, 2008.

[4] T. K. Sharma, G. A. P. Rao, and K. M. Murthy, "Numerical analysis of a vortex tube: a review," Archives of Computational Methods in Engineering, vol. 24, pp. 251-280, 2017.

[5] J. P. O'Connell, "Detailed thermodynamics for analysis and design of Ranque-Hilsch vortex tubes," AIChE Journal, vol. 64, pp. 1067-1074, 2018.

[6] J. Lagrandeur, S. Croquer, S. Poncet, and M. Sorin, "Exergy analysis of the flow process and exergetic optimization of counterflow vortex tubes working with air," International Journal of Heat and Mass Transfer, vol. 152, p. 119527, 2020.

[7] N. Li, G. Jiang, L. Fu, L. Tang, and G. Chen, "Experimental study of the impacts of cold mass fraction on internal parameters of a vortex tube," International Journal of Refrigeration, vol. 104, pp. 151-160, 2019.

[8] F. Liang, H. Wang, and X. Wu, "Study on energy separation characteristics inside the vortex tube at high operating pressure," Thermal Science and Engineering Progress, vol. 14, p. 100432, 2019.

[9] A. Aghagoli and M. Sorin, "Thermodynamic performance of a CO2 vortex tube based on 3D CFD flow analysis," International Journal of Refrigeration, vol. 108, pp. 124-137, 2019.

[10] Y. Xue, M. Arjomandi, and R. Kelso, "A critical review of temperature separation in a vortex tube," Experimental Thermal and Fluid Science, vol. 34, pp. 1367-1374, 2010.

[11] F. Gao, Z. Hu, Y. Gao, R. Li, and M. Yang, "Numerical Analysis of Energy Separation in Vortex Tube with Various Nozzles," in 2019 2nd World Conference on Mechanical Engineering and Intelligent Manufacturing (WCMEIM), 2019, pp. 27-30.

[12] H. Skye, G. Nellis, and S. Klein, "Comparison of CFD analysis to empirical data in a commercial vortex tube," International journal of refrigeration, vol. 29, pp. 71-80, 2006.

[13] A. Nouri-Borujerdi, M. Bovand, S. Rashidi, and K. Dincer, "Geometric parameters and response surface methodology on cooling performance of vortex tubes," International Journal of Sustainable Energy, vol. 36, pp. 872-886, 2017.

[14] R. K. Chaurasiya, L. Kanwar, N. Taparia, and D. Verma, "Fabrication and Experimental Analysis on L/D Ratio of Vortex Tube," 2016.

[15] K. Devade and A. Pise, "PARAMETRIC ANALYSIS OF THERMAL PERFORMANCE OF RANQUE-HILSCH VORTEX TUBE," Journal of Thermal Engineering, vol. 4, pp. 2333-2354, 2018.

[16] Y. Xue, M. Arjomandi, and R. Kelso, "The working principle of a vortex tube," international journal of refrigeration, vol. 36, pp. 1730-1740, 2013.

[17] Y. Xue, M. Arjomandi, and R. Kelso, "Experimental study of the flow structure in a counter flow Ranque–Hilsch vortex tube," International Journal of Heat and Mass Transfer, vol. 55, pp. 5853-5860, 2012.