SINAI International Scientific Journal (SISJ)
Volume 1, Issue 4, April 2025

Experimental Investigation of Vortex Tube Performance: Influence of Inlet Pressure and Cold Mass Fraction on Thermal Outputs

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Citation:

E. Koraim, S. Selim, A. Abdel-Hamied, A. Hussien. "Experimental Investigation of Vortex Tube Performance: Influence of Inlet Pressure and Cold Mass Fraction on Thermal Outputs", SINAI International Scientific Journal (SISJ), vol.1 issue 4, pp. 36-45, 2025

Received: 27 May 2024

Accepted: 27 July 2024

ABSTRACT

This research examines the performance of a vortex tube with two intake nozzles at a diameter ratio of 2:1, a cold tube diameter (d_c) of 0.6 cm, a cold tube length (L_c)of 1 cm, and a cone valve angle (θ) of 45°. The vortex tube has a 25 cm hot tube length (L_h) and a 1.3 cm hot tube diameter (D_h) with the length to diameter ratio (L/D) equal to 20. The study examined the impact of different entrance pressures (ranging from P_i= 1 to 3 bar) and cold mass fractions ($\dot{m}_{cf}$) on the temperatures of the hot (T_h) and cold (T_c) streams. Results show that although decreasing the overall cooling and heating performance (COP), raising the input pressure increases the temperature differential between the cold and hot streams. These results offer information for enhancing vortex tube performance and open a window over possible industrial applications.

KEYWORDS: Vortex tube, Operating inlet pressure, Energy separation, Coefficient of performance.

1. INTRODUCTION

Rudolph Hilsch [1] developed the vortex tube, a device that divides compressed air into hot and cold streams, after Georges J. Ranque [2] initially presented it in 1931. The Ranque-Hilsch effect is a phenomenon that has generated a lot of interest as it may be used for temperature control, gas liquefaction, and spot cooling in a variety of industrial processes. Though it could appear simple, the vortex tube's underlying mechanics remain complicated and only half understood. Operational circumstances, intake gas characteristics, and geometric configurations are some of the aspects that affect a vortex tube's performance. These elements have been the subject of earlier research to clarify the energy separation process and enhance its performance.

The purpose of this study is to look at how a vortex tube with certain geometrical dimensions' thermal outputs are affected when intake pressure and cold mass fraction are coupled. The study aims to provide more understanding of the vortex tube's performance and practical suggestions for its use and design improvements by systematically influencing these parameters.

2. LITERATURE REVIEW

The arrangement and number of input nozzles play a crucial role in defining a vortex tube's performance. Research has indicated that the utilization of several nozzles can improve performance through improved compressed gas distribution and an increase in the vortex's

Online ISSN: 3009-7800
Print ISSN: 3009-6324

rotating speed. According to research by Behera *et al*. [3], two nozzles are better than a single nozzle setup in terms of cooling when it comes to vortex tube performance. According to the study, using more than one nozzle increases the efficiency of energy and angular momentum separation. Dincer *et al*. [4] observed that two nozzles greatly increase the cooling effect after conducting experiments on vortex tubes with different numbers of nozzles. Better flow properties inside the tube and higher tangential velocity were credited with this improvement. Eiamsa-ard and Promvonge [5] investigated how the performance of vortex tubes was affected by various nozzle designs and by their amount. They realized that the cooling performance was much enhanced by the employment of two nozzles that were angled and shaped to perfection. Although Aydin and Baki [6] investigated the way the L/D ratio affected vortex tube performance, they discovered that an L/D ratio of 20 offered the best trade-off between mechanical and thermal performance, resulting in effective energy separation. The thermodynamic and fluid dynamic properties of vortex tubes with varying L/D ratios were studied by Skye *et al*. [7]. Their results confirm the hypothesis that a high degree of temperature separation may be obtained at an L/D ratio of 20, since the effective length permits the vortex flow to grow enough. Xue *et al*. [8] performed extensive studies to investigate how vortex tube performance is affected by L/D ratios. According to their findings, an L/D ratio of 20 provides the best compromise for reaching the optimal level of cooling performance. In a vortex tube, the valve angle affects the separation efficiency and flow characteristics. After researching various valve angles, Markal and Kirmaci [9] discovered that a 45° angle improves separation efficiency by maximizing the exit conditions for the hot and cold streams. Pourmahmoud and Farhadi [10] found that a 45° valve angle maximized the temperature differential between the hot and cold streams after studying the effect of valve angles on vortex tube performance.

For some applications, an L/D ratio of 20 is thought to be optimum as it combines the tube's length and diameter to optimize the separation of hot and cold streams. Numerical analysis of two input nozzle vortex tubes operating at a 20 L/D ratio was conducted by Soni and Thompson [11]. Their testing configuration outperformed several modifications of different L/D ratios and nozzle configurations in terms of both temperature separation and performance. Gao *et al*. [12] studied the effect of multiple nozzles and L/D ratio through experimental and CFD testing. They concluded that the two-nozzle vortex tube, with an L/D ratio of 20, sustains a regime of flow that is relatively steady and effective for cooling capacity. Khan *et al*. [13] conducted performance tests on vortex tubes with two input nozzles and different L/D ratios, up to 20. They reported that the highest temperature separation and efficiency were observed for a setup with two nozzles and an L/D ratio of 20. Xue *et al*. [14] investigated the optimal performance characteristics of vortex tubes by using a combination of experimental and computational methods. Their findings showed how well a two-nozzle system with an L/D ratio of 20 may produce noticeable temperature variations.

The new publications [15-25] introduce the experimental and numerical approaches performed to study the performance of vortex tubes; in these papers, analyses related to thermal performance, effects of pressure ratio, as well as results of several design optimizations are presented. The research into vortex tubes with two input nozzles and L/D of 20 gives consistent evidence of the much better performance on the grounds of energy efficiency and temperature separation. Due to the optimization of internal flow dynamics, these design factors can bring forth better cooling and heating effects without complicated equipment or extra power sources. Further studies may focus on the impact of nozzles, the influence of cold mass fractions, and the operating pressures of such optimized vortex tubes.

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3. MATERIAL AND METHODS

3.1. Geometry and Design

The vortex tube was designed, manufactured, and assembled in the workshops of the Faculty of Engineering, Sinai University, North Sinai, Egypt. It was manufactured with local raw materials available in the market, as shown in Table (1). The details of the main components of tested vortex tubes with dimensions are shown in Fig. 1. The inlet nozzle is machined tangentially inside the hot tube thickness circumferentially.

Table 1: Components of tested vortex tubes with materials.

Component	Material
Hot tube	Un-plasticized Poly Vinyl chloride (UPVC)
Cold tube	Copper
Vortex chamber	Un-plasticized Poly Vinyl chloride (UPVC).
Cone valve	Artelon

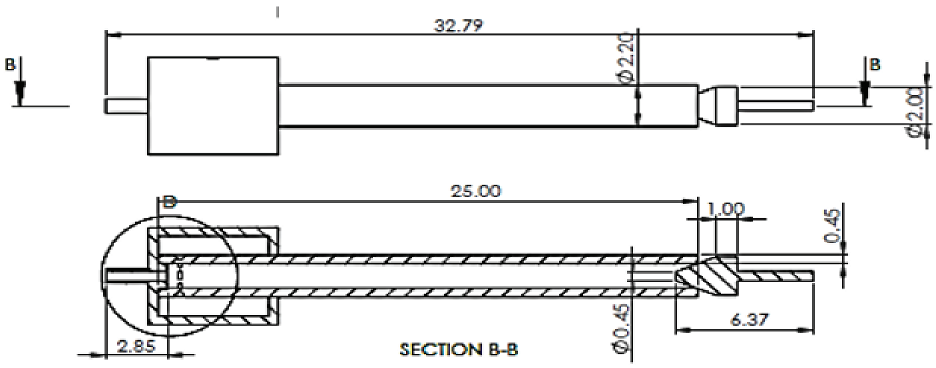

Fig. 1: Dimensional components of vortex tube (cm).

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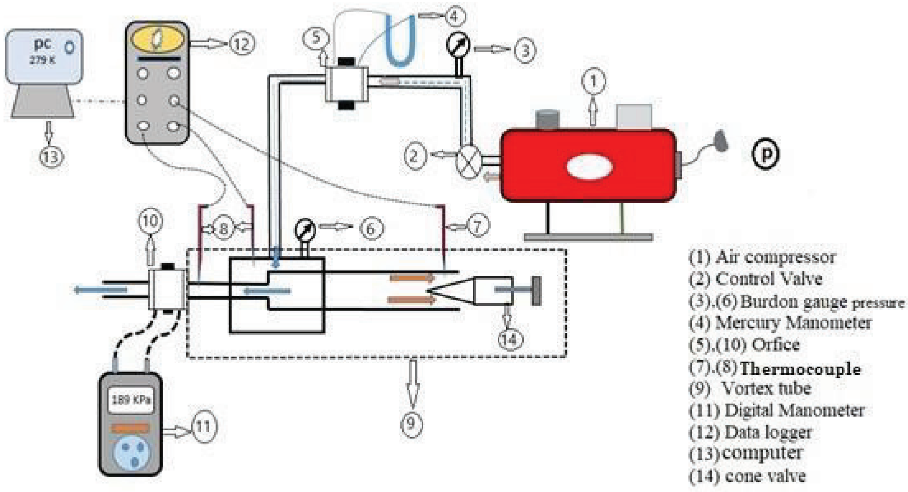

Fig. 2: Layout of experimental setup.

3.2. Experimental Layout

The experimental setup consists of an air compressor, a tested vortex tube, and measuring devices. The layout and photograph of the experimental setup are shown in Fig. (2). Vortex tube consists of inlet nozzles, vortex chamber, cone valve, cold tube and hot tube. The vortex tube's inlet is connected with pipes, and care is taken to prevent the pressure drop and leakages through the pipe connections. The entire system should be leak-proof to avoid experimental errors during measurements. Shows the accuracy and range of various instruments used in Table (2).

Table 2: Accuracy and range for various measuring instruments.

No.	*Instrument*	*Accuracy*	*Range*
1	Thermocouple (Type-K)	$\pm 1^{o}C$	-270-1820^{o}C
2	Differential manometer	$\pm 1pa$	0-5000pa
3	Mercury manometer	$\pm 0.5\ cm$	0-65cm

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4. METHODOLOGY

4.1. Experimental Test Procedure

1- Check the compressor storage tank and remove previously stored air if presented.
2- Test all connections for air leakage and test the measurement devices.
3- Switch on the air compressor till the required pressure is stored in the storage tank of the compressor.

4- The temperature and the amount of cold air and hot air produced depend on the position of the control valve, so adjust the control valve to the position where maximum cold and hot temperatures are produced.
5- Repeat the experiment with different pressures and different positions of the control valve.
6- Repeat steps 3, 4 and 5 for another inlet pressure value (1 to 3 bar with 1 bar increment in step).

4.2. Calculation of Performance Metrics

The performance of the vortex tube can be discussed by some parameters, which depend on the measurements. The cold mass fraction ($m^{\cdot}{}_{cf}$) is the most essential metric for determining vortex tube performance. It can be defined as a cold mass fraction($m^{\cdot}{}_{cf}$) as follows:

$$m^{\cdot}{}_{cf} = \frac{m^{\cdot}{}_{c}}{m^{\cdot}{}_{i}} \tag{1}$$

where $m^{\cdot}_{c}$ is the mass flow rate of the discharged cold stream *(kg/s)* and $m^{\cdot}_{i}$ is the inflow or total mass flow rate of the pressurized air at the inlet *(kg/s)*. The cold air temperature difference is defined as the difference between the input flow temperature and the cold air temperature. This is done using Equ. (2),

$$\Delta T_c = T_i - T_c \tag{2}$$

where T_i is the temperature of the inlet air flow and T_c is the temperature of the cold air. Similarly, the hot air temperature difference is described as:

$$\Delta T_h = T_h - T_i \tag{3}$$

Because RHVT may be used as both a cooler and a heater at the same time, both the cooling and heating impacts are addressed. The system's COP is computed appropriately. The cooling performance is defined as the ratio of the system's cooling impact to the work done on the system, which equals the compression work [26]. The work of compression from the atmospheric pressure to the inlet pressure of the nozzle tube is considered a reversible isothermal process. The COP of the system is given as [26]:

$$W_P = \; m^{\cdot}{}_{in} \, R_m \, T_i \;\; ln \, ln \left(\frac{P_i}{P_a}\right) \tag{4}$$

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$$COP_{cooling} = \frac{Q_c^{\cdot}}{W_P} \tag{5}$$

$$COP_{cooling} = \frac{m^{\cdot}_{cf}(T_{i}-T_c)}{\frac{\gamma-1}{\gamma} T_i \ln \ln \left(\frac{P_i}{P_a}\right)} \tag{6}$$

$$COP_{heating} = \frac{Q_h^{\cdot}}{W_P} \tag{7}$$

$$COP_{heating} = \frac{(1-m^{\cdot}_{cf})(T_{h}-T_i)}{\frac{\gamma-1}{\gamma} T_i \ln \ln \left(\frac{P_i}{P_a}\right)} \tag{8}$$

The pressure drop in the supply pipe has been ignored in the above relation, and the pressure at the exit of the cold and hot air in the vortex tube is considered to be atmospheric.

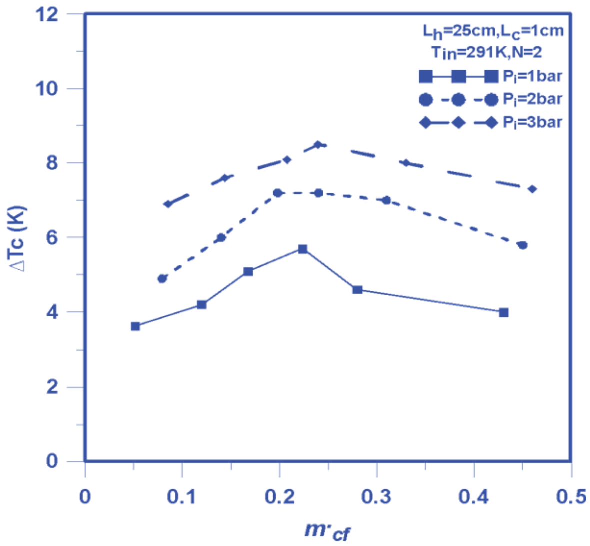

Fig. 3: Effect of cold mass fraction ($m^{\cdot}_{cf}$) on the cold temperature difference at different values of inlet pressure, 2 nozzles and $L_h = 25cm$.

5. RESULTS AND DISCUSSION

The experimental results will be presented and discussed to determine the best performance of the vortex tube. The tested experimental model is designed and fabricated. The characteristics of the tested experimental model are hot tube length $L_h = 25cm$ and D_h=1.3 cm, cold tube length $L_c = 1.0\ cm$ with D_c≈0.6 cm and the number of inlet nozzles (N=2 nozzles). The results include some of the operation conditions, such as the effect of the inlet pressure and cold mass fraction. Figures 3 and 4 show the effect of the cold mass fraction on the cold and hot temperature differences, respectively.

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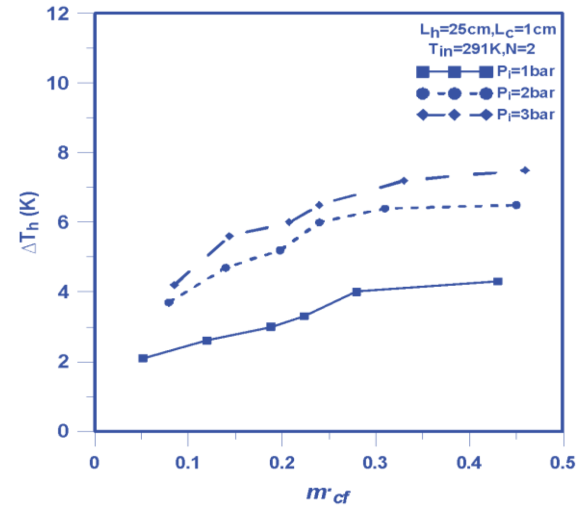

Fig. 4: Effect of cold mass fraction ($m^{\cdot}_{cf}$) on the hot temperature difference at different values of inlet pressure, 2 nozzles and $L_h = 25cm$.

From Fig. (3), it can be concluded that the cold temperature difference increases with increasing the cold mass fraction to reach the maximum value, then decreases when its value increases. The maximum cold temperature difference is achieved when the cold mass fraction changes in the range $m^{\cdot}_{cf}$ ≈0.28 to $m^{\cdot}_{cf}$≈0.35 depending on the value of inlet pressure. At the same time, it can be noticed from Fig. (4) that the increase of the cold mass fraction and inlet pressure increases the hot temperature difference. The maximum hot temperature difference is achieved at large values of cold mass fraction and inlet pressure. The cooling and heating performances were calculated as per the described methodology. Figures 5 and 6 present the effect of the cold mass fraction on the cooling and heating efficiency of a vortex tube at different values of inlet pressure.

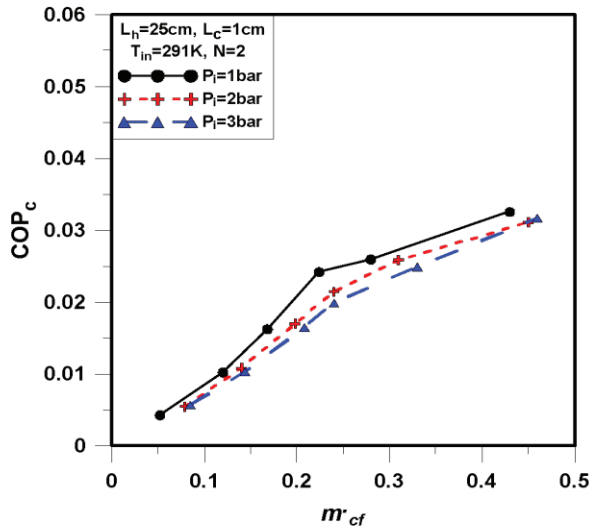

Fig. 5: Effect of cold mass fraction ($m^{\cdot}_{cf}$) on the COP_c at different values of inlet pressure, 2 nozzles and $L_h = 25cm$.

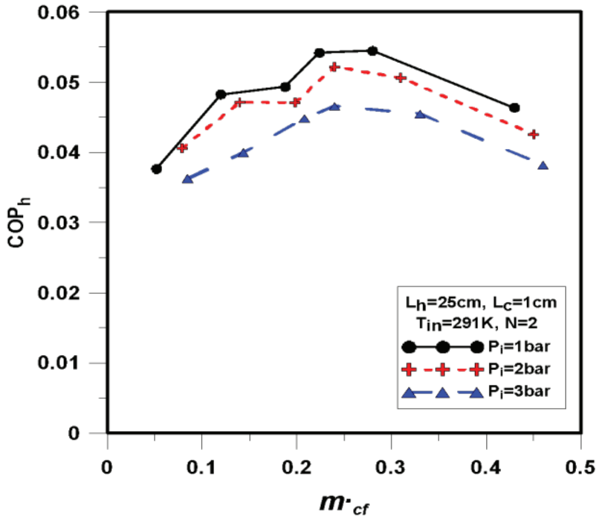

Fig. 6: Effect of cold mass fraction ($m^{\cdot}_{cf}$) on the COP_h at different values of inlet pressure, 2 nozzles and $L_h = 25cm$.

It can be noticed from Fig. (5) that the increase of the cold mass fraction increases the cooling performance for all values of inlet pressure. Also, the maximum cooling performance is achieved at small values of the inlet pressure (i.e., 1 bar). At the same time, the maximum COP_c is achieved at $m^{\cdot}_{cf}$ between 0.4 and 0.44 based on inlet pressure that is changing from 1 bar to 3 bar. From Fig. (6), it can be observed that the increase of the cold mass fraction increases the heating performance to reach the maximum value, then decreases at all inlet pressures. At the same time, the maximum heating performance is achieved when using small values of inlet pressure. Also, the maximum COP_h is achieved around $m^{\cdot}_{cf}$ between 0.21 and 0.35, based on different values of inlet pressure changing from 1 bar to 3 bar.

6. CONCLUSION(S)

This study shows that two important factors influencing vortex tube performance are cold mass fraction and inlet pressure. The results show that larger inlet pressures improve the temperature differential for the hot and cold streams, but they also reduce the performance of both heating and cooling. These discoveries offer a basis for vortex tube design optimization for particular applications, implying that careful control of these parameters can yield notable improvements in thermal efficiency. To further enhance performance, future studies might examine the impact of additional factors, including the vortex tube's material and the inlet nozzles' shape.

ACKNOWLEDGMENTS

The authors acknowledge that this paper has not been published on any research platform.

CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

REFERENCES

[1] Hilsch R. The use of the expansion of gases in a centrifugal field as a cooling process. Rev SciInstrum. 1946;18(2):108-113.
[2] Ranque GJ. Experiences sur la detente giratoire avec production simultanee d'un echappementd'air chaud et d'un echappement d'air froid. J Phys Radium. 1933;4:112-114.
[3] Behera U, Paul PJ, Kasthurirengan S, Karunanithi R, Ram SN, Dinesh K, et al. CFD analysis and experimental investigations towards optimizing the parameters of Ranque-Hilsch vortex tube. Int J Heat Mass Transf. 2005;48(10):1961-73.
[4] Dincer K, Baskaya S, Uysal BZ, Sakoglu C. Experimental investigation of the performance of a Ranque-Hilsch vortex tube with regard to a nozzle cross-section and inlet pressure. Int J Refrig. 2009;32(7):1484-9.
[5] Eiamsa-ard S, Promvonge P. Review of Ranque-Hilsch effects in vortex tubes. Renew Sustain Energy Rev. 2008;12(7):1822-1842.
[6] Aydin O, Baki M. An experimental study on the design parameters of a counterflow vortex tube. Energy. 2006;31(14):2763-72.
[7] Skye HM, Nellis GF, Klein SA. Comparison of CFD analysis to empirical data in a commercial vortex tube. Int J Refrig. 2006;29(1):71-80.
[8] Xue Y, Arjomandi M, Kelso R. The effect of vortex angle and temperature separation in a vortex tube. Int J Heat Mass Transf. 2011;54(1-3):215-21.
[9] Markal B, Kirmaci V. Optimization of counterflow Ranque-Hilsch vortex tube performance using Taguchi method. Int J Refrig. 2007;30(2):250-5.
[10] Pourmahmoud N, Farhadi M. Numerical analysis of the influence of the nozzle number on the thermal and flow field of a vortex tube. J Mech Sci Technol. 2013;27(6):1811-23.
[11] Soni SM, Thompson SM. Numerical investigation of vortex tube performance with various nozzle and length to diameter ratios. Appl Therm Eng. 2014;65(1-2):185-94.
[12] Gao C, Jia L, Shen B. Effects of geometric parameters on the performance of vortex tube. Energy. 2017;125:978-85.
[13] Khan MI, Jafri YZ, Sheikholeslami M. Effect of orifice diameter and nozzle number on the performance of counter flow vortex tube. Appl Therm Eng. 2015;90:1009-15.
[14] Xue Y, Arjomandi M, Kelso R. A critical review of temperature separation in a vortex tube. Exp Therm Fluid Sci. 2014;34(1):136-43.
[15] Zhuohuan Hu, Dan Wang, Fan Gao, Cao Yan. Experiment investigation on cooling performance of vortex tube with rectifier using Taguchi method. Case Stud Therm Eng. 2023;41:102062.
[16] Song Y, Zhang X, Xu Y, Li Y. Experimental evaluation of vortex tube and its application in refrigeration systems. Int J Refrig. 2023;144:245-253.
[17] Yasuo S, Masayuki T, Koji K. Numerical analysis for the thermal performance and flow behavior in a vortex tube. Heat Mass Transfer. 2023;59(7):1073-1081.
[18] NEHETE, Jayesh J.; GANDHI, Shirish S.; MALI, Kundlik V.Performance investigation on counter flow vortex tube. AIP Conf Proc. 2023;2890(1):020021.
[19] Maki T, Sakai K, Yamamoto K. Experimental study on the impact of pressure ratio on temperature drop in vortex tube. Exp Therm Fluid Sci. 2023;133:110632.
[20] RAFIEE, S. E.; SADEGHIAZAD, M. M. Experimental and 3D CFD investigation on heat transfer and energy separation inside a counter flow vortex tube using different shapes of hot control valves. Applied Thermal Engineering, 2017, 110: 648-664.

Online ISSN: 3009-7800
Print ISSN: 3009-6324

[21] Chen X, Liu J, Wang H. Optimization of Ranque-Hilsch vortex tube performances via Taguchi method. J Therm Sci. 2023;32(3):822-831.
[22] GODBOLE, Rutika; RAMAKRISHNA, P. A. Design guidelines for the vortex tube. Experimental Thermal and Fluid Science, 2020, 118: 110169.
[23] Azadi M, Mohammadi A. Prediction of temperature separation of a nitrogen-driven vortex tube using CFD. Appl Therm Eng. 2023;215:118145.
[24] HU, Zhuohuan, et al. Experimental investigation on cooling performance of vortex tube with rectifier using Taguchi method. Case Studies in Thermal Engineering, 2023, 49: 103373.
[25] Koraim, E., Selim, S. M., Abdel-hamid, A. H. A., & Hussien, A. A. .Numerical Investigation on the Performance of Vortex Tube. ERJ. Engineering Research Journal,2023, 46(3), 323-338.
[26] HAMDAN, Mohammad O.; AL-OMARI, Salah-AB; OWEIMER, Ali S. Experimental study of vortex tube energy separation under different tube design. Experimental Thermal and Fluid Science, 2018, 91: 306-311.