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A CFD Analysis of Energy Separation of Rectangular Shape Cold Orifice Vortex Tube

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Abstract–The present work investigates the influence of cold orifice shape on the thermal performance of vortex tube (VT). Two 3D (three-dimensional) geometries were created i.e., circular and rectangular shapes of cold orifice vortex tubes with four number of nozzles. The two geometries of the vortex tube had the same area and other dimensions for comparison. The operating inlet pressure was 4 bar for both shapes with air as a working fluid. The turbulence model used to predict the temperature magnitude was the standard k- ε turbulence model. The present work illustrated the flow physics of temperature separation in a rectangular-shaped cold orifice for different cold mass fractions. Furthermore, the study also discussed fluid parameters like axial velocity and tangential velocity for different radial locations inside the tube to understand the flow mechanism. A novel attempt to determine the feasible flow physics of a rectangular shape cold orifice vortex tube. The circular and rectangular shape cold orifice vortex tube was compared based on various fluid characteristics and temperature separation magnitude. It was found that energy separation is elevated in the hot region for rectangular shape cold orifice i.e. 28.7 ºC at a cold mass fraction of 0.9. In contrast, the maximum cold energy separation magnitude in the cold region is achieved by the circular shape cold orifice vortex tube which is 18.8 ºC.

***Keywords*:** Energy separation, Cold orifice, Vortex tube, CFD

1. Introduction

Hence, researchers persistently try to develop new techniques to harvest maximum energy. The extracting and storing of energy is known as harvesting of energy. Energy harvesting can be done from various natural sources such as solar, thermal, ocean etc. This harvested energy can be used for various engineering applications. The harvested energy can also utilized for power generation and running the power plants. The extraction of energy has great importance in the region where it is hard to reach such engineering applications as mines or down holes where the accessibility is low. Moreover, this region required a specific amount of energy to operate the underground equipment and cooling devices. Various engineering equipment like turbine generators, piezoelectric devices, and vortex tube are available to overcome such difficulties. These engineering equipment has the potential to use the maximum available energy. A vortex tube is a device which separates the high pressure compressed fluid into two different streams that is hot and cold shown in fig. 1. A vortex tube is used for cooling purposes i.e. spot cooling, refrigeration, gas conditioning and gas separation from many years. The quality of compact size and low maintenance of a vortex tube constantly develop an interest in researchers exploring this area. A vortex tube was invented by Ranque [1] in 1937 and later updated by Hilsch [2] in 1947 therefore named as Ranque-Hilsch vortex tube (RHVT).Hamdan, Al-Omari, and Oweimer [3] experimentally investigated the importance of the inlet nozzle on the coefficient of performance (COP) of the vortex tube.

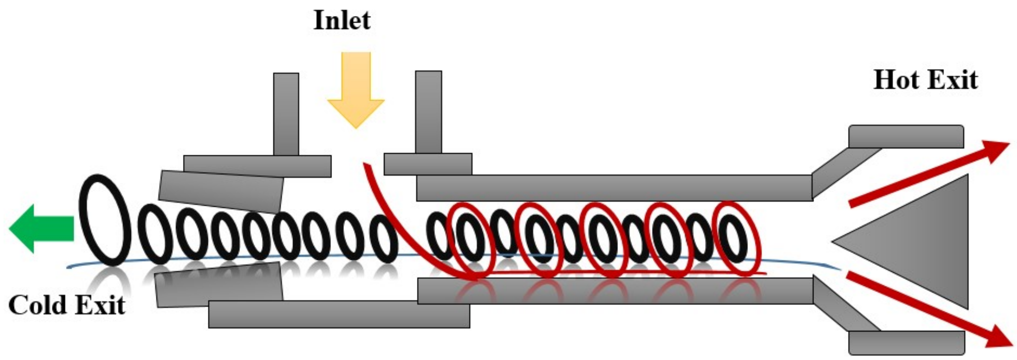


Fig. 1 The flow mechanism of vortex tube

It was found that the performance of the vortex tube increases with the number of nozzles Alsaghir, Hamdan, Orhan, and Awad [4] numerically examined three different parameters, i.e., tapering, length, and diameter of the VT. According to the result, the vortex tube's highest cooling and heating effect can be achieved by 66 and 158 mm length of the tube, the diameter is 9 to 26 mm, and 4o taper angle. However, design is not only the criteria, but the working fluid of the vortex tube also plays a significant role in the performance of the vortex tube. An article by Bagre, Parekh, and Patel [5] explained the importance of selecting a working fluid. The work investigated three different working fluid i.e. Nitrogen, CO2, and air. It concluded that N2 achieved the maximum energy separation. In our own research article by Bagre, Parekh and Patel [6] the study of rectangular shape cold orifice was carried out experimentally. The results shows that the performance of vortex tube is significantly affected by the shape of cold orifice. Thakare and Parekh [7] tested various tube materials of vortex tube and discussed the effect of different tube materials on the energy separation of the vortex tube. Results determined that the highest energy separation can be achieved by PA6 material among the rest. This shows that researchers always try to improve VT's cooling and heating effect by modifying its design parameters. It was found that the shape of the cold orifice had not been reported previously. So, the object of the present study is to attempt to explain the effect of cold orifice shape approaching the CFD method and compare it with the standard vortex tube.

2. OBJECTIVES

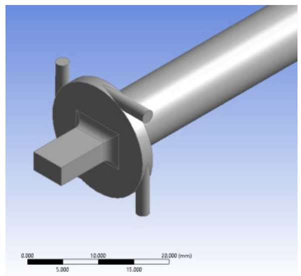
The current study aims to investigate the flow mechanism and determine the energy or temperature separation magnitude of air used as a working fluid in a vortex tube for a rectangular cold orifice and compare it with a circular cold orifice. Following are the objectives:

- To determine the temperature values for a vortex tube's cold and hot region using the CFD technique for both the shapes of the cold orifice.
- To investigate vortex tubes' cooling and heating effect by comparing the shapes of the cold orifice.
- To study the flow characteristics of a vortex tube based on its cold orifice shape.
- To determine the cooling power separation capacity of rectangular and circular cold orifice vortex tube.

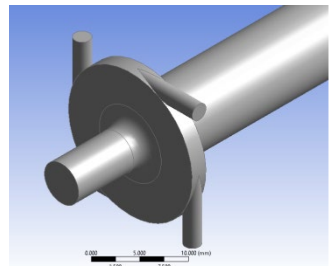
3. MODELING, MESH & BOUNDARY CONDITIONS

Geometry was created with a rectangular shape cold orifice vortex tube represented in fig. 1(a). The area of the rectangular cold orifice was kept the same as the circular cold orifice so that an **apple-to-apple** comparison could be made. The computational domain details of the vortex tube used in the present study are cold orifice diameter (COD), number of nozzles, and length of the tube, as shown in table 1. The present study carried out with an inlet pressure of 4 bar for both the tubes, and the working fluid was air. The vortex tube geometries were created with four nozzles, similar to the study of

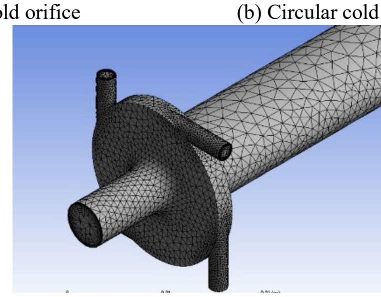
Ouadha, Baghdad, and Addad [8]. The two computational domains used in the present study and the generated mesh are shown in fig.1 (c). A Fluent™ 18.2 was used to obtain the results.



(a) Rectangular Cold orifice



(b) Circular cold orifice



(c) Generated grid

Fig. 2 Computational domain for CFD analysis and Generated mess

The boundary conditions for the present work were specified at inlet and outlets through pressure values. Here, the inlet was kept as a pressure inlet and both the outlets were kept as the pressure outlet. The hot outlet is set as the fraction of inlet and the cold outlet is obtained as an output to achieve the desire mass flow rate. This type of boundary conditions replicated the experimental set up.

In experimental set up the pressure is controlled by operating valves to obtain the desire mass flow rate. Here, air is used as a working fluid considering idea gas with the no-slip condition. According to Thakare and Parekh [9], the k- ε turbulence model determines more consistent results than the rest. Therefore, a k-ε turbulence model was selected to solve the computation work. Also, the convergence factor was set to 10-4 for all the equations which is continuity, energy and momentum.

TABLE 1 GEOMETRICAL DETAILS OF COMPUTATIONAL DOMAIN USED IN PRESENT STUDY

1.	Hot tube length	133 mm
2.	Diameter at inlet	10 mm
3.	Nozzle height	9 mm
4.	Nozzle width	2mm
5.	COD	5 mm

4. Governing Equations

The working fluid air was assumed to be compressible and Newtonian fluid. Hence, FLUENT 18.2 was used to solve the following equations:

- **Continuity equation**

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) + \frac{\partial}{\partial z}(\rho w) = 0 \quad (1)$$

Where, ρ is the density
u,v and *w* are the velocity component in *x, y* and *z* direction
t is the time

- **Energy Equation**

$$\frac{\partial \rho h_o}{\partial t} - \frac{\partial P}{\partial t} + \text{div}(\rho h_o U) = div(\lambda grad T_s) \quad (2)$$

- **Momentum Equation**

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v}\vec{v}) = -\nabla p + \nabla \cdot (\bar{\bar{\tau}}) + \rho g + \vec{F} \quad (3)$$

5. GRID TEST AND VALIDATION

A grid independence test was conducted for a different number of cells that varies from 104 to 204, as shown in fig. 3. It was found that the significance of temperature magnitude after 150000 is significantly less. Therefore, further studies can be carried out having this mesh size which resulting less simulation time. The methodology was validated by repeating the simulation and compared with Dincer, Baskaya, Uysal, and Ucgul [10] at a Pinlet of 200 kPa. A low deviation was found with Dincer, Baskaya, Uysal, and Ucgul [10] shown in fig. 4, in which ΔT for hot and cold outlets are represented, which authenticates the methodology. A temperature separation can be observed by this method inside the vortex tube. The number of elements for the computational domain of circular and rectangular shape cold orifice vortex tube are 1,24,664 and 1,23,378, respectively.

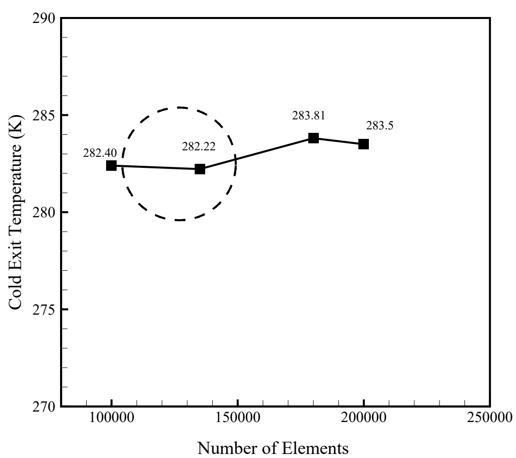


Fig. 3 Cold temperature variation along with number of elements

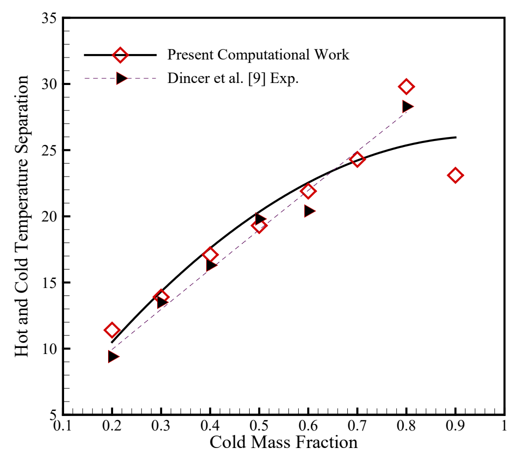


Fig. 4 Temperature difference with respect to cold mass fraction at 200 kPa

6. Results And Discussion

The deviations of temperature separation for various cold mass fractions of a circular and rectangular cold orifice of a vortex tube are shown in fig. 5. The maximum value of cold temperature separation was achieved by the circular cold orifice, which is 18.1oC at 0.2 cold mass fraction. In contrast, at the hot exit the maximum value of hot temperature separation is achieved by the rectangular cold orifice, which is 28.7oC at 0.9 cold mass fraction. A graphical representation of cold temperature separation shows a continuous declination when the cold mass fraction increases, but the magnitude of hot temperature separation increases as the cold mass fraction increases for both the geometries. This temperature difference is due to the cold orifice shape of the vortex generator. According to Rafiee, Sadeghiazad, and Mostafavinia [11] Vortex tube cooling and heating effect significantly depends on cold orifice diameter (COD). The hot temperature separation is shown in fig. 6. The deviations of temperature separation for various cold mass fractions of a circular and rectangular cold orifice of a vortex tube are shown in fig. 5. The maximum value of cold temperature separation was achieved by the circular cold orifice, which is 18.1oC at 0.2 cold mass fraction. In contrast, at the hot exit the maximum value of hot temperature separation is achieved by the rectangular cold orifice, which is 28.7oC at 0.9 cold mass fraction. A graphical representation of cold temperature separation shows a continuous declination when the cold mass fraction increases, but the magnitude of hot temperature separation increases as the cold mass fraction increases for both the geometries. This temperature difference is due to the cold orifice shape of the vortex generator. According to Rafiee, Sadeghiazad, and Mostafavinia [11] Vortex tube cooling and heating effect significantly depends on cold orifice diameter (COD). The hot temperature separation is shown in fig. 6.

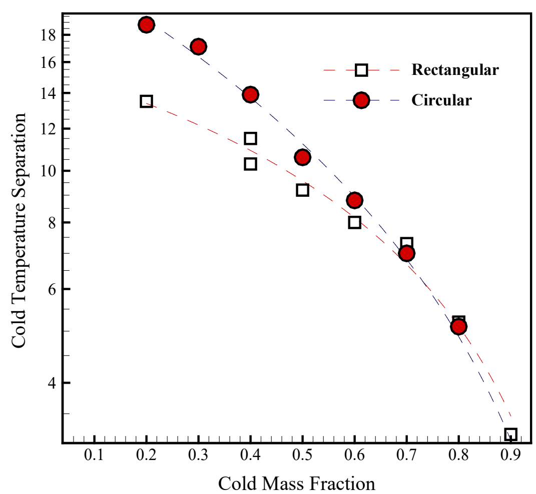


Fig. 5 Magnitude of vortex tube based on cold temperature separation along with cold mass fraction for rectangular and circular shape of cold orifice

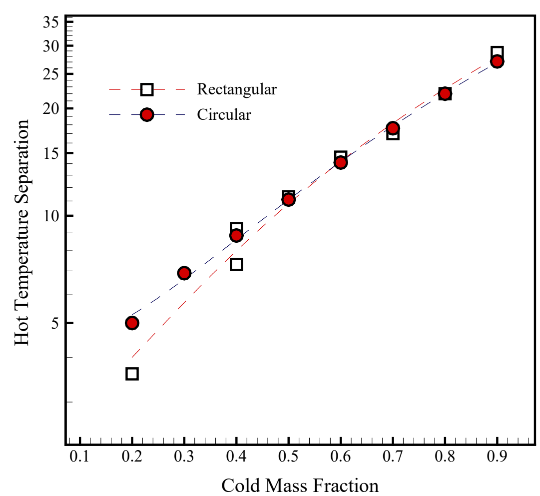


Fig. 6 Magnitude of cold temperature separation along with cold mass fraction for rectangular and circular shape of cold orifice

It was found that a rectangular shape cold orifice achieves the maximum temperature separation. The energy or temperature separation inside the vortex tube can be observed in the total temperature contour illustrated in fig. 7 and 8. The flow separation can be observed near the entrance of the vortex tube, and as it progresses towards the hot end, the flow separation diminishes. The velocity magnitude of fluid inside the vortex tube is represented in fig. 9 and 10. It was found that as the swirl velocity progress towards the end of the tube, its magnitude decreases. This is because the operating fluid enters with high pressure, and the sudden expansion of airdrop the pressure this pressure gradient is also one reason for the fluctuating temperature separation magnitude. In addition, the rotational flow inside the vortex tube also creates temperature separation. The angular momentum of fluid because of the vortex generator causes the rotational flow inside the tube. This angular momentum progress from the center to the wall surface of the tube, as shown in fig. 9 and 10; the intensity of rotational flow also decreases as the fluid moves in the longitudinal direction of the vortex tube.

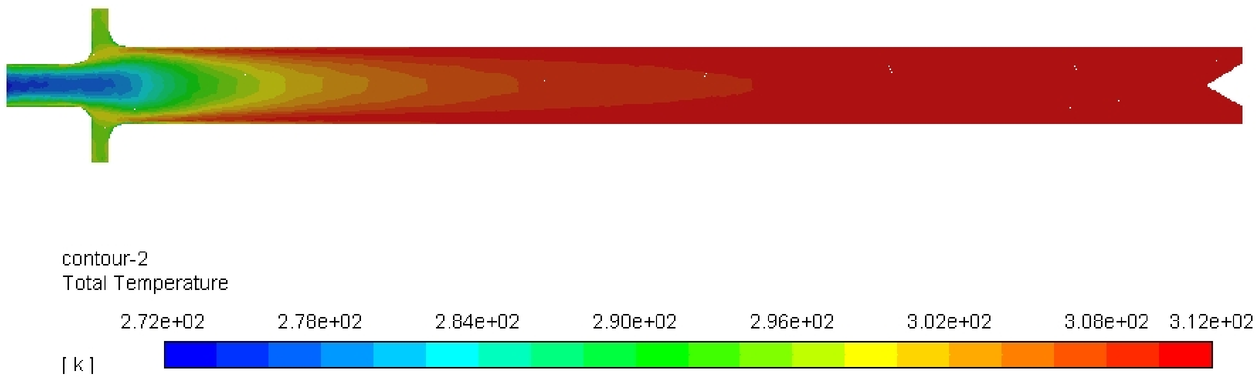


Fig. 7 Contour of total temperature separation in a circular cold orifice

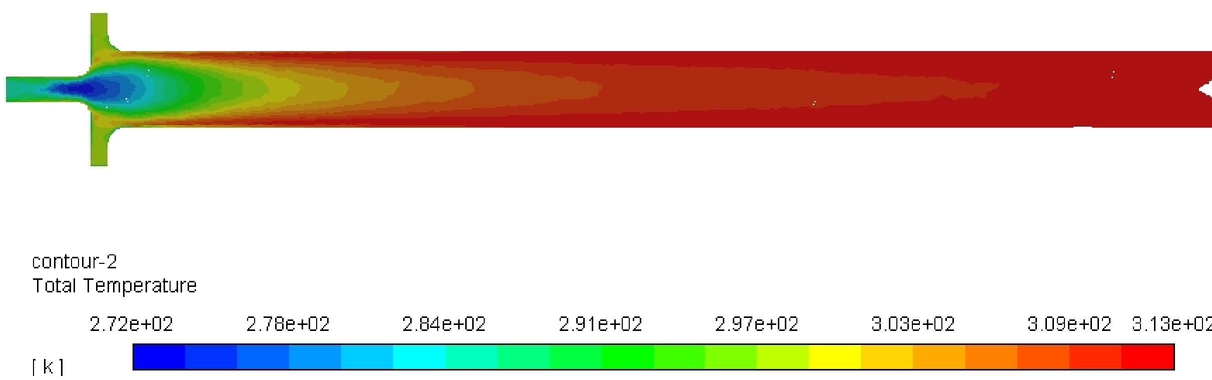


Fig. 8 Contour of total Temperature separation in a rectangular cold orifice

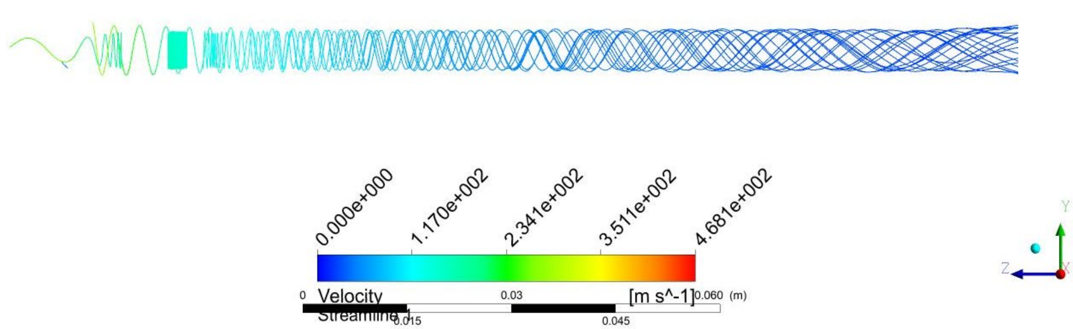


Fig. 9 Streamlines of a circular shape cold orifice vortex tube

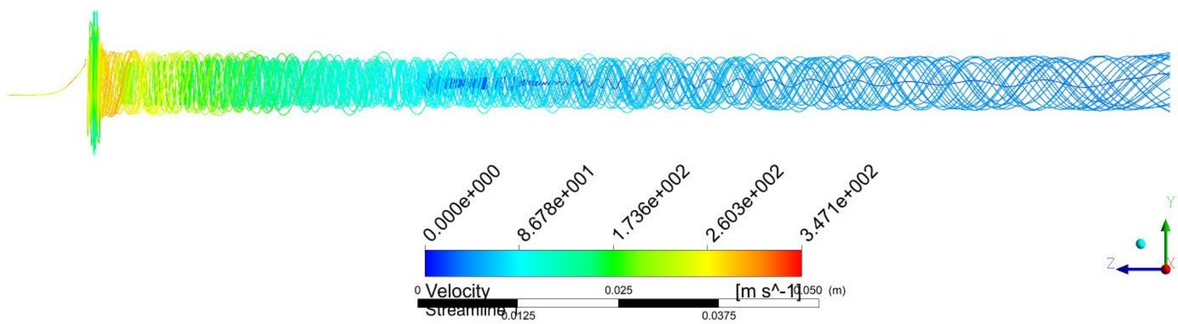


Fig. 10 Streamlines of a rectangular shape cold orifice vortex tube

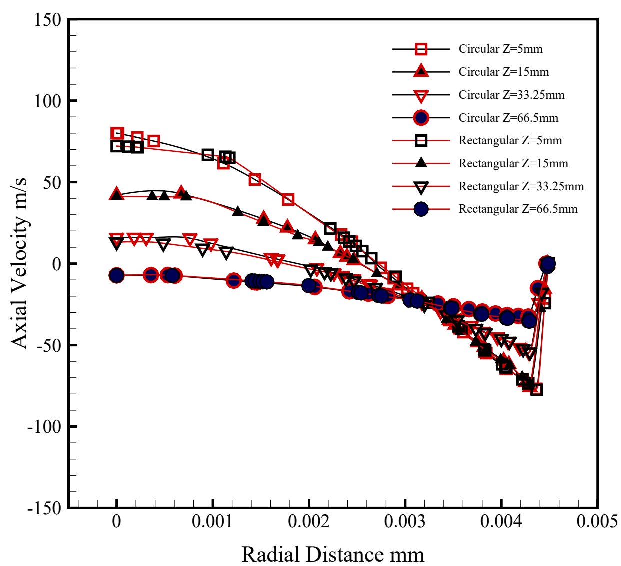


Fig.11 Axial velocity concerning radial distance of vortex tube

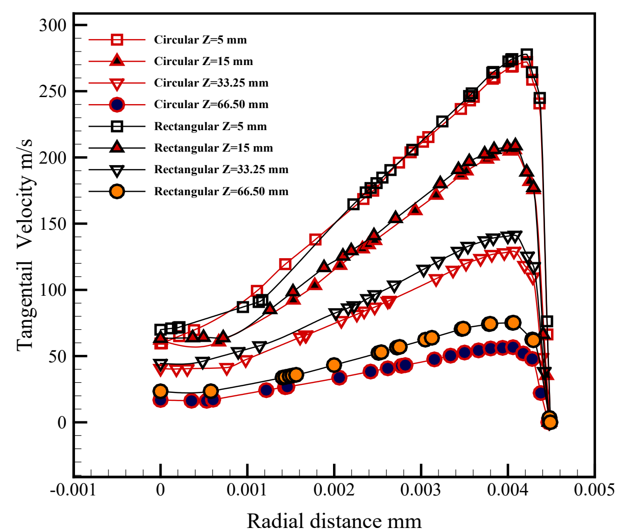


Fig. 12 Tangential velocity concerning radial distance of vortex tube

It was found that the maximum magnitude of both the velocities, i.e., axial and tangential velocity attained at the cold peripheral. The fluid velocity magnitude decreases as it moves towards the end of the vortex tube. According to the results, the velocity domain is dominated by tangential velocity inside the tube shown in fig.11 and 12. The results show that at the cold junction, the velocity remained high due to the incoming fluid having high kinetic energy (K.E.). Henceforward, as the flow transfers near the tube, the intensity of K.E. and pressure decrease at the hot junction. The sudden fluid expansion within the tube significantly elevates the axial velocity, as shown in fig.11. Here, the cold region is represented by negative and positive region shows the hot temperature separation.

The cooling power separation of vortex tube can be determine by;

$$Q_c = mC_p\Delta T_c \tag{4}$$

Where,

Q_c is the cooling power separation, kW
m is the mass flow rate of air at cold exit, kg/s
C_p is the specific heat capacity of air which is 1.005 kJ/kg K
$\Delta T_c$is the temperature difference between inlet and cold air K.

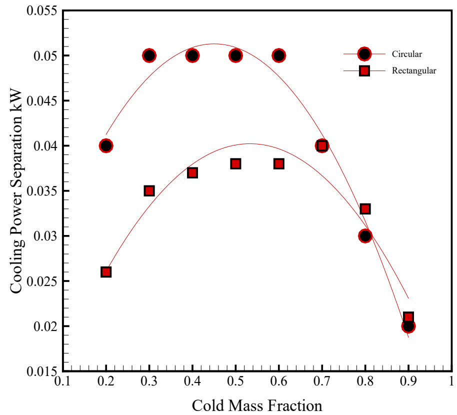


Fig. 13 Cooling power separation along with cold mass fraction

The cooling power separation was calculated at 4 bar for both the shapes of cold orifice vortex tubes. It was found that the highest magnitude of cooling power separation was achieved by a circular cold orifice vortex tube, i.e., 0.05 kW at 0.3-0.6 cold mass fraction. The same trend was observed in rectangular cold orifice vortex tubes with low cooling power separation magnitude, which is 0.035 kW at 0.3-0.6 cold mass fraction. The same trend can be observed in the research article of Skye, Nellis, and Klein [12]. The results show that as the cold mass fraction increases, the value of cooling power separation decrease, irrelevant to the shape of the cold orifice of the vortex tube. This is due to the pressure difference between the system and its surrounding, which cause the entrance of small air from the cold side. Therefore, it can be concluded that the cooling power separation can be considered with the cooling and heating effect of the vortex tube for various engineering applications.

7. Conclusion

The current study deals with the flow physics of vortex tube approaching the CFD method. The study investigated the rectangular shape of the cold orifice of a vortex tube. The obtained result was compared with a circular cold orifice at the same inlet pressure. The cold and hot temperature was determined for various cold mass fractions. The following conclusion has been made on the bases of the present study:

1. The present study determined the temperature separation effect considering the cold orifice shape. It was observed that the temperature separation is high affect by the shape of the cold orifice. The rectangular shape cold orifice generates high-temperature distributions compared to circular in the hot region at the high cold mass fraction.
2. The highest cooling power separation achieved by circular cold orifice vortex tube as compared to rectangular cold orifice vortex tube.
3. The maximum value of cold temperature separation was achieved by a circular shape cold orifice vortex tube, whereas at the hot region the maximum hot temperature separation was obtained through a rectangular shape cold orifice vortex tube.
4. The velocity and pressure are high at the centre and drop as the air displaces near the VT's hot junction in both the vortex tubes.
5. The temperature separation inside the tube is due to the kinetic energy irrespective of the cold orifice shape.
6. In addition, various fluid characteristics like axial and tangential velocity was discussed concerning to the radial distance in a VT. The reason behind the high and low velocity at the centre and wall surface respectively of hot tube was also discussed. The current work demonstrated an explanation for the temperature difference and flow physics inside a rectangular shape cold orifice vortex tube.
7. The energy exchange between the kinetic energy and angular momentum which generates turbulence, controls the flow, and causes the temperature difference inside the tube.

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