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DESIGN & FABRICATION OF VORTEX TUBE FOR INDUSTRIAL COOLING

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Certificate of research

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ABSTRACT

A cooling system is very important for both man and machine. In general vapor compression refrigeration system and vapor absorption refrigeration system are used for refrigeration purpose. Vortex tube cooling system is a non-conventional type of cooling system which is not used widely for cooling purpose. But it has many advantages over the conventional cooling system. This project attempt has been made to construct a counter flow vortex tube and its experimental setup has also been designed. Our objective is to check the performance of counter flow vortex tube by changing the various geometrical parameters such as Tube Length and diameter of hot end pipe and cold end pipe, Ratio of tube length over diameter and Vortex angle so that we increase the performance of the vortex tube. We had also predicted some of the experimental data that are available and observed the performance variation by changing working parameters at inlet such as temperature and pressure.

Introduction

The Vortex tube, also known as the Ranque-Hilsch vortex tube, is a mechanical device operating as a refrigerating or cooling machine without any moving parts, by separating a compressed air/gas stream into a low temperature region and a high one. Such a separation of the flow into regions of low and high temperature is referred to as the temperature (or energy) separation effect. Generally, the vortex tube can be classified into two types. One is the counterblow type (often referred to as standard type) and another is parallel or uni-flow type. The air emerging from the "hot" end can reach temperatures of 200 °C, and the air emerging from the "cold end" can reach - 50 °C. It contains the following parts: one or more inlet nozzles, a vortex chamber, a cold-end orifice, a hot-end control valve and a tube. When high-pressure gas is tangentially injected into the vortex chamber via the inlet nozzles, a swirling flow is created inside the vortex chamber. When the gas swirls to the centre of the chamber, it is expanded and cooled. In the vortex chamber, part of the gas swirls to the hot end, and another part exist via the cold exhaust directly. Part of the gas in the vortex tube reverses for axial component of the velocity and move from the hot end to the cold end. At the hot exhaust, the gas escapes with a higher temperature, while at the cold exhaust, the gas has a lower temperature compared to the inlet temperature.

1.1 WORKING OF VORTEX TUBE

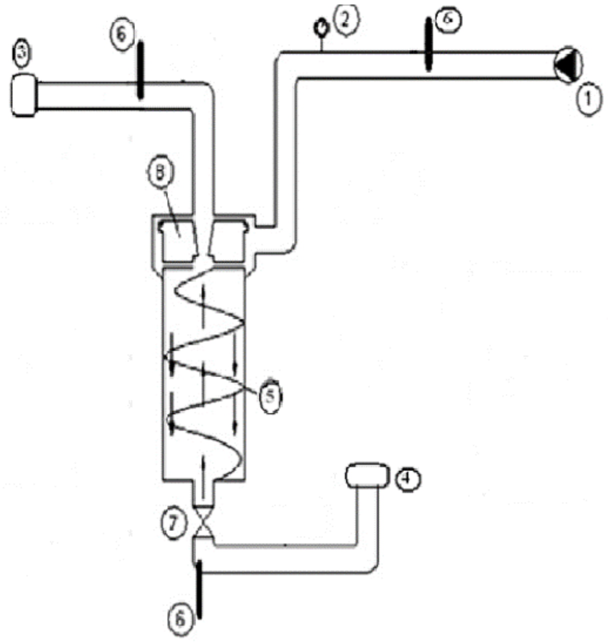

Figure 1.1 Working of vortex tube

1- Compressor
2- Inlet nozzle
3- Cold air outlet
4- Hot air outlet
5- Vortex tube
6- Digital temperature indicator
7- valve
8- orifice

Compressed air is passed through the nozzle as here; air expands and acquires high velocity due to particular shape of the nozzle. A vortex flow is created in the chamber and air travels in spiral like motion along the periphery of the hot side. This flow is restricted by the valve. When the pressure of the air near valve is made more than outside by partly closing the valve, a reversed axial flow through the core of the hot side starts from high-pressure region to low-pressure region. During this process, heat transfer takes place between reversed stream and forward stream. Therefore, air stream through the core gets cooled below the inlet temperature of the air in the vortex tube, while air stream in forward direction gets heated up.

The cold stream is escaped through the diaphragm hole into the cold side, while hot stream is passed through the opening of the valve. By controlling the opening of the valve, the quantity of the cold air and its temperature can be varied.

1.2 Classification

Two types of vortex tube used in industry are

- parallel flow
- counter flow

Because of wide applications of the latter, it is studied in the present work.

1.3 Geometrical parameters on vortex tube performance

- Inlet nozzles
- Tube length
- Tube shape
- Ratio of tube length over diameter
- Vortex angle
- Tube exits
- Diffuser

1.3.1 Parameters experimented on

- Tube Length
- Ratio of tube length over diameter
- Vortex angle
- Inlet nozzle

1.4 Optimization of Vortex Tube for Industrial Cooling

- Vortex tube has two outlet one is cold another is hot. Both can be used for Industrial purpose.
- Cold output will be used for cooling effect, constant temperature, HVAC system, machining process.
- Cold airflow and temperature are controlled by adjusting the slotted valve in the hot air outlet. Opening the valve reduces the cold airflow and the cold air temperature. Closing the valve increases the cold airflow and the cold air temperature.
- Hot output will be used for Industrial Heating, heating water tanks, hot tub and as a substitute for Geyser system.

Working Principle

2.1 Flow Structure of the Vortex Tube

In a vortex tube compressed air enters tangentially into it through one or more nozzles. One part of the flow rotationally passes alongside the wall and exits as hotter fluid from the hot end and the other part comes back from the hot end alongside the axis to the cold end and exits as colder flow. Geometry of the vortex tube including flow inlets, cold and hot outlets and associated flows including cold and hot streams are shown in fig –

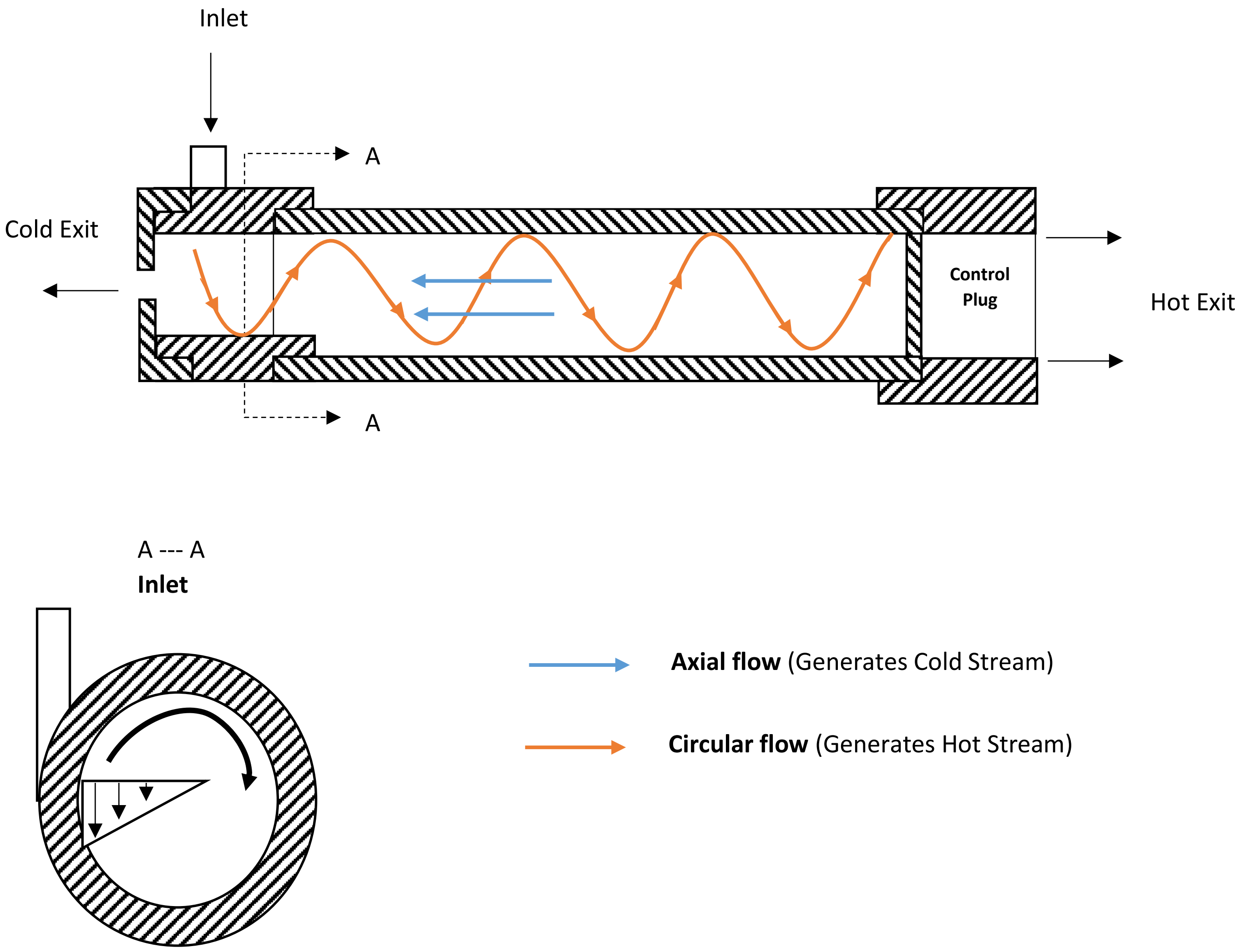

Figure 2.1 Flow Structure of the Vortex Tube

2.2 Working principle of a vortex tube

Based on the discussions above, the flow behaviour inside a vortex tube is summarised in detail as shown in Figures 2 and 3. This basic on which the temperature separation in a vortex tube can be explained is as follows: When compressed air is injected into the tube from the tangential inlet, it forms a highly vortical flow and moves to the end of the tube. The inner part of the flow moves towards the hot end and turns back in front part of the tube. This part of the flow gets expanded due to the low pressure in the central part of the tube and escapes from the cold nozzle at a lower temperature than the injected air. Small amount of the inner flow mixes with the multi-circulation and forms small vorticities that separate the cold flow and multi-circulations. Due to the pressure gradient in a vortex tube, the lowest temperature will be found in the central part of the flow near the injection port. After mixing with other clod flow, which has been inwardly turned back, the minimum temperature of the exhausted stream from the cold nozzle will be found to be higher than the lowest temperature inside the tube. The cold and hot regions are also shown in the above figures, and between them is the mixing and separating region. The peripheral part of the airflow escapes from the hot exit at a higher temperature than the inlet temperature and the inner part of the flow is forced back by the plug at the hot end. Due to the increase of the swirl velocity, the centrifugal force of the swirling flow increases and leads to the outwards flow of the central fluid. On its way to the cold end, the central flow moves outwards, mixes with the peripheral flow, and turns back to the hot end again. In this way, the central flow performs multiple circulations before being exhausted from the hot exit. Because of the strong swirling flow in the hot region of the tube, sub-cycles of the multi-circulation might be found in the principal multi-circulation. The temperature of the peripheral flow arises due to the partial stagnation and mixture induced by the multi-circulation. The maximum temperature should be found at the outwards turn back to the hot end of the central flow, i.e., about one third of the overall tube length distant from the hot end as discussed in The maximum temperature along the wall was also reported to be some distance from the hot exit.

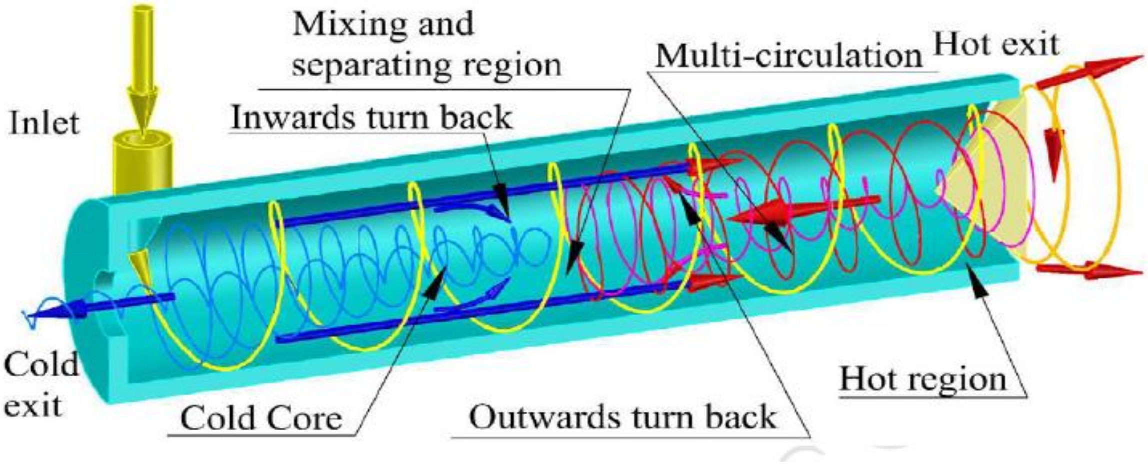

Figure 2.2 Flow Structure of the Vortex Tube (3D)

Based on this proposed flow behavior, the working principle of a vortex tube at variable cold mass flow ratio, which is generally controlled by adjusting the hot end plug, is discussed below. To perform an accurate analysis of the working process inside a vortex tube, the flow pattern is divided into several regions, which are the vorticities in the corner of the tube, the cold core, the peripheral flow, the mixing and separating region, and the hot region or multicirculation region. The vorticities in the corner of the tube are induced by the injected fluid and may be noticed as the secondary circulation when the cold exit is small. When the cold exit of the vortex tube is larger than a critical value (i.e.
dc/dt=0.62, here dc is the diameter of cold exit and dt is the diameter of the vortex tube), all the flow moving to the cold end will be exhausted from that exit and there will be no flow being forced back to form the vorticities in the corner. The cold core region locates near the injection point, and it is the region where expansion occurs and the temperature drops due to the pressure gradient of the forced vortex. The minimum temperature inside a vortex tube is always found in the central part of the cold core opposite the injection port. The size of the cold core varies in the vortex tube with different experimental parameters. The peripheral flow is that flow which moves in the peripheral layer and escapes from the hot exit. It mixes with the multi-circulations and leaves the tube at a higher temperature due to energy transformation from the kinetic energy of the peripheral flow, as discussed in the previous exergy analysis. The mixing and separating region (4) may be found between the inwards turn back flow in the cold core, and the outwards turn back flow of the multi-circulation in a vortex tube. This region ensures the best performance of an ideal vortex tube by preventing the mixture of cold and hot flow regions. In a vortex tube, which is not designed properly, the

mixing and separating region of the respective flow are not well delineated, and hence, this leads to a reduction in the separating performance. Due to the complexity of the flow condition, there has not been any theoretical analysis of the flow pattern in this region.
The multi-circulation locates near the hot end and causes the temperature rise of the working fluid in the process of stagnation and mixture with the peripheral flow. It is also indicated by the red and pink helix in, which show flow movement to the hot end and cold end, respectively. For a vortex tube with small hot exit, the central part of the multi-circulation region may move towards the cold end through the mixing region and mix with the cold flow in the cold core region. Hence, the temperature drop of the cold flow is reduced by this mixing.

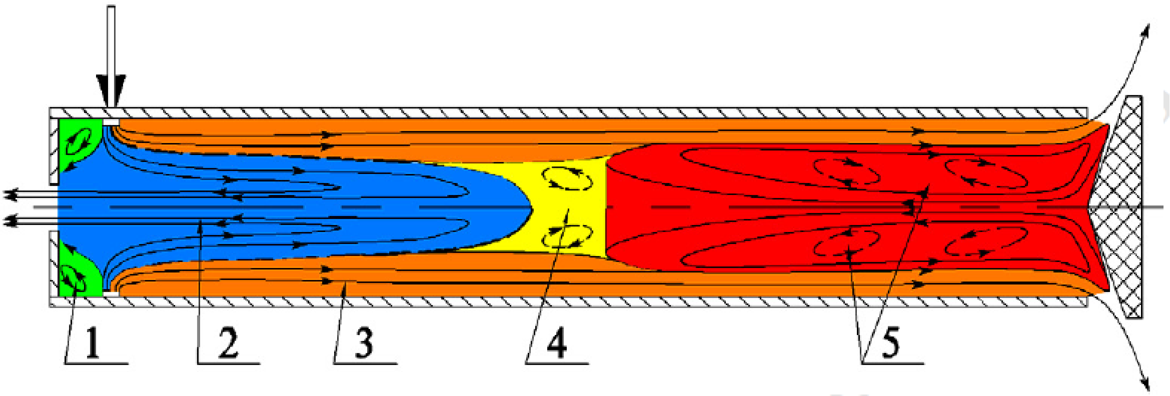

Figure 2.3 Divisional flow pattern inside a counter-flow vortex tube

When the hot exit of a vortex tube is relatively large, there will not be any flow forced back by the plug. Instead, all of the injected flow will escape from the hot exit. Due to the strong swirling flow, a low pressure region in the central part of the tube near the cold exit will be formed, reducing the extent of the temperature drop. Hence, entry of ambient air into the vortex tube through the cold exit by suction, can occur and may lead to more fluid from the hot end being exhausted than the injection. The inward suction of the ambient air has previously been reported by the authors due to this low pressure region near the cold exit. The temperature of the exhausted gas will show a small increase due to the mixture and friction effect, which is weakened both by the temperature drop near the injection point and entry of ambient air by suction. The flow inside the tube will perform as a forced vortex and decay towards to the hot end. The flow behavior in a vortex tube with a large hot exit, shows that only the peripheral flow in the vortex tube, as well as the sucked ambient air moving along the center exist under this condition.

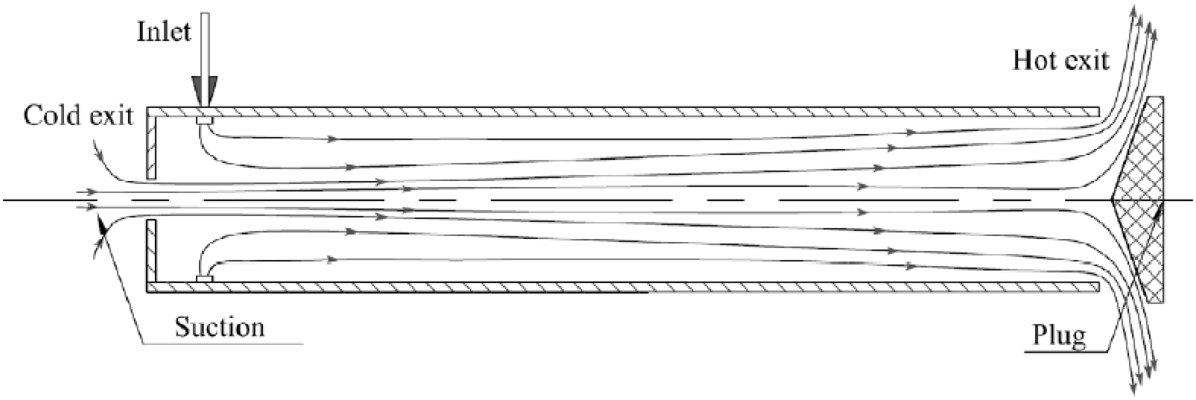

Figure 2.4 Flow structure in a vortex tube

When the area of the hot exit is reduced, there will be some gas escaping from the cold exit and as a result, less gas leaves from the hot end. Part of the peripheral flow will be forced back by the plug and multi-circulation with small scale will be formed. A transformation from forced vortex at the cold end to the irrotational vortex at the hot end will be observed. Partial stagnation and mixture due to this small scale multi-circulation causes a rise in the temperature of this flow, although the temperature in this region is lower than the maximum temperature generated by the vortex tube. The inner flow starts turning back because of the blockage by the multicirculation. Temperature drops in the cold core is caused by the pressure gradient in the tube, although there may be some suction of ambient air, which reduces the temperature drop at the cold exit, depending on the dimensions of the cold and hot exits. The vortex tube under this condition could generate cold and hot streams, and its likely flow structure inside the tube is shown in Figure.

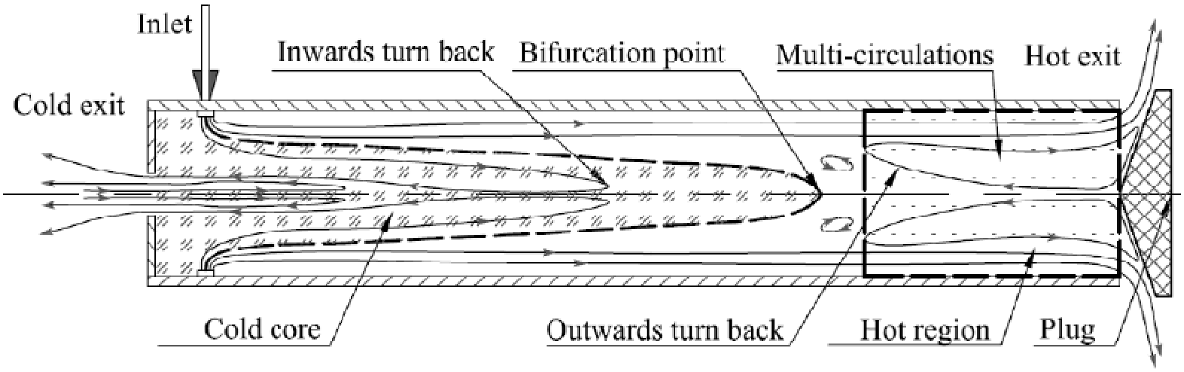

Figure 2.5 Flow structure in a vortex tube

Once the hot exit is further decreased, more cold stream and less hot stream will be exhausted from the vortex tube. At certain cold mass flow ratio, the pressure at the cold exit becomes greater than the ambient pressure; hence suction at the cold exit will no longer be observed. The temperature of the inner flow decreases due to the pressure gradient, and represents the minimum temperature within the vortex tube, and is the result of both the maximum volume of the cold core, and the lack of mixing the ambient air or the hot stream. Concomitantly, the temperature of the hot stream increases due to the increased scale of the multicirculation, which strengthen the effect of partial stagnation and mixture.

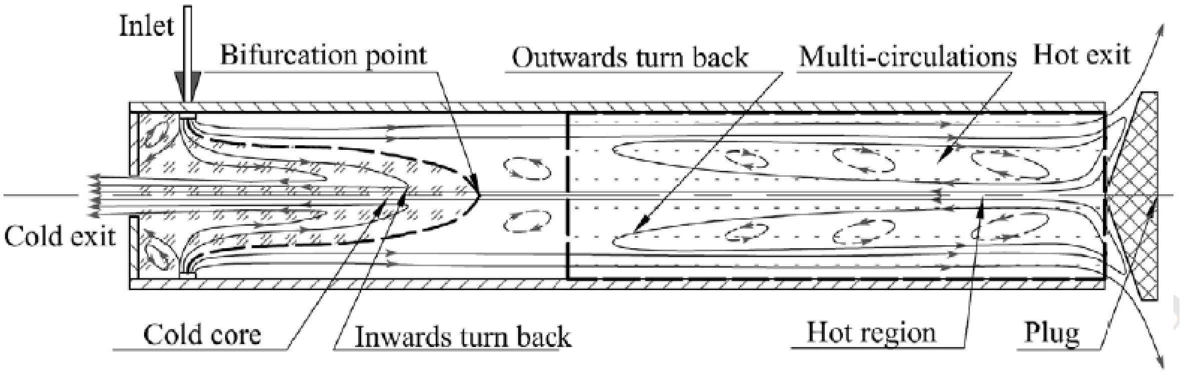

Figure 2.6 Flow structure in a vortex tube

If the cold mass flow ratio keeps increasing, a concomitant increase of the multicirculation and a decrease of the cold core region would be expected. Therefore, due to the smaller region for expansion and more gas in the cold region, the temperature drop of the cold stream would be reduced. As a result, the effect of partial stagnation and mixture is therefore strengthened by the increased scale of the multi-circulation, which leads to the increase of the hot stream temperature. Moreover, due to the decreased hot exit area, more gas will be forced back by the plug and subsequently, move to the cold end along the central part of the tube. Thus, part of the central flow may mix with the cold flow and escape from the cold exit. This mixture of two flows at different temperature causes the rise of cold temperature at the cold exit and weakens the cooling effect of the vortex tube. In condition when the hot exit of a vortex tube is blocked, all the injected gas leaves from the cold nozzle, i.e. the cold mass flow ratio equals 1, and the flow structure in the vortex tube is represented in Figure 13. It is seen from the Figure that the main part of the injected gas gets expanded in the cold core and is exhausted from the cold exit. In such a condition, part of the peripheral flow then moves to the hot end and forms the structure of multi-circulation in the rear part of the tube. Hence, the temperature of flow in the rear part of the tube still increases due to the partial stagnation and mixture in the multi-circulation region, which is indicated by the measured temperature of the tube wall at the hot end. It was reported that the temperature of the tube wall at the hot end had a 14 centigrade degree rise when the hot exit was blocked. As the cold core region decreased and the amount of the expanding stream increased, the temperature drop near the injection was not obvious as that in the vortex tube with other settings. The mixture of the high temperature stream coming from the multi-circulation region further reduced the temperature drop, which was reported as a 3.2 centigrade degree drop at the cold exit. The tube performance when the hot end is blocked has also been reported in others' studies.

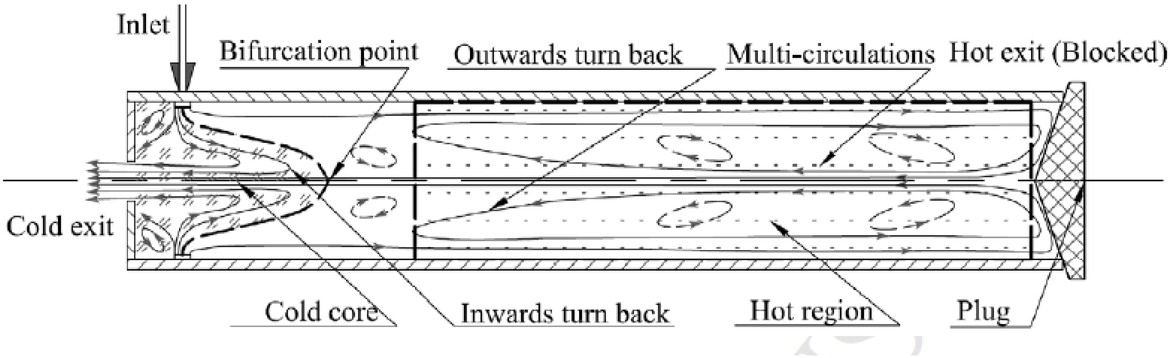

Figure 2.7 Flow structure in a vortex tube

According to the proposed explanation, the parameters influencing the temperature change as a function of the variable cold mass ratios discussed above, is in agreement with the experimental results reported. With regard to the temperature drop of the cold stream at a cold mass ratio from 0 to 0.3, the improving performance of the cooling effect may be caused by the decrease with the extent of ambient air suction, until such time the tube reaches its best cooling performance at a certain cold mass ratio. When the cold mass ratio is greater 0.3, the temperature of the cold flow increases with the increasing cold mass ratio. This is mainly due to the reduction of the cold core region and the increase of the hot stream emanated from the multi-circulation region. The temperature of the hot stream increases with the increase of clod flow ratio or decrease of the hot flow ratio. Furthermore, the increasing temperature is caused by stronger stagnation and mixture due to the increasing region of multi-circulation as discussed above. It should be noted that for a vortex tube having a cold mass ratio greater than 0.8, i.e. the settings between Figures 12 and 13, the decreased extent of the peripheral flow moving to the hot end, leads to the formation of a weaker region of multi-circulation. This may explain the reason for the decreasing temperature of the hot stream when the cold mass ratio is greater than 0.8. For the different vortex tubes employed in previous studies, different critical cold mass flow ratios were found. However, the similarities in the tendencies for change in the temperature profiles, show the reliability of these discussions and provide solid support for the proposed explanation.

Analysis

3.1 The heating effect in a vortex tube

The heating effect of a vortex tube could be induced by outwards energy transfer, including both thermal and kinetic energy, and partial stagnation of the swirling flow. As indicated in previous publication (Xue et al., 2010), the partial stagnation and mixture due to the flow structure located near the hot end, contributes significantly to the temperature rise in a vortex tube. At the hot exit of a counter-flow vortex tube, the outer layer of the peripheral flow escapes from the small gap between the control plug and the tube as represented by the yellow helix in figure 2. The inner part of the flow is forced back through the central region of the tube (pink helix) by the plug. On its way towards the cold end, the swirling flow moves outwards to the periphery, mixes with the peripheral flow, and then returns back to the hot end (red helix). In this way the flow structure, termed multi-circulation, is formed and its partial stagnation and mixture is the primary factor for the temperature rise. The flow structure in the rear part of a vortex tube, as in the area of multi-circulation.

3.2 The cooling effect in a vortex tube

The cooling effect of a vortex tube is identified in this research as the result of the sudden expansion of the working fluid near the injection port. When the fluid is injected into the vortex tube, the main part of the fluid rotates and moves along the periphery towards the hot end. Near the injection point, the inner part of the peripheral flow turns back and moves towards the cold exit. A cold core is formed near the injection due to the pressure gradient of the forced vortex, and the temperature drops due to the decreased pressure of the working fluid in this cold core. The flow behaviour in the cold part of a vortex tube can be seen in Figure 2, which shows the inwards turn back of the inner flow and the cold core. This explanation for the cooling effect is then validated in the following sections.

3.3 Estimation of the temperature drop

The temperature drop in a vortex tube is estimated based on the measured velocity profiles. The flow near the injection of a vortex tube performs as a forced vortex and the pressure distribution can be expressed as:

$$\frac{dp}{dr} = \rho\omega^2 r$$

Where, $\frac{dp}{dr}$ = pressure gradient in the radial direction, ρ = local density of the flow, ω = angular velocity, and r = radial location.

Using the state equation:

$$\rho = \frac{\mathrm{p}}{\mathrm{RT}}$$

The pressure gradient is written as:

$$\frac{RT}{p}\frac{dp}{dr} = \omega^2 r$$

For the adiabatic process, the relationship between the temperature and pressure of the control volume is:

$$p^{1-\gamma}T^{\gamma} = C$$

Substituting the relationship into the pressure gradient, it becomes:

$$RCp^{-\frac{1}{\gamma}}dp = \omega^2 r dr$$

Integrate the equation and substitute peripheral properties, including density, static pressure and temperature at the inlet as ρ_{in} , p_{in} *and* T_{in} respectively. The radius of the vortex tube and the heat capacity ratio of the fluid are R_t and γ, respectively.

The difference between the peripheral temperature and local temperature, which is also known as the temperature drop in a vortex tube, can be derived as:

$$T_{in} - T_i = \frac{\gamma-1}{2R\gamma}\omega^2(R_t^2 - r^2)$$

As the geometrical parameters of the vortex tube vary, the flow at different temperatures in the vortex tube, mix and escape as the cold stream at a higher temperature than the minimum temperature calculated by this equation.

Due to the different experimental conditions, a non-dimensionalized value of the temperature drop ratio (ε) was calculated using the relationship between the actual temperature drop and the calculated maximum value using the above-mentioned method and is defined as:

$$\varepsilon = \frac{\Delta T_{actual}}{\Delta T_{estimated}}$$

3.4 Geometrical effects on the tube performance

The effects of the geometrical parameters on vortex tube performance have been investigated by many researchers, using both experimental and numerical methods. It has been reported that when different geometrical parameters were selected for testing a vortex tube, such as length and diameter of the tube, shape and size of the inlet nozzle, cold and hot exits, and structure of the tube, the temperatures of the generated cold and hot streams varied. However, there has not been an explanation that can be used to explain all the effects of the variable parameters on the tube performance. Therefore, based on the explanation proposed in this study, the geometrical effects are discussed in this paper.

3.4.1 Tube Length

The effects of tube length, tube diameter and ratio of tube length over tube diameter were summarized. It was reported that the length of the tube should be longer than a critical length to achieve significant temperature separation within the vortex tube. When the vortex tube is shorter than the critical value, the separating vorticities between the cold core and multi circulation region became weaker or even disappear, and the cold flow will subsequently mix with the hot flow from the multi-circulation region. Hence, the temperature separation in a very short vortex tube will not be significant.

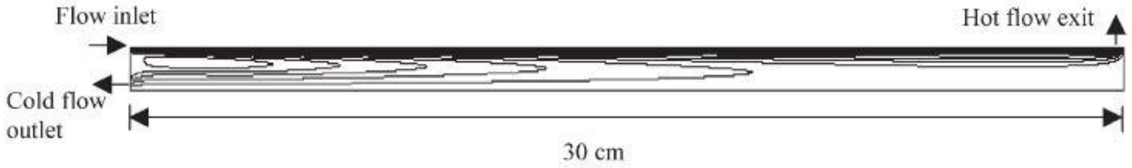

Figure 3.1 Tube Length

When the length of a vortex tube approximates or is longer than the critical length, the separation of the cold region and the multi-circulation region, i.e., the hot region, is ensured by the tube length and provides a better performance of the temperature separation. The critical length is different for the vortex tube with different tube diameter.

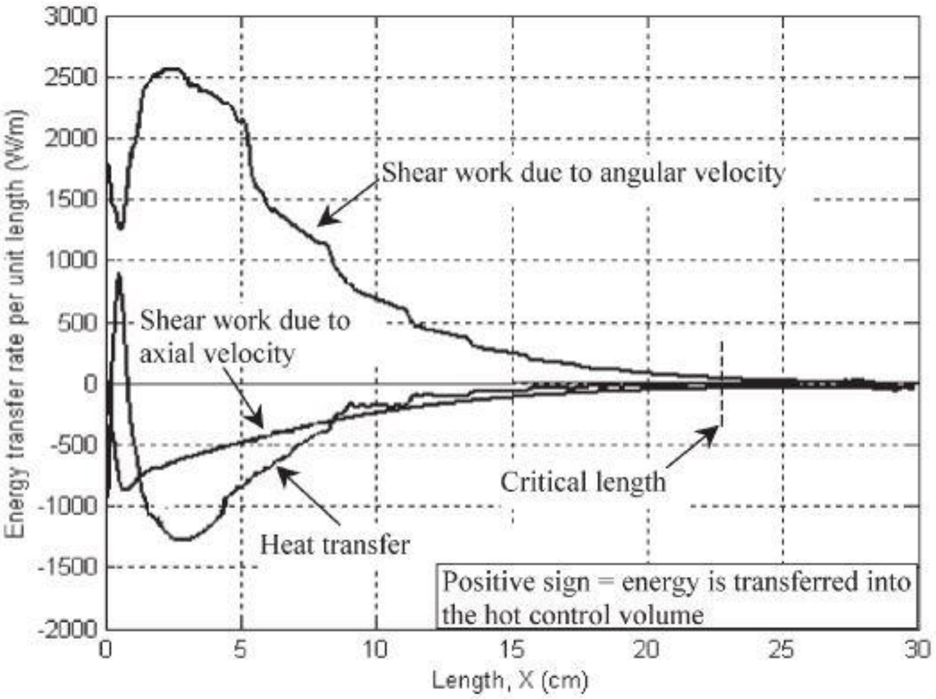

Figure 3.2 The rate of heat and work transfer per unit length along the control surface separating the hot and cold control volumes

3.4.2 Ratio of tube length over diameter

It has been reported that the ratio of tube length over diameter needs to be greater than 20 in order to have significant temperature separation in a vortex tube and this finding agrees with the current study. Once the ratio is greater than 45, it was reported that there is no further effect on the performance of the vortex tube.

This is likely due to the fact that the cold core region and the multi-circulation region have been fully separated when the ratio of length over diameter is 45. Therefore, it does not apparent that further lengthening of the vortex tube has any influence on the tube performance.

The ratio of length over diameter maintained in this experiment is 30.165 (490/16)

3.4.3 Vortex angle

It has been reported that vortex angle had negative effects on the magnitude of the temperature differential achieved. Based on the proposed explanation, vortex angle leads to a decrease of the tangential velocity and an increase in the axial velocity. Since both the temperature drop and temperature rise are caused by the strong swirling flow, the decrease of the tangential velocity is the reason for the reduction of temperature separation in a vortex tube with a vortex angle generator installed.

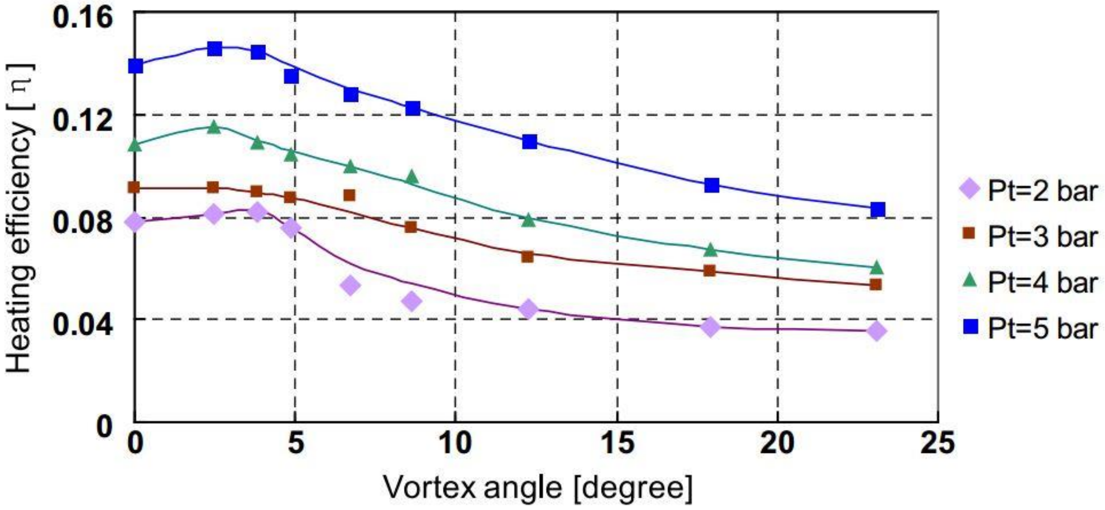

Figure 3.3 Heating efficiency of the vortex tube versus vortex angle.

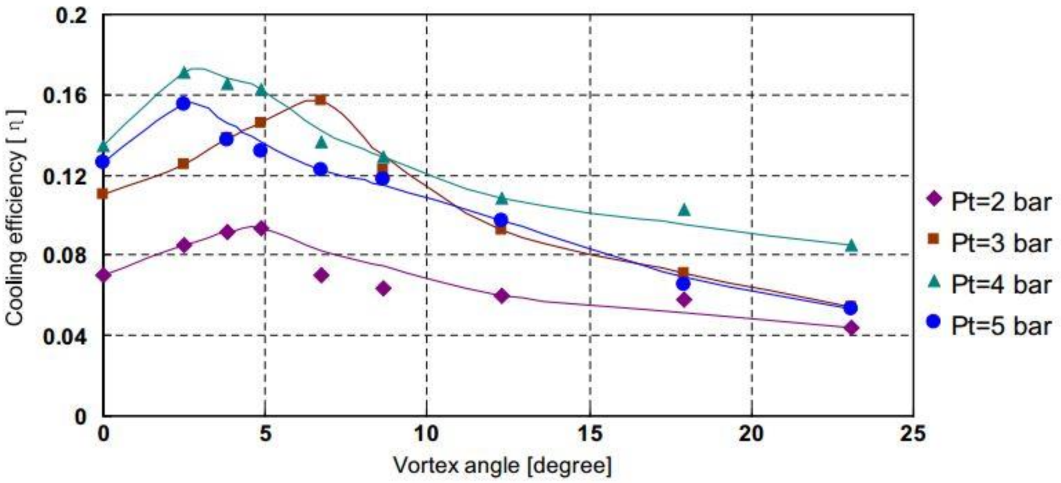

Figure 3.4 Cooling efficiency of the vortex tube versus vortex angle.

3.4.4 Inlet nozzle

The strong swirling flow, which is the reason for the temperature separation in the vortex tube, is generated by the injected high speed fluid through the inlet nozzle. Therefore, the inlet nozzle, which exhibits good characteristics in generating the swirling flow, is the primary component in generating the two streams which result in large temperature difference within the vortex tube. The dimension of inlet nozzle cannot exceed a critical value, in order to generate the strong swirling flow.

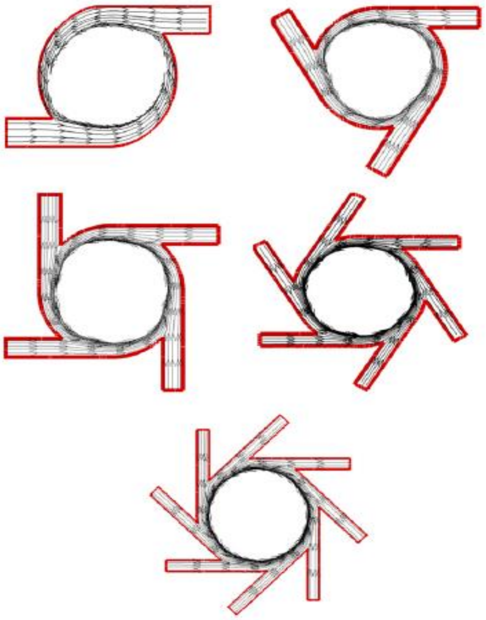

Figure 3.5 Arrangements of inlet nozzles of a vortex tube with 2, 3, 4 and 6 nozzles.

3.5 AIR MOVEMENT IN VORTEX TUBE

High pressure air enters into inlet enters the annular space around the generator. It then enters into the nozzle where it loses part of its pressure as it expands and increases the velocity. The nozzle is aimed so that the air is injected tangentially at the circumference of the vortex generation chamber. All of air leaves the vortex generation chamber and goes into the hot tube. It makes these choices because the opening to the hot tube is always larger than the opening to the cold tube. Centrifugal force keeps the air near the wall of the hot tube as it moves towards the valve at the end. By the time the air reaches the valve it has a pressure somewhat less than the exit pressure at the nozzle, but more than atmospheric. It is always true that the pressure just behind the control valve is higher than the cold outlet pressure.

3.6 EFFECT OF TEMPERATURE SEPRATION

The air in the hot tube has a complex movement. An outer ring of air is moving toward the hot end of the tube and an inner core of air is moving toward the cold end. Both streams of air are rotating in the same direction. More importantly, both streams of air are rotating at the same angular velocity. This is because intense turbulence at the boundary between the two streams and throughout both streams locks them into a single mass as far as rotational movement is concerned. The inner stream is a "forced vortex" which is distinguished from a "free vortex" in that its rotational movement is controlled by some outside influence other than the conservation of angular momentum. In this case, the outer hot stream forces the inner (cold) stream to rotate at a constant angular velocity. In a simple whirlpool a free vortex is formed. As the water moves inward, its rotational speed increases to conserve angular momentum. Linear velocity of any particle in the vortex is inversely proportional to its radius. Thus, in moving from a radius of one unit to a centre point at a radius of 1/2 unit, a particle doubles its linear (tangential) speed in a free vortex. In a forced vortex with constant angular velocity, the linear speed decreases by half as a particle moves from a radius of 1 unit to a centre point at a radius of 1/2 unit. In the situation above, particles enter the centre with four times the linear velocity in a free vortex compared with a forced vortex. Kinetic energy is proportional to the square of linear velocity, thus the particles leaving the centre of the forced vortex have 1/1 6th the kinetic energy of those leaving the centre of the free vortex in this example. In other words the air in the vortex tube has a complex movement. An outer ring of air is moving towards the hot end and an inner core of air is moving towards cold end.

Both streams of air are rotating in the same direction. More importantly, both streams of air are rotating with same angular velocity. This is because of intense turbulence at the boundary between the two streams and throughout both streams locks them into a single mass so far as rotational movement is concerned. Now a proper term for inner stream would be “forced vortex”. This is distinguished from a “free vortex” in that its rotational movement is controlled by some outside influence other than the conservation of angular momentum. In this case the outer hot stream forces the inner (cold) to rotate at a constant angular velocity. This is why hot end temperatures increase as cold fractions increase, and cold end temperatures decrease as cold fractions decrease.

3.7 VORTEX TUBE PERFORMANCE

In the vortex tube air that rotates around an axis (like a tornado) is called a vortex. Vortex Tube creates cold air and hot air by forcing compressed air through a generation chamber which spins the air centrifugally along the inner walls of the Tube at a high rate of speed (10, 00,000 RPM) toward the control valve. A percentage of the hot, high-speed air is permitted to exit at the control valve. The remainder of the (now slower) air stream is forced to counter flow up through the center of the high-speed air stream, giving up heat, through the center of the generation chamber finally exiting through the opposite end as extremely cold air. Vortex Tubes generate temperatures down to 40°C below inlet air temperature. A control valve located in the hot exhaust end can be used to adjust the temperature drop and rise for Vortex Tube.

3.8 THERMO DYNAMICAL ANALYSIS OF VORTEX TUBE

The cold flow mass ratio (cold mass fraction) is the most important parameter used for Indicating the vortex tube performance of RHVT. The cold mass fraction is the ratio of mass of cold air that is released through the cold end of the tube to the total mass of the input compressed air. It is represented as follows:

$$\mathrm{E} = \frac{m_c}{m_i} = \frac{T_i - T_h}{T_c - T_h}$$

Where, mc represents the mass flow rate of the cold stream released, mi represents the inlet or total mass flow rate of the pressurized air at the inlet.

Therefore, E varies in the range of 0-1.Cold air temperature difference or temperature reduction is defined as the difference between inlet flow temperature and cold air temperature:

$$\Delta T_c = T_i - T_c$$

Where Ti is the inlet flow temperature and Tc is the cold air temperature. Similarly, hot air temperature difference is defined as:

$$\Delta T_h = T_h - T_i$$

And the expansion been isentropic from inlet of the nozzle to the exit pressure and the air to behave like an ideal gas, isentropic efficiency is given by

$$\eta_{is} = \frac{T_i - T_c}{T_i - T_{is}}$$

For Isentropic expansion the exit temperature

$$T_s\text{-}T_i = \left(\frac{p_i}{p_o}\right)^{\frac{\gamma-1}{\gamma}}$$

Where, p_o is the exit pressure of the cold air i.e. atmospheric pressure (p_a) at outlet.

$$Q_c = m_c C_p (T_c - T_i)$$

Since cooling and heating streams are obtained simultaneously the heating effect produced by the vortex tube is give as:

$$Q_h = m_h C_p (T_h - T_i)$$

Since RHVT can be used as a cooler and heater simultaneously hence both the effect that Cooling effect and heating effects are considered. The COP of the system is calculated accordingly. The coefficient of performance of refrigerator is defined as the ratio of refrigerating effect produced by the system to the work done on the system. In the conventional vapour compression refrigeration (VCR) system work input or power is the work of compression or the compressor work. But, the vortex refrigeration systems are used where compressed air or gas is available. Making analogy to the VCR system, the work of compression from the exit/atmos. i.e. from pe to pi by a reversible isothermal process, the COP of the system is given as:

$$(COP)_{ref} = \frac{1}{\left(\frac{p_i}{p_o}\right)^{\frac{\gamma-1}{\gamma}} - 1}$$

In the above relation the pressure drop in the supply pipe has been neglected and the pressure at the exit of the cold and the hot air in the vortex tube are assumed to be atmospheric.

3.9 EFFICIENCIES OF THE VORTEX TUBE

The various efficiencies of Vortex tube:

1. Thermal efficiencies: The RHVT can be used not only as a cooler, but also as a heater. So the definition of the efficiency should consider both effects. For different applications, different efficiencies are used. The coefficient of performance (COP) of a cooler is normally defined as the cooling power Qc gained by the system divided by the work power P input. So the COP of the cooler, denoted by COP is expressed as:

$$\mathrm{COP}= \frac{Q_c}{P}$$

Here the cooling power can be calculated according to the cooling capacity of the cold exhaust gas (e.g. the heat necessary to heat up the cold exhaust gas from the cold exhaust temperature to the applied temperature to the applied temperature. Here Tin is chosen.)

$$Q_C= M_C\, C_P\, (T_{in} - T_c)$$

2. Carnot Efficiency: The Carnot COP is the maximum efficiency for all heat engines. So, it is also the maximum for the RHVT system. The COPs for Carnot cycles are:

$$\mathrm{COP}= \frac{T_{in}}{T_{in} - T_c}$$

Design and Fabrication

4.1 MATERIAL AND DESIGN

Vortex tube generally using three materials for its construction namely:

- Stainless Steel
- Aluminium
- Plastic

It depends on its function to use for cooling purpose or for heating. Generally it is made up of stainless steel because of its high thermal conductivity and better corrosion resistance but because of its heavy weight it lags behind the aluminum. On the other hand aluminum is also used for constructing vortex tube because it may have good thermal conductivity and light weight. Plastic is used where the weight required is very less and the hot fluid temperature is also very less because it may not have high thermal conductivity as compared to the other two.

The Design of vortex tube is not very much complicated because it may not require any moving parts. The design of vortex tube depend on its requirement just like the place where it is used either it is used in vehicles or in mines. But the design aspect is important because we may require more and more cooling so for that we may need to change the ratio of length to diameter because of changing that we may acquire cool air according to our need.

We have used Stainless Steel for tubes in this project. Some small parts are made of Mild Steel.

4.2 Specification

- **Cold Outlet:** Material – Stainless Steel & Mild Steel
  Diameter – 10 mm

- **Inlet Hub:** Material – Mild Steel
  Small Diameter – 10 mm ; Big Diameter – 19 mm

- **Main Tube:** Material – Stainless Steel
  Diameter – 16 mm ; Length – 470 mm

- **Hot Outlet:** Material – Stainless Steel
  Diameter – 22 mm; Length – 102 mm

- **Hot End Valve:** Material for Head – Mild Steel
  Material for Rod – Nickel Plated Mild Steel
  Small Diameter – 10 mm ; Big Diameter – 17.5 mm;
  Length – 77 mm

- **Tube Thickness:** 3 mm

4.3 Design of Vortex Tube

The design are done in Solid Works 2017. All dimensions used for design are calculated and analyzed from analytical data.

4.3.1 Cold Outlet

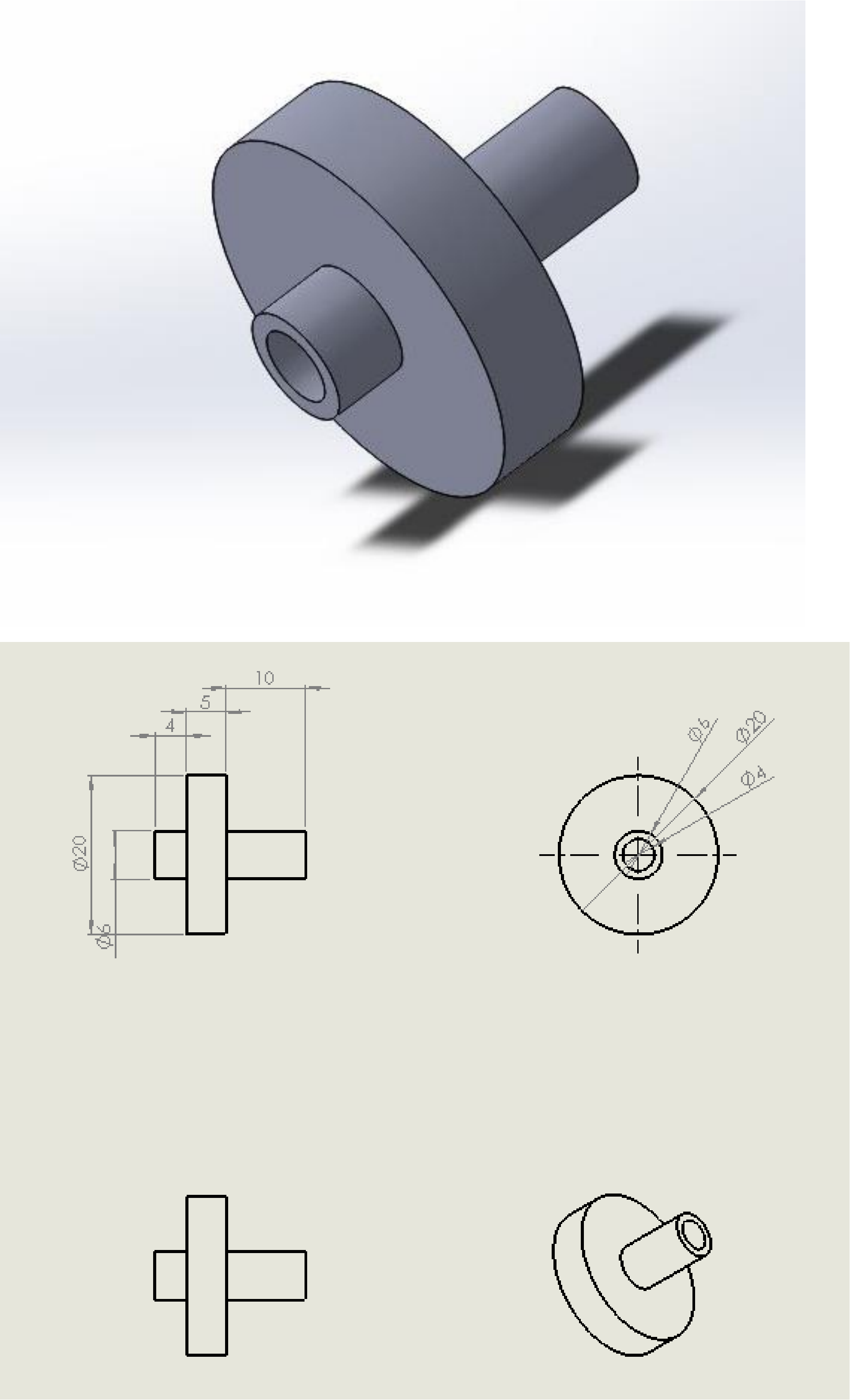

Figure 4.1 Cold Outlet (with dimension)

4.3.2 Inlet Hub

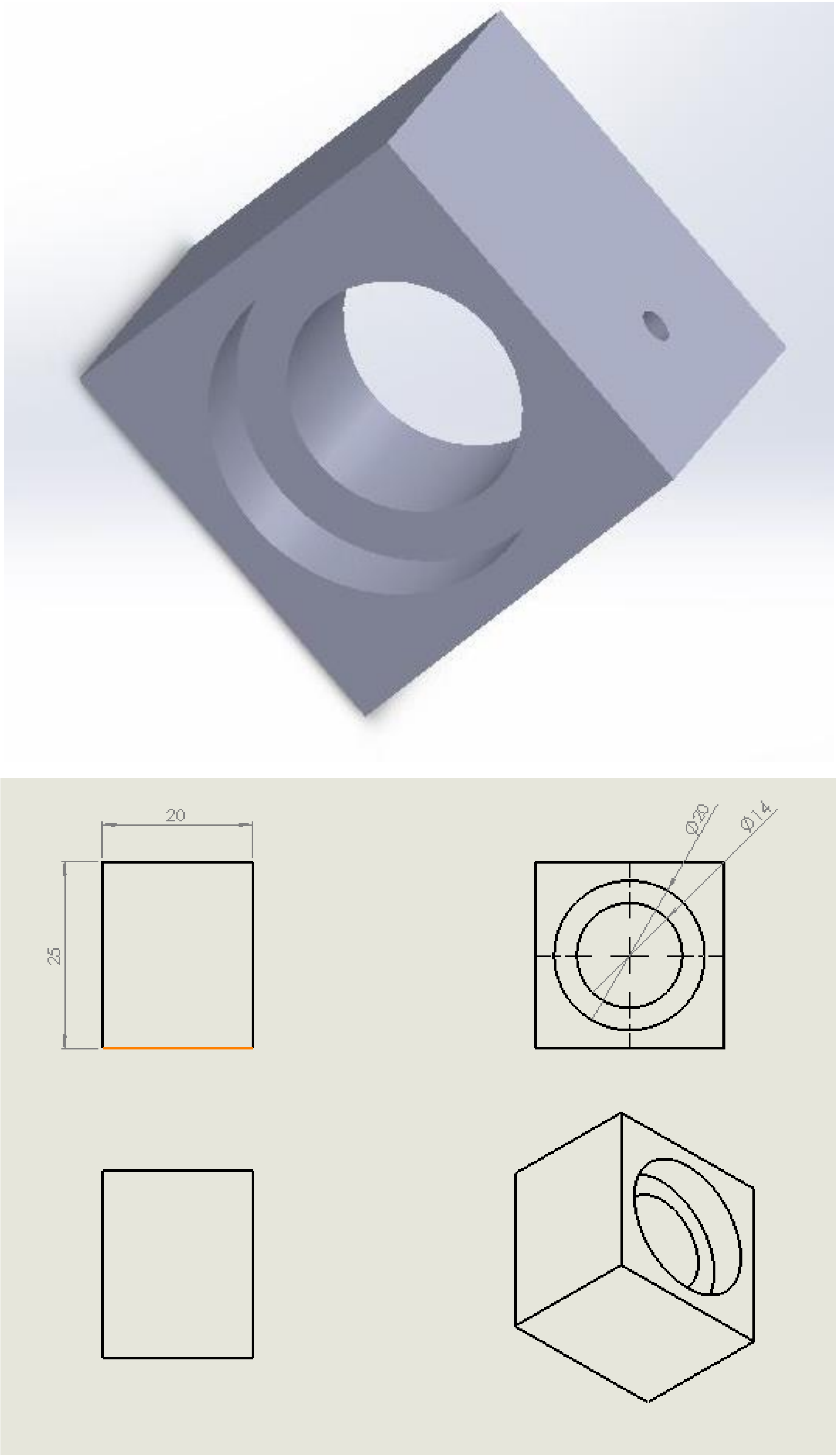

Figure 4.2 Inlet Hub (with dimension)

4.3.3 Main Tube

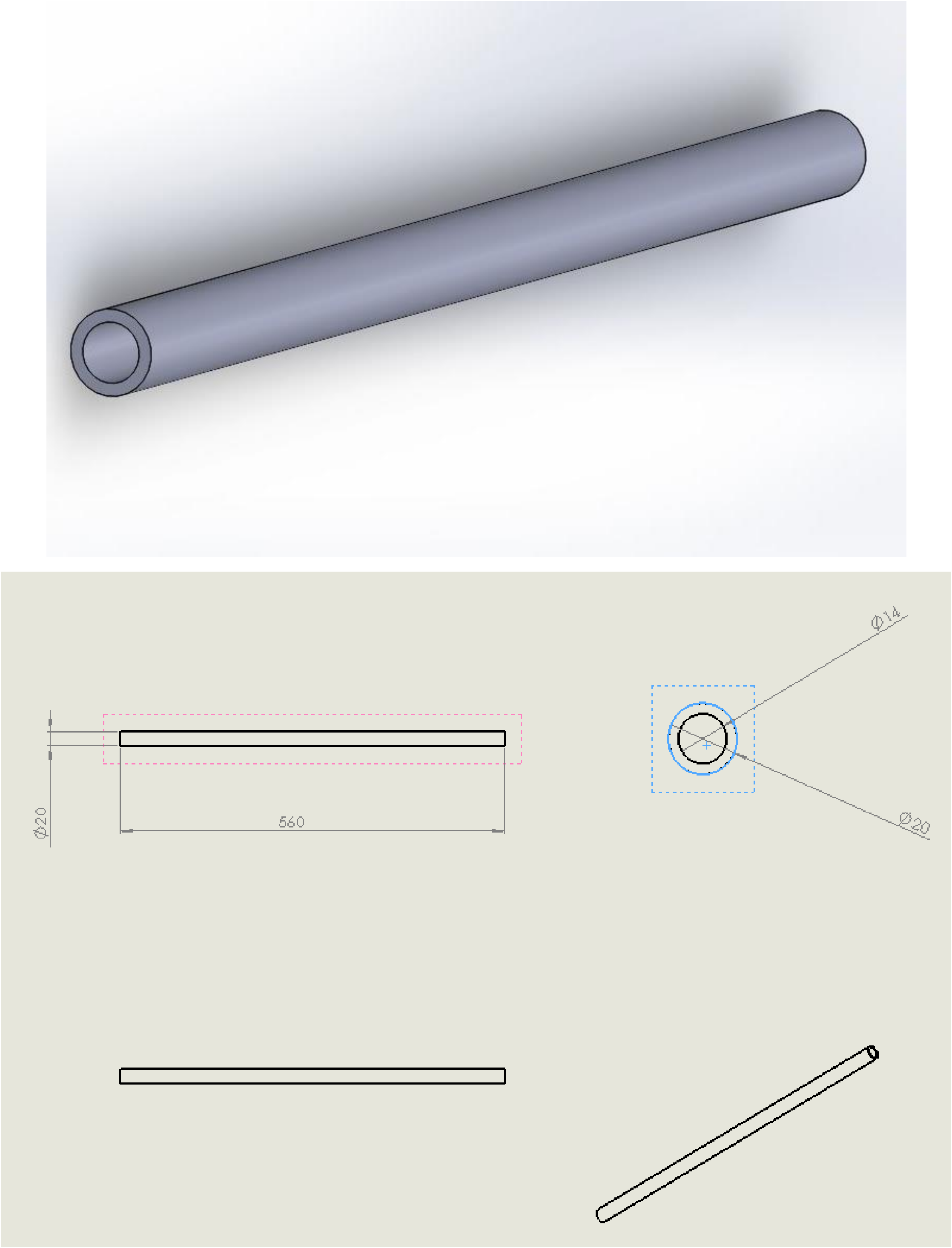

Figure 4.3 Main Tube (with dimension)

4.3.4 Hot Outlet

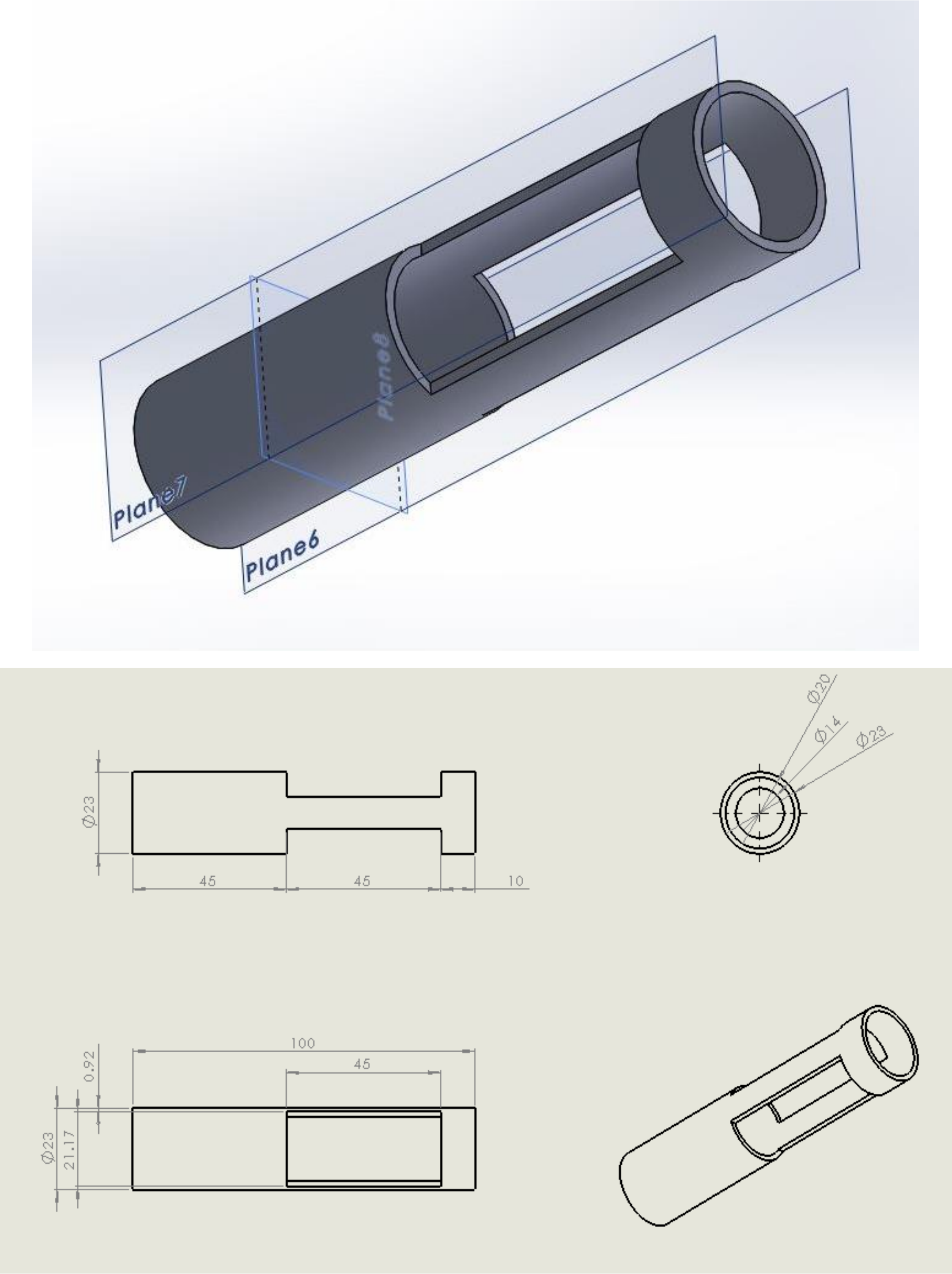

Figure 4.4 Hot Outlet (with dimension)

4.3.5 Hot End Valve

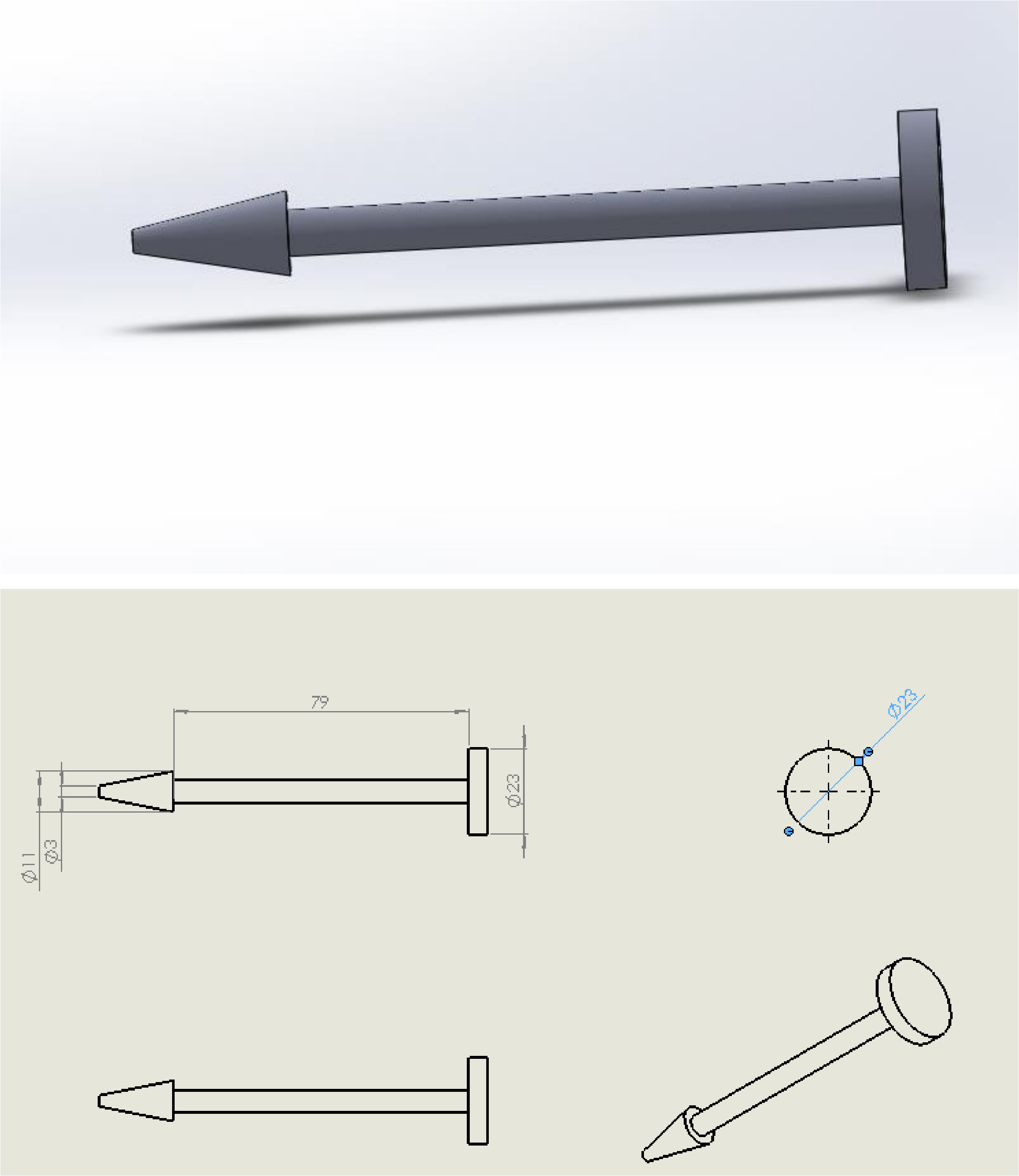

Figure 4.5 Hot End Valve (with dimension)

4.3.6 Vortex Tube (3D-view & Sectional view)

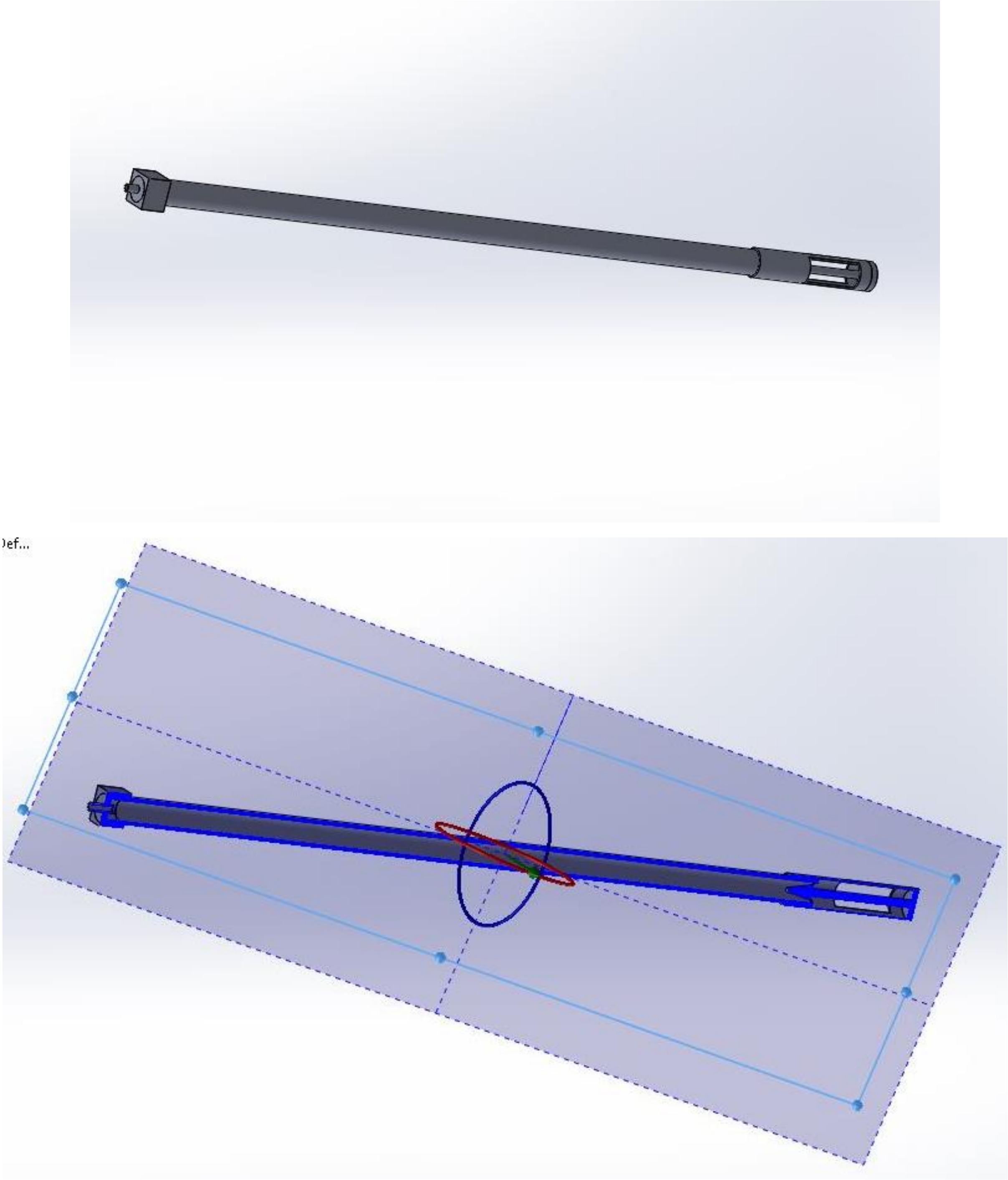

Figure 4.6 Vortex Tube (3D-view & Sectional view)

4.3.7 Vortex Tube (Experimental Setup)

Figure 4.7 Vortex Tube (Experimental Setup)

CONCLUSION

In this work an attempt is made to focus on the flow behavior inside a counter-flow vortex tube aiming to locate the dominant reason for the temperature separation in a vortex tube. Variable geometrical parameters have been tested in the experiment, and their effects on the temperature separation in the vortex tube are discussed. The inner stream is having a forced vortex flow and the outer stream is having free vortex flow. In a vortex flow as the radius is decreasing the linear velocity of the fluid also decreases hence kinetic energy decreases and this decrease in kinetic energy is converted in heat which is dominant reason for the temperature separation in a vortex tube. We have observed the performance variation by changing working parameters at inlet such as temperature and pressure and found out as is decreasing we obtain colder air. We had determined that we are getting colder air when we used smaller size of hot end pipe.

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