A Case Study of Vortex Tube under Different Cold Mass Fractions

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ABSTRACT

This article discusses the case studies performed on the vortex tube based on distinct conical valve displacements and its nature of size in order to improve the vortex tube's design characteristics. By doing simulations to determine the temperatures of the cold and hot exits at a constant pressure of 5bar. This study investigates how the cold mass fraction alters with regards to variations in conical valve displacement as well as varying lengths of the tube for the two distinct types of conical valves (sharp & blunt cones). The graphs compare the variations in cold mass fraction for simulation and theoretical results.

Keywords –Blunt& Sharp Conical Valves, Cold Mass Fraction, Cold Exit Temperature, Hot Exit Temperature, Inlet Temperature, Inlet Pressure, Length Of The Tube, Mass Flow Rate

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INTRODUCTION

The vortex tube was invented in 1931 by French physicist Georges J. Ranque It was rediscovered by PaulDirac in 1934 while he was searching for a device to perform isotope separation see helicon vortex separation process Germany physicist Rudolf Hilsch [de] improved the design and published a widely read paper in 1947 on the device, which he called a Wirbelrohr (literally, whirl pipe). In 1954,Westley. Published a comprehensive survey entitled ‘‘A bibliography and survey of the vortex tube’’, which included over 100 references. In 1951 Curley and Mc Gree, in 1956 Kalvinskas, in 1964 Dobratz, in 1972 Nash,and in 1979 Hellyar made important contribution to the RHVT literature by their extensive reviews on the vortex tube and its applications. From 1952 to 1963, C. Darby Fulton, Jr. obtained four U.S. patents relating to the development of the vortex tube. In 1961, Fulton began manufacturing the vortex tube under the company name Fulton Cryogenics. Ratnesh Sahu et al.[1] A vortex tube uses the second rule of thermodynamics, which demonstrates how energy degrades from being of better quality and quantity to being of lower quality and quantity. Manisha. V. Makodeet al. [2] explains some experimental and CFD analytical work carried out on the various nozzle diameters. Comparing the CFD model to experimental measurements using various diameters (D, 2D, 0.5D, 0.25D, and 0.125D), concluded that tiny diameters perform the poorest. J. Prabakaranet al. [3] Inhis study, the impact of orifice diameter and intake pressure is examined and discussed. The temperature differential between the cold end and the hot end grows as the incoming pressure rises.

The Carnot COP decreases as the intake pressure rises. R. Madhu Kumar et al. [4] Analysis is done on the conical hot tube's impact on the Vortex tube's COP, cold temperature decline, and hot temperature increase. Increases in input air pressure result in a rise in the cold drop temperature, Tc. With an increase in incoming air pressure, the hot temperature rises. An increase in intake pressure leads to a rise in the COP of the vortex tube. The performance of the vortex tube is better for the conical hot tub. The best performance is provided by opening the end gate at its ideal value. In order to achieve greater temperature decreases, the influence of nozzle design is more crucial than the cold orifice design. H.R. Thakareet al. [5] The RHVT's small size makes it extremely difficult to forecast its internal temperature, pressure, and flow field. Using turbulence models like the Standard k-model, RNG k-model, Realizable k-model, Large Eddy Simulation Technique (LES), etc., many scholars have attempted this investigation. To avoid being monotonous, care has been taken to investigate a variety of flow physics-related factors inside RHVT. Dr. Ing. Ramzi Raphael Ibraheem Barwari et al.[6] The performance of a uni-flow vortex tube was studied using two nozzles with a constant nozzle diameter (dn = 6.5 mm) and varying inlet air pressure (Piabs) as well as cold air mass ratio (Y) within the ranges of (Piabs=2-6 bar) and (Y=0-1) sequentially. The investigations revealed an ideal configuration for a uni-flow vortex tube that provided high energy separation for cone valve diameters of 12, 20, 15, and taper. Regarding the 10 mm diameter vortex tube, the cone valve diameter that produced high energy separation was (dc= 8 mm) with a number of nozzles (N = 2), (dn= 6.5 mm). E. Torrella et al. [7]

Three independent experimental tests that were validated by the device's energy balance are included in the study as an investigation of the energy performance of an air vortex cooling tube under changes in the parameters of the air inlet. The impact of the air inlet pressure on the vortex tube was with an emphasis on the measurement of temperature fluctuations in the output cold stream and in the cooling capacity when the cold flow fraction varied. Second, conducted an investigation not previously reported in the literature by looking at the fluctuations in air entry temperature at the vortex tube under various cold flow fractions. The performance of the vortex tube is also examined in both cases of insulation provision and absence. Jaykumar D. Golhar et al. [8] In his study, experimental data on energy separation in vortex tubes for various nozzle diameters, with all other geometrical parameters held constant are presented. Experimental evidence shows that the nozzle diameter has a significant impact on cooling and separation performance. The most significant finding in his research is the existence of an ideal nozzle diameter for vortex tube performance. Mahyar Kargaranet al. [9]An experimental investigation has been carried out to ascertain the impact of geometrical parameters on the performance of vortex tubes with air also being employed as a working fluid. The best parameters for the cold orifice diameter to the VT inlet diameter (d / D) and the length of the VT to its inlet diameter (L / D) for this experiment were proposed in order to maximize the efficiency of a vortex tube.

Working Principle

A vortex is a swirl of air that swirls around an axis like a tornado. A vortex tube generates cold and hot air by driving compressed air through a generation chamber, which rapidly spins the air into a vortex. When the high-speed air spins along the inner walls of the tube towards the control valve, it warms up. A portion of the heated, high-speed air is allowed to depart through the valve. The remaining (slower) air stream is forced to counter flow up through the center of the high-speed air stream in a second vortex. When the slower moving air spins up the tube, it releases energy in the form of heat and cools. The interior counter flow vortex exits as extremely cold air at the other end. The temperature reduction along the vortex tube was experimentally proven to be precisely proportional to the input pressure.

Design

In general, there are two design features associated with a vortex tube namely; maximum temperature drops vortex tube design for producing small quantity of air with very low temperature and maximum cooling effect, vortex tube design for producing large quantity of air with moderate temperatures. The cold mass fraction has been studied using these two design factors at various design considerations. The parameters investigated in the study to understand their inter relationship & their effect on the performance of the vortex tube.

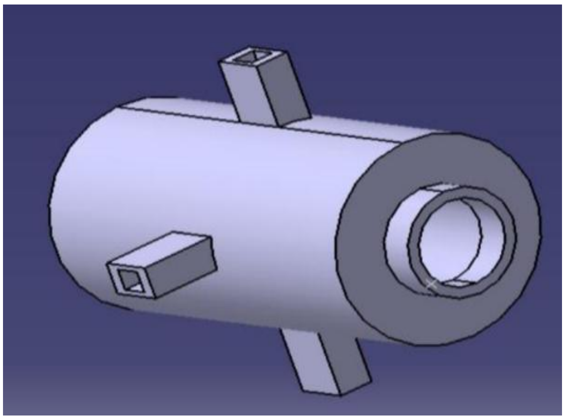


Figure 0-1 Vortex Chamber

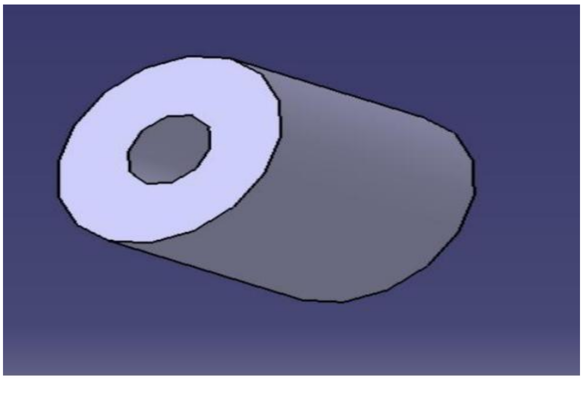


Figure 0-2 Cold End Tube

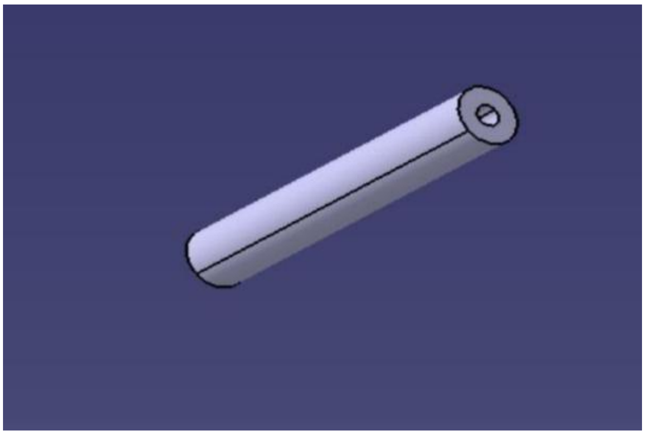


Figure 0-3hot End Tube

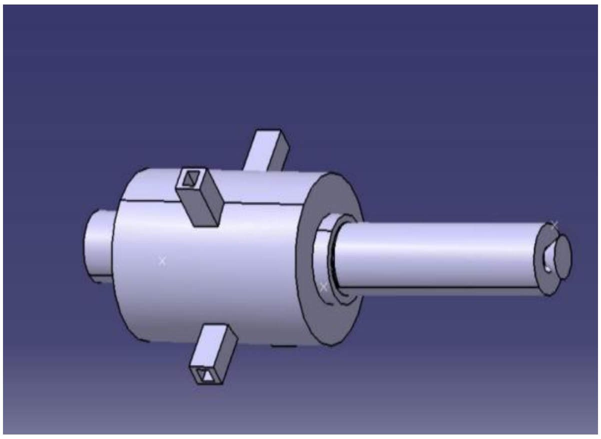


Figure 0-4 Assembly of Vortex Tube

Simulations of Vortex Tube

The fluid flow of the vortex tube is analyzed in the fluid flow CFX solver with the K epsilon model as turbulence, the fluid is single phase fluid with an inlet temperature of 303K and a constant pressure of 5 bar, the average static pressure at the cold outlet is limited to 0.5bar and the average static pressure at the hot outlet is considered to be 2bar. Temperature, pressure, and velocity contours are determined for both blunt and sharp conical valves. This simulation is run for three distinct tube lengths: 100mm, 75mm, and 50mm, and thus the results are summarized.

1.1 Simulations of Blunt Conical Valve

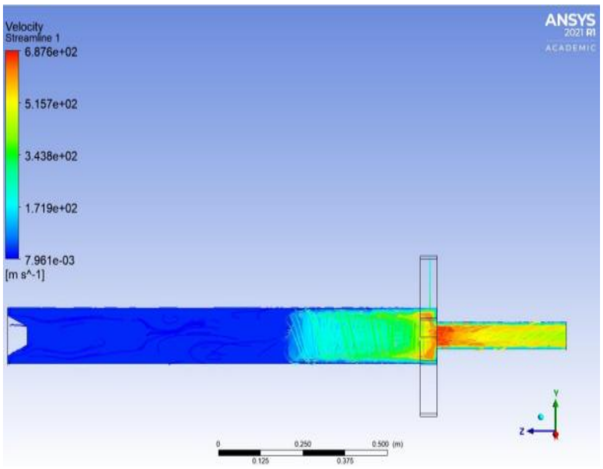


Figure 0-5Velocity Contour for L=50mm, N=2.3mm of Blunt Conical Valve

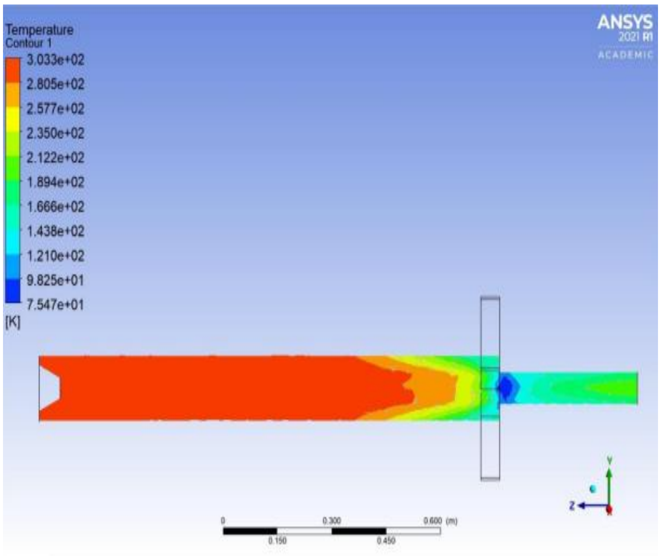


Figure 0-6Temperature Contour for L=50mm, N=2.3mm of Blunt Conical Valve

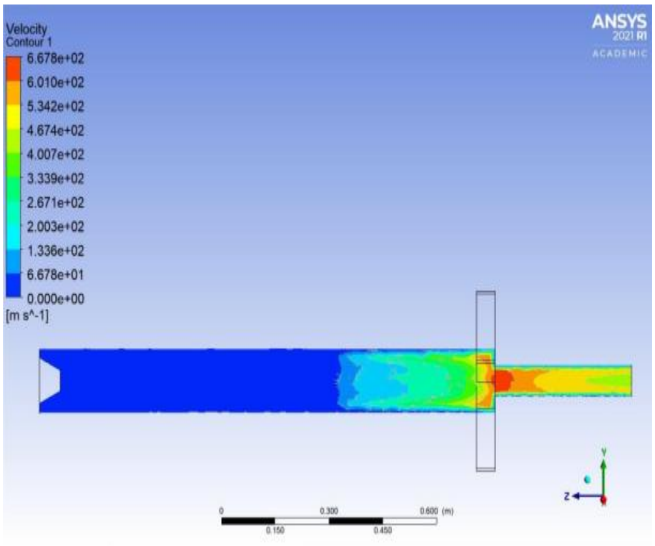


Figure 0-7 Velocity Contour for L=50mm, N=2.3mm of Blunt Conical Valve

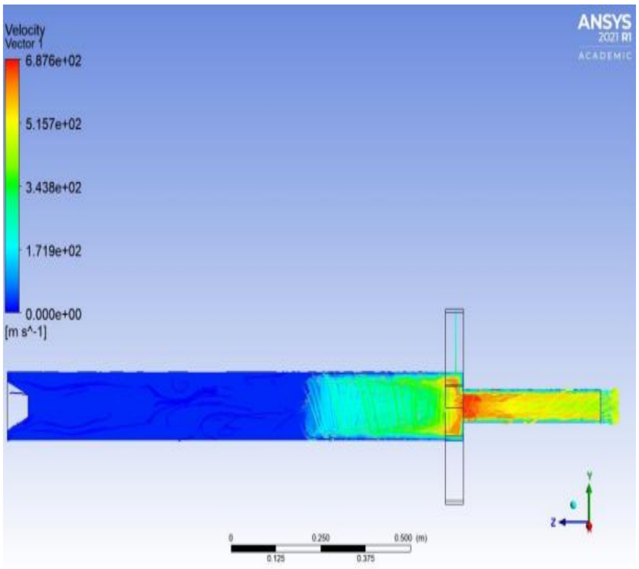


Figure 0-8 Velocity Contour for L=50mm, N=2.3mm of Blunt Conical Valve

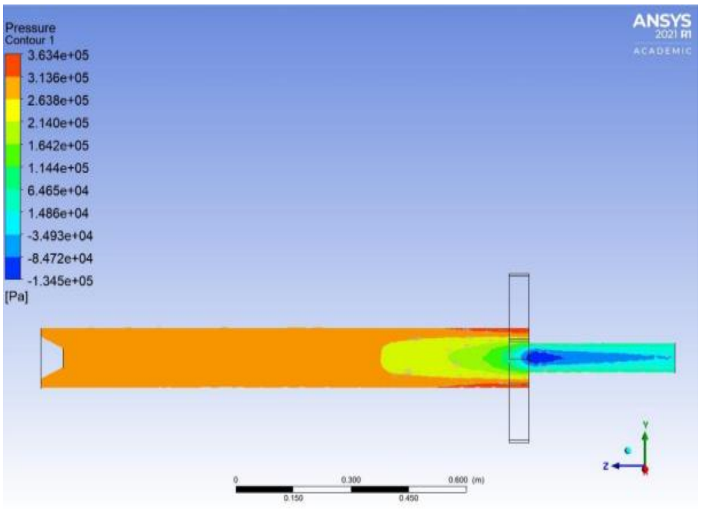
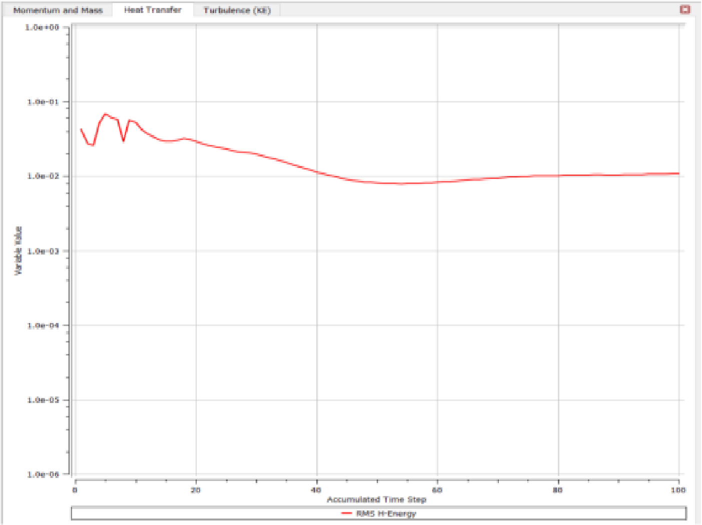
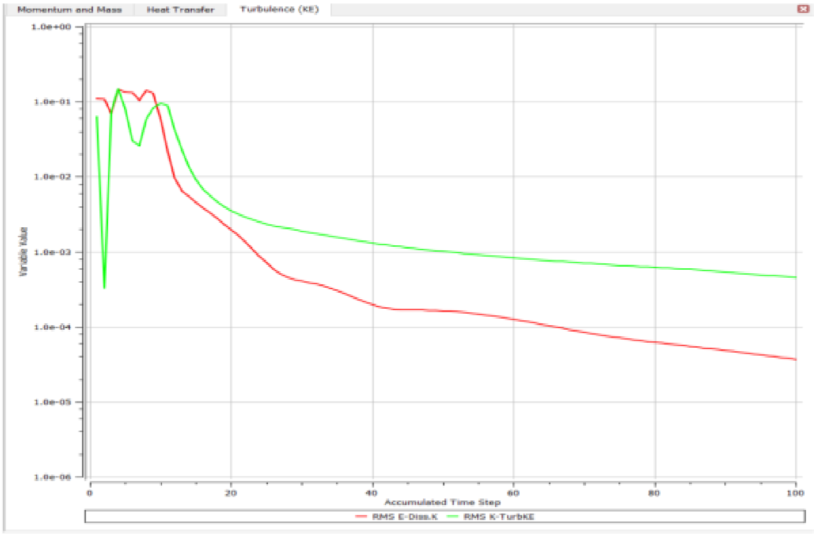


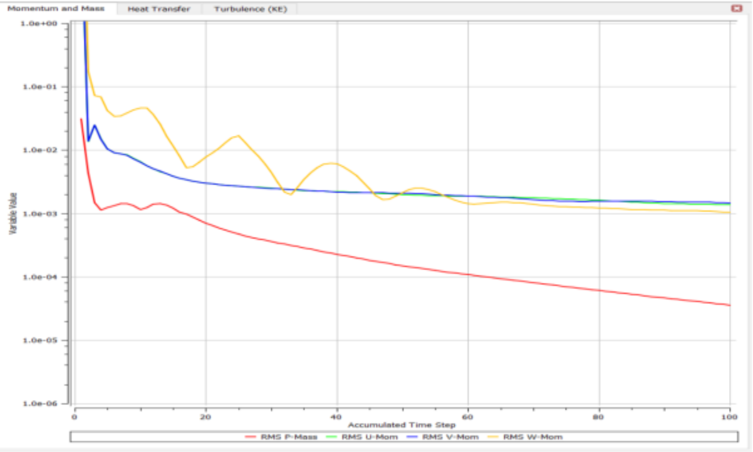
Figure 0-9 Pressure Contour for L=50mm, N=2.3mm of blunt Conical Valve



Graph 0-1 Heat Transfer for L=50mm, N=2.3mm of Blunt Cc Valve



Graph 0-2 Turbulence for L=50mm, N=2.3mm of Blunt Cc Valve



Graph 0-3 Momentum And Mass for L=50mm, N=2.3mm of Blunt Cc Valve

1.2 Simulations of Sharp Conical Valve

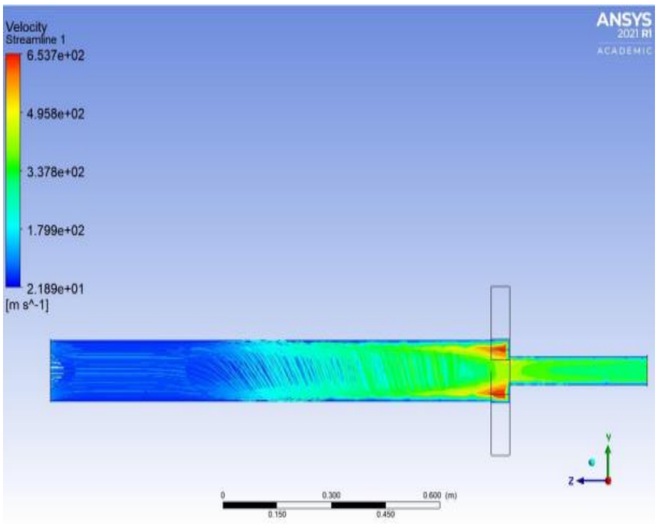


Figure 0-10 Velocity Contour for L=50mm, N=2.3mm of Sharp Conical Valve

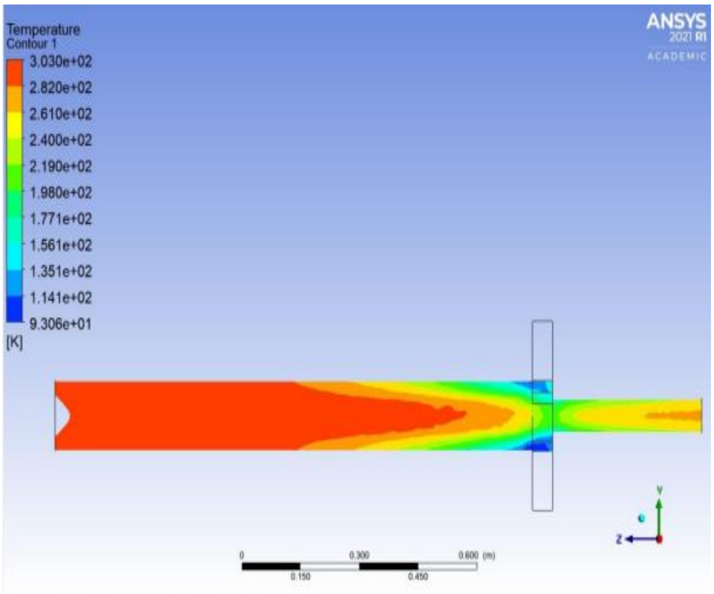


Figure 0-11 Temperature Contour for L=50mm, N=2.3mm of Sharp Conical Valve

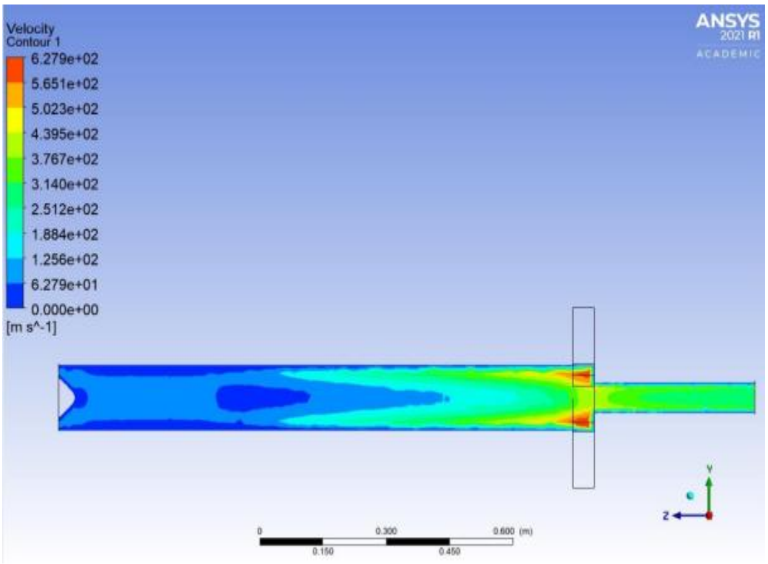


Figure 0-12 Velocity Contour for L=50mm, N=2.3mm Of Sharp Conical Valve

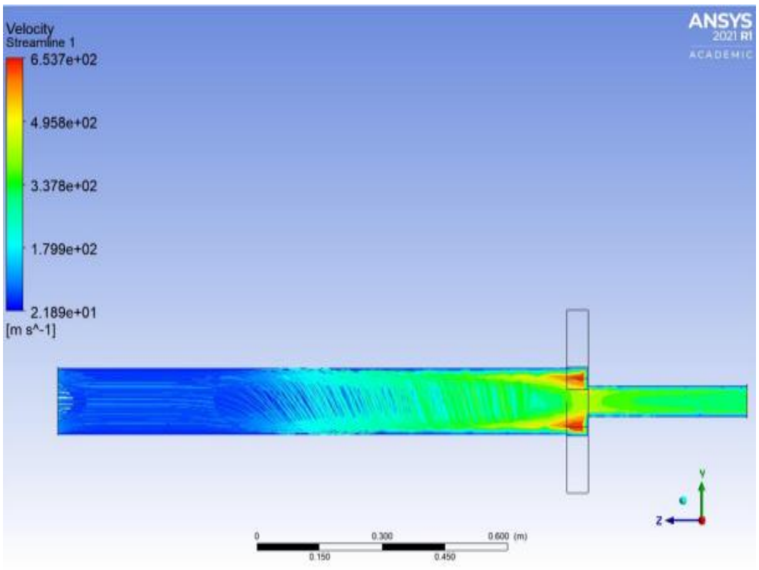


Figure 0-13 Velocity Contour for L=50mm, N=2.3mm of Sharp Conical Valve

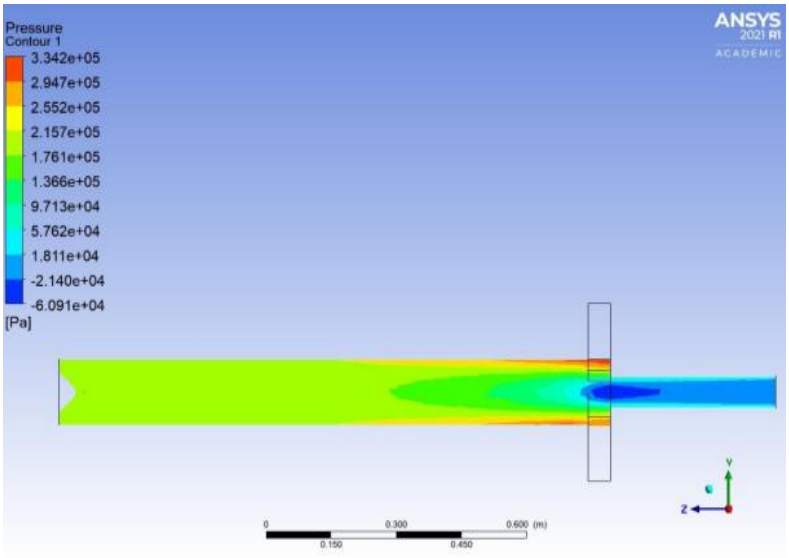
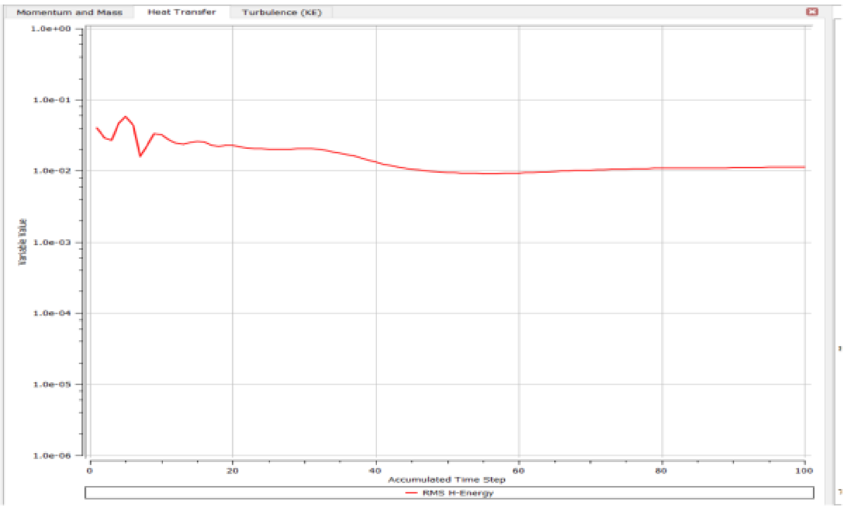
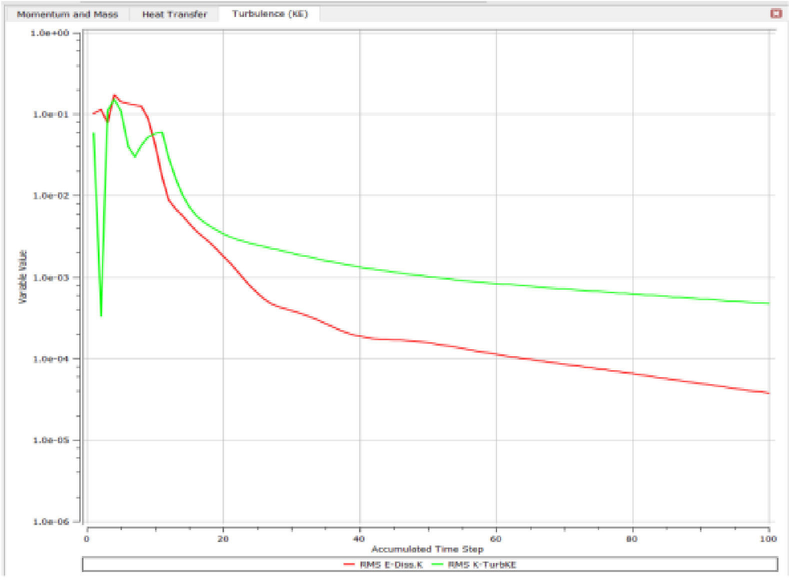


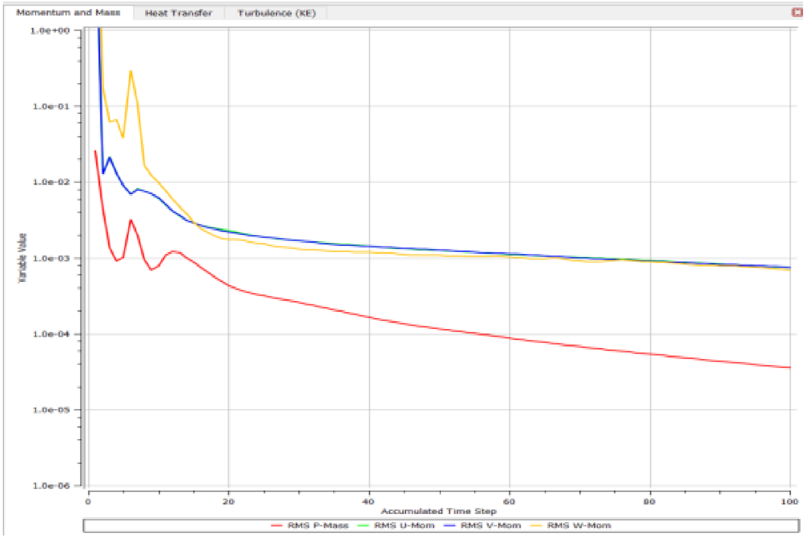
Figure 0-14 Pressure Contour for L=50mm, N=2.3mm of Sharp Conical Valve



Graph 0-4 Heat Transfer for L=50mm, N=2.3mm of Sharp Cc Valve



Graph 0-5 Turbulence for L=50mm, n=2.3mm of sharp cc valve



Graph 0-6 Momentum And Mass for L=50mm, N=2.3mm of Sharp Cc Valve

Formulae Used

μ_c =cold mass fraction
$\mu_c = m_0 / m_c$
$m_i = \rho \times a \times v \times n$
$m_c = \rho_c \times a_c \times v_c$
$M_i = m_c + m_h$
$A = \pi/4 \times d^2$
Overall input of vortex tube
$m_i = \rho \times a \times v \times n$
Area of Cold exit (A)= $\pi/4 \times d^2$ (d=3mm)
$A = \pi/4 \times 3 \times 10^{-6}\ m^2$
$= 0.0037\ m^2$

Observations

Table 0-1 Temperature Readings at Cold End Side For Different Conical Valves

S. No	Tube Length in mm	Sharp cc valve displacement			Blunt cc valve displacement		
		2.3	2.5	2.8	2.3	2.5	2.8
1	100	265	267	230	272	230	260
2	75	252	272	256	270	245	279
3	50	263	260	261	230	220	253

The table 5-1 shows the cold outlet temperature readings for different tube lengths compares sharp and blunt conical valves with 2.3,2.5,2.8 displacements. The results in the table emphasize that temperature for sharp cc valve with displacement 2.5mm for the length 75mm hot tube gives the better results and for blunt cc valve with 2.8mm for the length 75mm hot tube gives the better results.

Table 0-2 Pressure Readings at Cold End Side for Different Conical Valves

S. No	Tube Length in mm	Sharp cc valve displacement			Blunt cc valve displacement		
		2.3	2.5	2.8	2.3	2.5	2.8
1	100	$3.3x10^4$	$5.5x10^4$	$8x10^3$	$5.734x10^4$	$2x10^4$	$2.72x10^4$
2	75	$2.2x10^3$	$2.2x10^3$	$7.2x10^3$	$2.42x10^4$	$6.73x10^3$	$6.75\ x10^3$
3	50	$1.812x10^4$	$3.32x10^4$	$3.565x10^2$	$1.48x10^4$	$2.3x10^4$	$2.32x10^4$

The table 5-2 shows the cold outlet pressure readings for different tube lengths compares sharp and blunt conical valves with 2.3,2.5,2.8 displacements. The results in the table emphasize that pressure for sharp cc valve with displacement 2.8mm for the length 100mm hot tub and for blunt cc valve with displacement 2.8mm for the length 75mm hot tube gives the better results.

Table 0-3 Velocity Readings at Cold End Side for Different Conical Valves

S. No	Tube Length in mm	Sharp cc valve displacement			Blunt cc valve displacement		
		2.3	2.5	2.8	2.3	2.5	2.8
1	100	320	411	400	320	360	340
2	75	310	260	320	330	280	67.5
3	50	376	364	372	467	391	350

The table 5-3 shows the cold outlet velocity readings for different tube lengths compares sharp and blunt conical valves with 2.3,2.5,2.8 displacements. The results in the table emphasize that velocity for sharp cc valve with displacement 2.5mm for the length 100mm hot tub and for blunt cc valve with displacement 2.3mm for the length 50mm hot tube gives the better results.

Table 0-4 Mass Flow Rate for Cold End Side for Different Conical Valve

S. No	Tube Length in mm	Sharp cc valve displacement			Blunt cc valve displacement		
		2.3	2.5	2.8	2.3	2.5	2.8
1	100	0.0027	0.0035	0.0034	0.0027	0.0031	0.0029
2	75	0.0026	0.0022	0.0027	0.0028	0.0049	0.00058
3	50	0.0032	0.0031	0.0032	0.0036	0.0033	0.0030

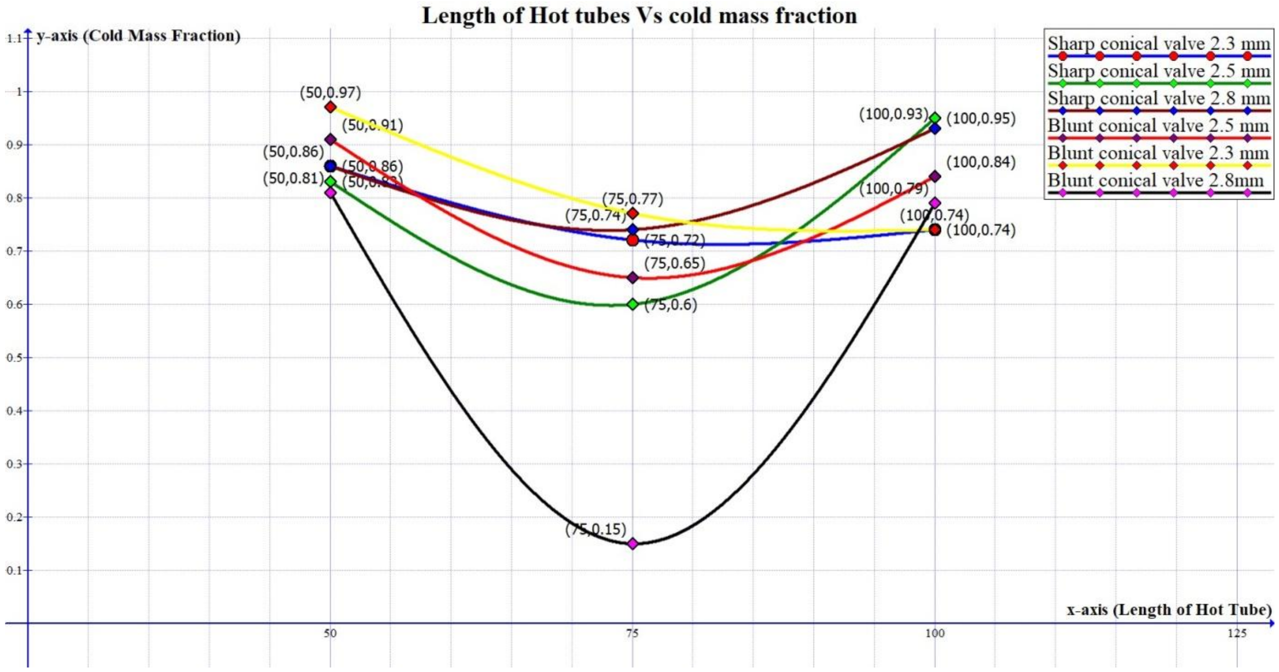
The table 5-4 shows the mass flow rate readings for different tube lengths compares sharp and blunt conical valves with 2.3,2.5,2.8 displacements. The results in the table emphasize that mass flow rate for sharp cc valve with displacement 2.5mm for the length 100mm hot tub and for blunt cc valve with displacement 2.5mm for the length 75mm hot tube gives the better results.

Table 0-5 Cold Mass Fraction for Cold End Side for Different Conical Valve

S. No	Tube Length in mm	Sharp cc valve displacement			Blunt cc valve displacement		
		2.3	2.5	2.8	2.3	2.5	2.8
1	100	0.74	0.95	0.93	0.74	0.84	0.79
2	75	0.72	0.60	0.74	0.77	0.65	0.15
3	50	0.86	0.83	0.86	0.97	0.91	0.81

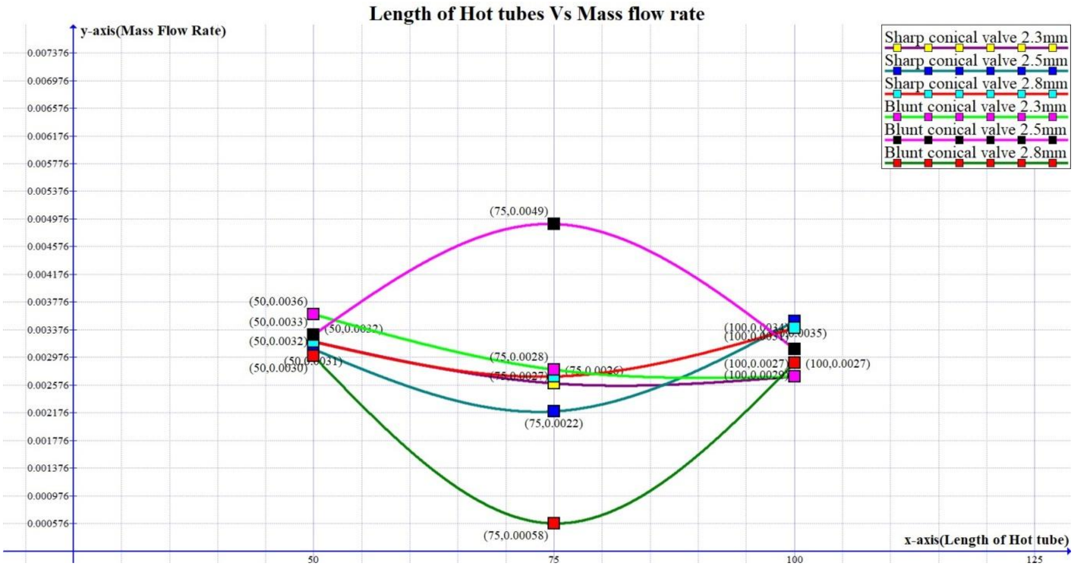
The table 5-3 shows the cold mass fraction readings for different tube lengths compares sharp and blunt conical valves with 2.3,2.5,2.8 displacements. The results in the table emphasize that cold mass fraction for sharp cc valve with displacement 2.5mm for the length 100mm hot tub and for blunt cc valve with displacement 2.3mm for the length 50mm hot tube gives the better results.

Graphs



Graph 0-1 Length of Hot Tubes Vs Cold Mass Fraction

The graph 6-1 shows the lengths of the hot tubes vs. cold mass fraction. The results emphasize that for length of 50mm hot tub of blunt conical valve with 2.3mm displacement gives the better results.



Graph 0-2 Length of Hot Tube Vs Mass Flow Rate

The graph 6-1 shows the lengths of the hot tubes vs. cold mass fraction. The results emphasize that for length of 75mm hot tub of blunt conical valve with 2.5mm displacement gives the better results.

CONCLUSION

According to the simulation analysis report, the hot end tube length of 50mm with the blunt conical control valve that is displaced at is the optimal solution that was produced for the vortex tube of all combinations. 2.3mm from the hot tube's outer end is the inlet's 2×2mm cross section.

According to the data, an increase in cold mass fraction is attained for sharp conical valves at maximum conical valve displacements that correlate to an increase in hot tube length. However it is noted that for shorter lengths, the hot tube is maximized at shorter conical valve displacement in the case of blunt valves.

Similarly the Temperature at cold end side is increases within increase in length of Hot tube correspondingly increase in displacement in the case of sharp conical Valve, while increases with increase in length with decrease in displacements of blunt conical valve.

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