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Computational Investigation of Optimum Vortex Tube and Experimental Validation

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Abstract

Vortex tube is a device which is used to separate the energy of a compressible flow of liquid into two streams viz. hot stream and cold stream. In this research paper Computational fluid dynamics (CFD) and experimental studies are conducted towards the optimization of the Ranque–Hilsch vortex tubes on a macro scale. Simulations of more than 20 models of vortex tube were studied and performed; these models included change in length, change in inlet pressure, change in cold orifice diameter, change in cross section of nozzles, change in material of apparatus, number of inlets. Conclusions and inferences were drawn based on maximum cold end temperature difference in the studied models. The obtained computational results for optimum cold diameter (dc), l/d ratio, number of inlet, profile of inlet were validated through experiments.
Keywords: Cold End Temperature Difference (ΔT_c), Cold Orifice Diameter (d_c), Computational Fluid Dynamics (CFD) Analysis, l/d ratio, Ranque –Hilsch Vortex Tube

I. INTRODUCTION

Vortex tube is a device which can be used as an alternative to refrigeration systems. This device has no moving parts, no cloro-fluro carbons and uses only compressed gas. This device can also be used effective cooling device with cold end temperatures of some tubes dropping down to minimum of 4 degree Celsius. Compressed stream of gas enters tangentially in a cylinder with conical valve at farther end and cold orifice at the nearer end, this stream is then separated in two streams cold and warm respectively. Cold stream comes out of the cold orifice and hot stream is allowed to escape from the conical hot valve. History of this device can be traced back to 1933, when a French scientist Ranque observed this phenomenon of flow separation in a cylindrical tube. Further in 1940 research was carried out by a German scientist named Hilsch, hence the tube has the name Ranque-Hilsch Vortex Tube (RHVT). Their design was primitive now there have been a lot of improvements in design, but an optimum model is still in research phase.

Current research focuses on obtaining optimum parameters for vortex tube by using CFD and experimental techniques. Objective of this research was to study different geometric parameters, inlet profile, number of inlets, and effect of inlet pressure on vortex tube and obtain optimum set of all these parameters for maximum temperature drop at cold outlet. This work uses many previous experimental results to provide comparisons with theoretical approximations and thus validation of suggested method is described.

The first part of research focuses on computational analysis of vortex tube by creating a flow domain to determine the initial optimum cold end temperature difference and geometric parameters like l/d ratio and dc and validating previous experimental results. Second part of the research involves in more advanced parameters like number of inlet, profile of inlet and intermediate parameters like length of inlet nozzle from cold orifice and pressure at conical valve (hot outlet). Third part of this research was comparison on performance parameters and obtaining an optimum model of the observed results. Final part of this research comprises of manufacturing the obtained optimum tube and comparing the experimental results of this tube with results of Computational analysis.

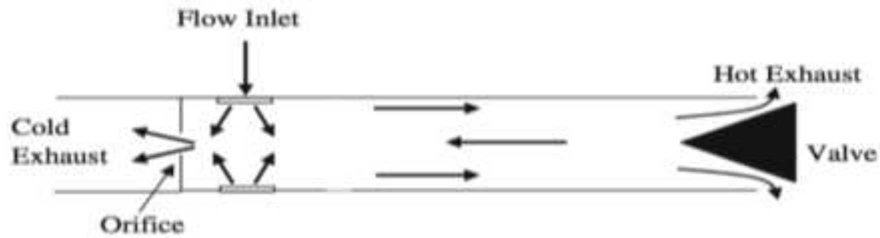

Fig. 1: Schematic Diagram of Vortex Tube

II. LITERATURE SURVEY

N. Agrawal, S.S. Naik, Y.P. Gawale [1] has done an experimental investigation on Ranque–Hilsch vortex tube (RHVT). Experiments are conducted on three different vortex tubes with L/D ratios; 12.5, 17.5 and 22.5. Inlet pressure is also varied from3 to 5 bars in the increment of 1 bar. For the testing, cold mass fraction is varied in the range of 10 to 90% with the step size of 10%. Three different gases — air, nitrogen and CO_2 are tested. It is found that vortex tube performs better with carbon dioxide as working fluid. An experimental investigation is made by D.D. Pawar, B. Sridhar Babu [2] to determine optimum geometry of Ranque-Hilsch vortex tube by increasing number of nozzle and supply pressure. Numerical investigation is carried out by Hitesh R. Thakare, Aniket Monde, Bhushan S. Patil, and A. D. Parekh [3] of flow characteristics in counter-flow vortex tube. A vortex tube with internal diameter 11.4 mm and working length of 106 mm was used. Air was admitted as working fluid of vortex tube. The cold end diameter was fixed to be 6.2 m. Maximum cooling power separation is obtained for cold mass fraction in the range of 0.6 to 0.7, unlike maximum cold end temperature separation. Hitesh R. Thakare, Aniket Monde, A. D. Parekh [4] performed three-dimensional (3-D) computational fluid dynamics (CFD) analysis of counter-flow vortex tube. CFD simulation of vortex tube was attempted in order to understand nature of flow physics inside the tube.

III. VORTEX TUBE DESIGN

A. *Vortex Tube Terminology:*

Schematic diagram of vortex tube is shown in figure 2 and consists of following parts,

1) Nozzle (Inlet)
2) Cold orifice (cold outlet)
3) Hot valve (hot outlet)
4) Tube

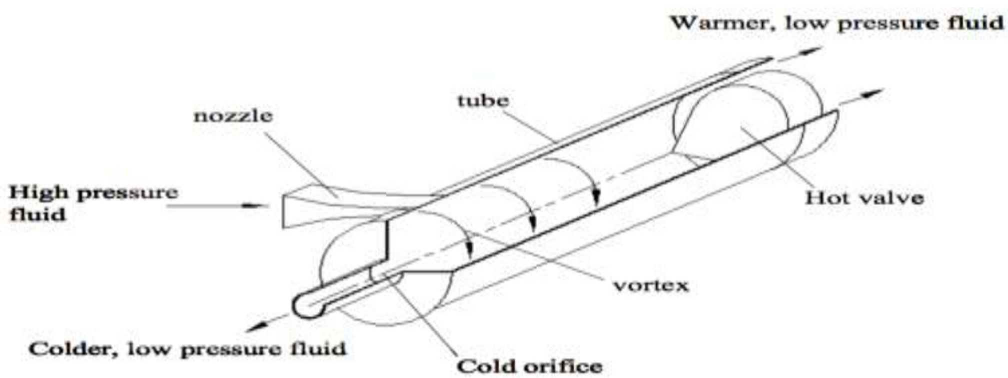

Fig. 2: Vortex Tube Terminologies

B. *Design Constraints:*

Geometrical parameters play an important Role in performance characteristics of vortex tube. Many researchers have obtained an optimum model, for the same but still follow a certain amount of ambiguity. However following restrictions are suggested while designing a vortex tube,

1) For obtaining maximum temperature difference l/d ratio of the tube needs to be kept in the range of $10 \leq l/d \leq 30$.
2) For maximum efficiency and temperature difference at cold end dc/d ratio should be in range of $0.4 \leq dc/d \leq 0.6$.
3) Cold mass fraction for maximum efficiency should be between $0.3 \leq \mu \leq 0.6$.

IV. COMPUTATIONAL FLUID DYNAMICS ANALYSIS

A. *Governing Equations in Computational Fluid Dynamics:*

The equations governing the fluid motion are the three fundamental principles of mass, momentum, and energy conservation.

- Continuity $(\partial\rho/\partial t) + \nabla\cdot(\rho V) = 0$
- Momentum $\rho\,(dV/dt) = \nabla\tau ij - \nabla p + F$
- Energy $\rho\,(de/dt) + p\,(\nabla.V) = (\partial Q/\partial t) - (\nabla.q) + \Phi$

Where ρ is the fluid density, V is the fluid velocity vector, τij is the viscous stress tensor, p is pressure, F is the body forces, e is the internal energy, Q is the heat source term, t is time, Φ is the dissipation term, and ∇.q is the heat loss by conduction. Fourier's law for heat transfer by conduction can be used to describe q as: $q = -k\nabla T$

B. *Mesh Parameter:*

No. of Tetra Elements: 1100400, Quality: 0.4, Volume Mesh: Tetragonal Robust Octree with prism layers.

C. *Boundary Conditions:*

Table – 1
Boundary Conditions for all Types of Vortex Tube

Sr. no.	*Parameters*	*Value*
1	*Cold Pressure Outlet*	*Type- Pressure Outlet, Gauge Pressure = 0, Hydraulic Dia.= 9 mm*
2	*Hot Pressure Outlet*	*Type- Pressure Outlet, Gauge Pressure = 0, Hydraulic Dia.= 0.9 mm*
3	*Mass flow inlet*	*Super-sonic Pressure=5.6 bar, Hydraulic Dia.=2 mm*
4.	*Inlet Pressure*	*Type- Mass Flow-rate, 5 bar*
5.	*Inlet Temperature*	*300 K*
6.	*Turbulence Model*	*K-epsilon, realizable, simple.*
7.	*Turbulent Wall Function*	*No slip*

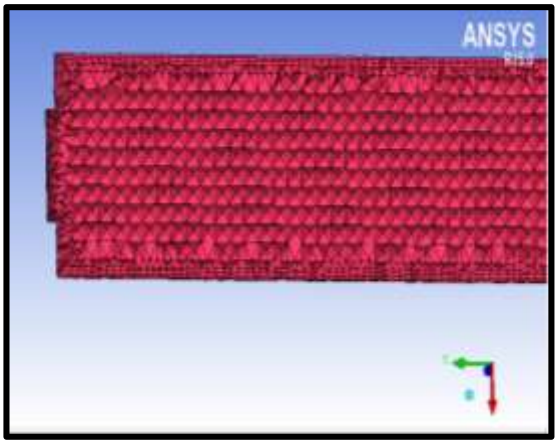

Fig. 4 Volume Mesh of Cold Orifice

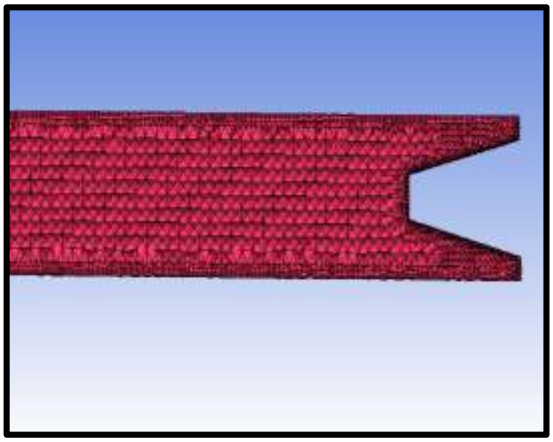
Fig. 5 Volume Mesh of Hot Orifice

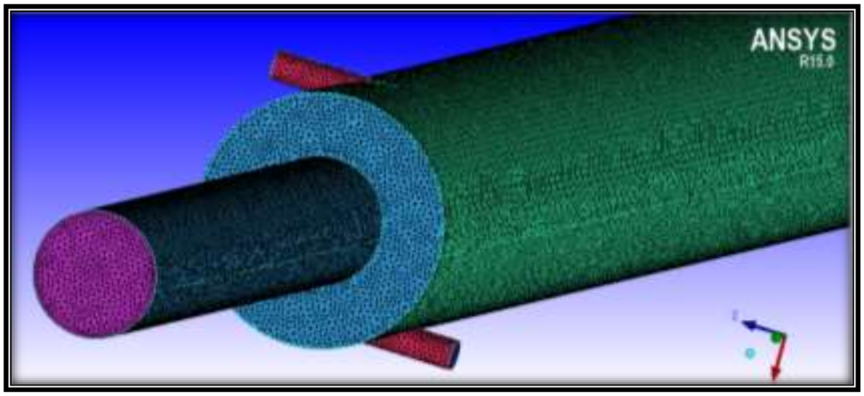

Fig. 6: Surface Mesh of Vortex Tube

V. COMPUTATIONAL RESULTS AND DISCUSSIONS

In this chapter the CFD results are summarised and relative comparison has been presented. This section deals with different inlet parameters like number of inlet, l/d ratio, cold orifice diameter and these are compared with maximum temperature drop at cold outlet at different pressures from 5 bar to 6.5 bar.

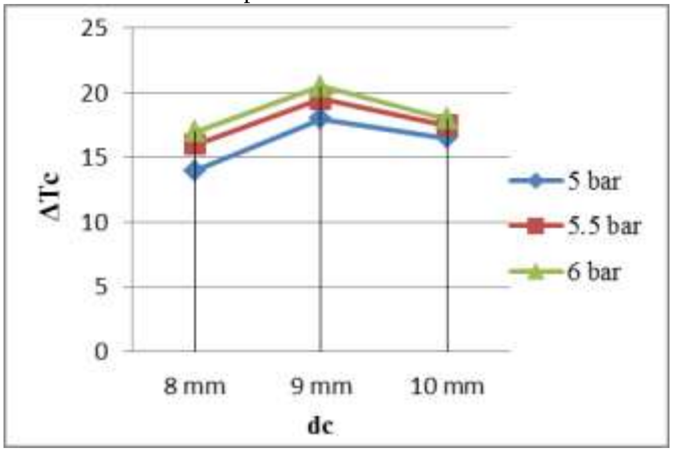

Fig. 7: d_c Vs ΔT_c of Computational Results

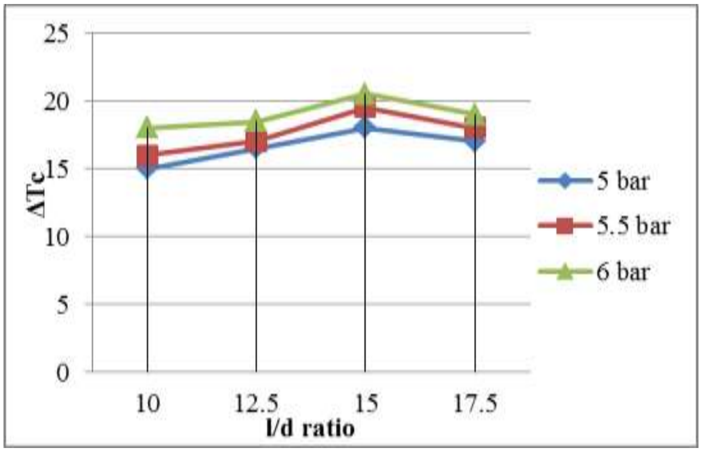

Fig. 8: l/d ratio Vs ΔT_c of Computational Results

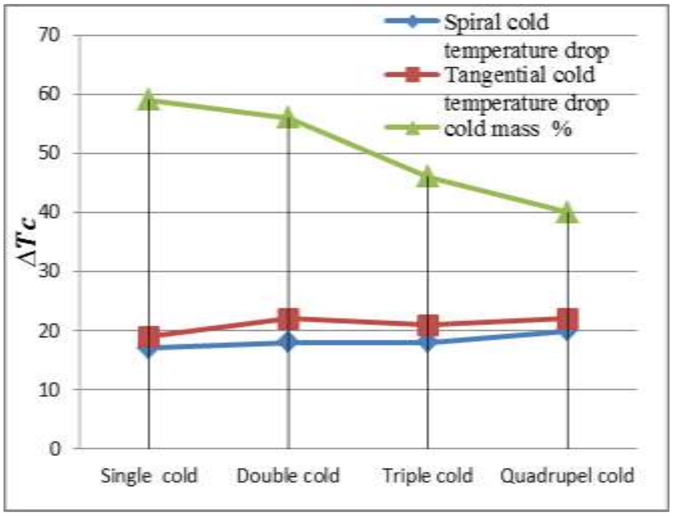

Fig. 9 No. of Inlet Vs ΔT_c of Computational Results

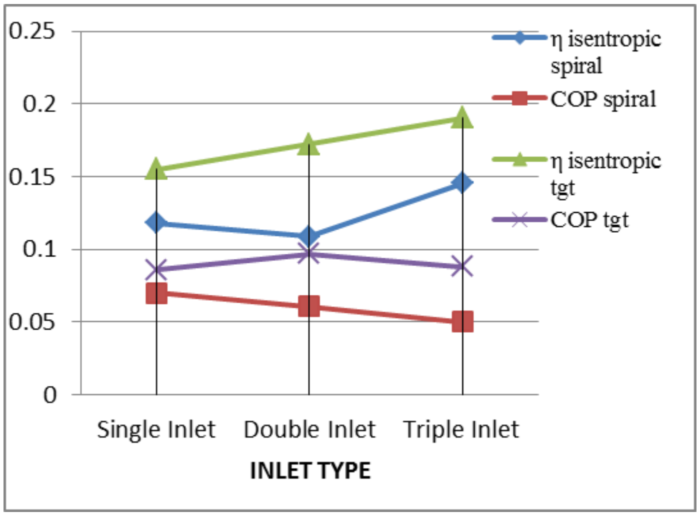

Fig. 10 η Vs COP isentropic vs. No. of inlet of CFD Results

Following table contains the values of COP obtained for each inlet profile and number of inlet:

Table – 2
Performance Characteristics of Different Vortex Tube

Sr. No.	*Types of Vortex Tubes*	*Isentropic Efficiency %*	*COP*
1	*Single Inlet Spiral*	*11.8*	*0.07*
2	*Single Inlet Tangential*	*15.53*	*0.09*
3	*Double Inlet Spiral*	*10.89*	*0.06*
4	*Double Inlet Tangential*	*17.26*	*0.1*
5	*Triple Inlet Spiral*	*14.53*	*0.05*
6	*Triple Inlet Tangential*	*19.07*	*0.09*

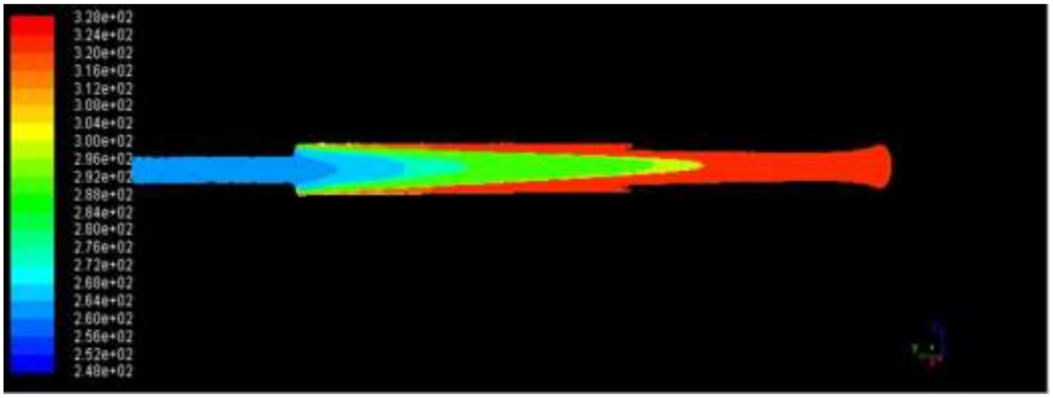
Fig. 11: Internal total temperature contours of optimized model

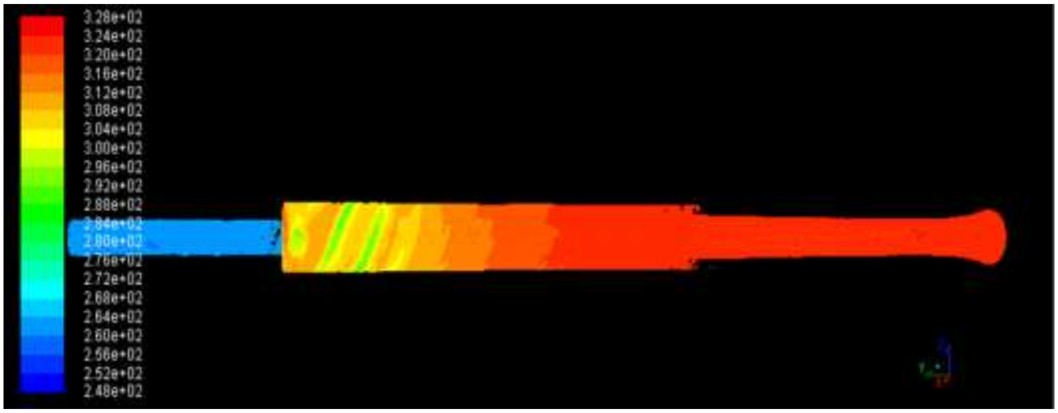
Fig. 12: Surface temperature values of optimum model

Table III Shows the comparison between the computational and experimental results of optimized vortex tube followed by performance characteristics of both results.

Table – 3
Comparison of Experimental and Computational results (Validation)

Sr. No.	*Parameters*	*Experimental value*	*Computational value*
1.	*Cold end temperature*	*282 k*	*281 k*
2.	*Hot end temperature*	*320 k*	*322 k*
3.	*Cold mass fraction*	*56.12%*	*56.12%*

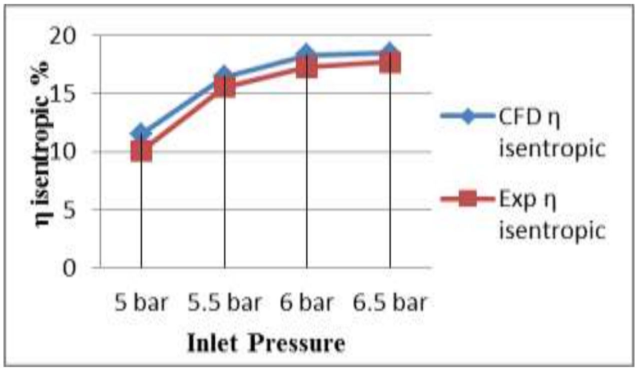

Fig. 13 Inlet Pressure in Vs η Isentropic

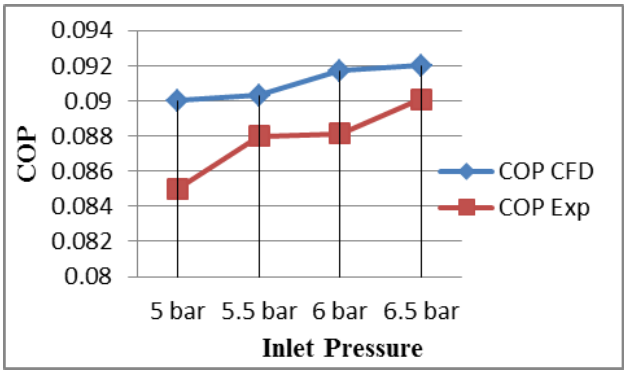

Fig. 14 Inlet Pressure in Vs COP

With increase in inlet pressure both COP and Isentropic efficiency of experimental as well as computational models increases with no notable fluctuation, hence results are validated when compared with increase in inlet pressure.

VI. Conclusion

From above results it was concluded that Double tangential inlet with cold mass fraction of 56%, l/d ratio of 15, cold orifice diameter of 0.5 times tube diameter gave optimum results for the pressure range of 5 to 6 bar and tube diameter of 18 mm. An experimental model was created on these parameters and results were compared with computational results. The results obtained matched with computational = 20 degree Celsius, experimental = 19 degree Celsius. Hence optimum parameters of vortex tube were obtained and verified experimentally. Computational fluid dynamic is very useful tool for carrying out all the flow simulations and it can be used for further advanced research related to vortex tube.

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