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Ranque-Hilsch Vortex Tube and its usage in cooling system – A Review

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Abstract:
The vortex tube, also known as the Ranque-Hilsch vortex tube (RHVT), is a mechanical device that separates a compressed air into hot and cold streams flowing in vortex motion/tangentially into the vortex chamber through inlet nozzles. This instrument has no moving parts, does not break or wear and therefore requires little maintenance. The vortex tube is well suited for different applications because it is simple, light, quite, compact and does not use Freon or other refrigerants (HFCs or CFCs). Though the vortex tube is simple in structure, the internal mechanism of air flow and energy transfer is very complex. A series of theories has been presented by researchers regarding the energy flow inside the vortex tube. This paper after a brief introduction and literature survey, focuses on the design criteria, applications of RHVT and the results obtained up to now. One of the objective of this paper is to highlight the application of this device and the usage in the industry, rough estimates of temperature that are achieved and which be used in particle applications. The review will conclude with comments on future directions that this device can be used and can be applied for further study and investigation.

(Key Words:- Vortex Tube, Ranque-Hilsch, Nozzles)

1. Introduction:

The phenomenon of generating two streams at different temperatures from a vortex tube with single injection was discovered by Ranque in 1930's, and hence was named as Ranque effect. Without any moving parts or chemical reaction within the tube, the phenomenon results only from the fluid dynamic effects.

The basic working pricipleis shown in Fig-1 below:

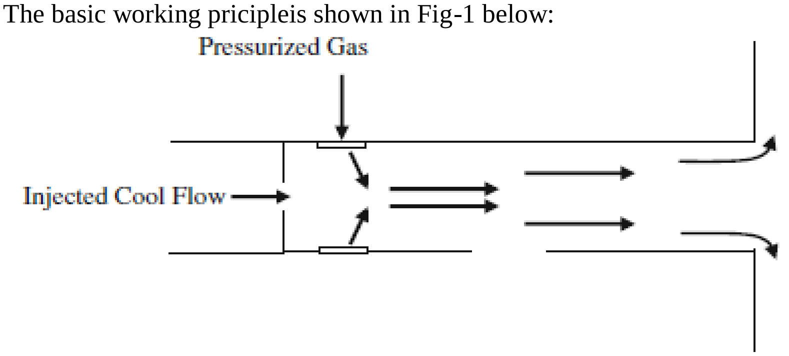

Fig-1: Basic working principle of RHVT tube.

The details air movement insie the tube is illustrated in the Fig-2 below:

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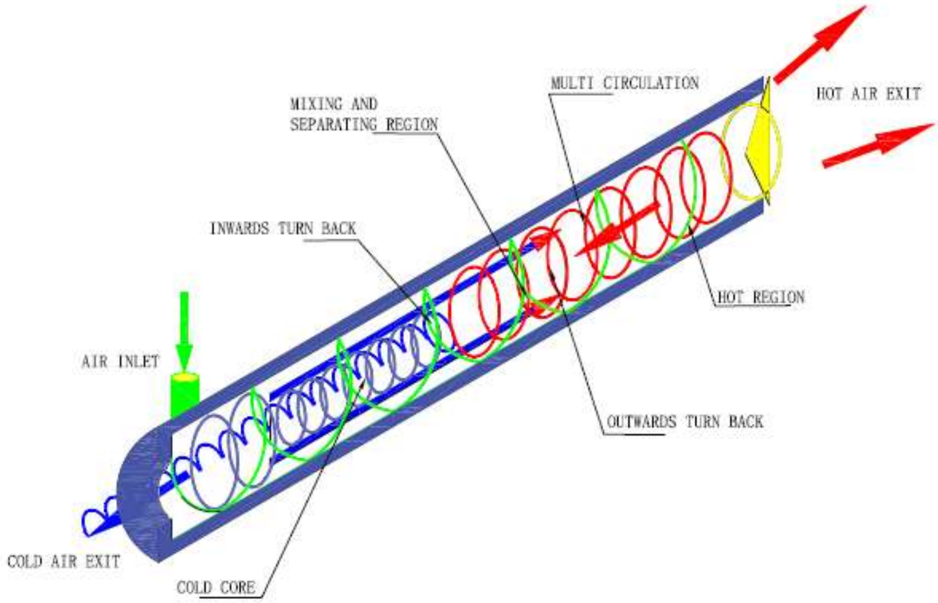

Fig-2: Air Movment inside the RHVT

It is shown in Fig-1 and Fig-2 that a typical counter flow vortex tube contains a straight tube with tangential injection, through which compressed gas is injected into the tube, and two exits located at each end of the tube, which allows the streams at different temperatures to be exhausted from the vortex tube. As shown, the tube is completely hollow and there are no other parts inside the tube; hence the separation of the two steams at different temperatures inside the vortex tube must be based on some fluid dynamic or thermodynamic effects.

When the compressed gas is injected into the tube tangentially at a high velocity, it starts rotating and moving to the hot end. A small portion of the flow escapes from the gap between the control plug and the tube with higher temperature than at the injection point, which is known as hot stream. The other part of the flow is forced back by the control plug and moves to the cold end through the central region of the tube. This central flow is then exhausted from the central exit near the injection point, at a lower temperature and this phenomenon is well known as the temperature separation in the vortex tube or Ranque effect.

2. Literature Survey:

2.1 Theory on Vortex Tubes:

A vortex tube, well known as the Ranque–Hilsch vortex tube (RHVT) is a mechanical device operating as a refrigerating machine without any moving parts, by separating a compressed air stream into a low temperature region and a high temperature region. Such a separation of the flow into regions of low and high total temperature is referred to as the temperature (or energy) separation effect. The vortex tube was first discovered by Georges Ranque [1,2], a metallurgist and physicist who was granted a French patent for the device in 1932, and a United States patent in 1934. The initial reaction of the scientific and engineering communities to his invention was disbelief and apathy. Since the vortex tube was thermodynamically highly inefficient, it was abandoned for several years. Interest in the device was revived by Hilsch [3], a German engineer, who reported an account of his own comprehensive experimental and theoretical studies aimed at improving the efficiency of the vortex tube. He systematically examined the effect of the inlet pressure and the geometrical parameters of the vortex tube on its performance and presented a possible explanation of the energy separation process. His experimental set up could generate Cold-side temperatures of -50C and hot-side temperatures of 100C. After World War II, Hilsch's tubes and documents were uncovered, which were later studied extensively. Indicative of early interest in the vortex tube is the comprehensive survey by Westley [4] which included over 100 references. Other literature surveys such as Curley and McGree [5], Kalvinskas [6], did significant works to understand the cause for getting cold and hot air from single compressed gas at predetermined temperature and pressure. Takahama [7] gave the general idea about nature of flow inside the tube behaving as force vortex. Ahlborn [8] added his work to Takahama [7] by measuring axial and radial velocity and called free vortex flow at the periphery and force vortex flow at the centerline of vortex tube. To remove the difficulty of measurement of flow

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inside the tube, Gao et al. [9] measured temperature, pressure
and 3-D velocity pattern. Dincer et al. [10,11] did the exergy analysis considering the different nozzles and working fluids like methane, air, oxygen and nitrogen.
Hilsch [3] investigated and stated that air leaving from cold orifice losses its kinetic energy due to internal fluid friction. Air enters tube at high pressure at periphery of tube and after expansion air attains low pressure at axis of tube. Hence, air losses most kinetic energy from centerline flow to outer flow. Therefore air leaving at the cold orifice is at lower temperature and remaining air leaving from control valve is at higher temperature. Simoes-Moreira et al. [12] stated that expansion of entering air is driving cause for getting hot and cold flow. Ramakrishna et al. [13] stated that temperature separation is due to shear work transfer. Shear work transfer is work associated with the friction between fluid layers caused by high speed rotating fluid surface which produces torque. Later Ahlborn et al. [14] introduced new theory to explain the concept of temperature separation as the classical thermodynamics cycle with adiabatic expansion and adiabatic compression. Arbuzov et al. [15] stated that Ranque effect inside the vortex tube due to viscous heating of the gas in the thin boundary layer near the wall of the tube and adiabatic cooling of the gas near the center. Williams [16] proposed another application of vortex tube in making of ice. An investigation is carried by Gordon [17] and explained the vortex tube as a classical refrigeration cycle. The region near the inlet nozzle, warm gas in secondary circulation transfer heat into cooler gas in primary circulation. Williams [16] explained that working fluid enters the vortex tube at high speed and high pressure and move towards the hot end nozzle and again come back towards the core central flow. In this region, gases are expanded. Mechanical energy gained from axial movement of compressed gas is utilized to push secondary circulation radially outwards. Amitani et al. [18] concluded that temperature separation is due to compressibility of working air. Lindstr/m-Lang [19] stated that turbulent flow of thermal energy is incompressible flow. Temperature separation totally depends upon the type of gas used in vortex tube; this was studied by Erdelyi et al. [20]. Heating and cooling in vortex tube is the due conversion of either energy into heat or heat into energy. Bovand et al. [21] compared experimentally the cold temperature difference between classical and newly designed Ranque-Hilsch and found greater for the new design.
Numerous numerical and theoretical investigations are performed to observe the phenomena and behavior associated with the flow and energy separation in the vortex tube. Westley [22] and Shamsoddini et al. [23] did a numerical investigation and found that the number of inlet nozzles is very important that change the performance of vortex tube. Bovand et al. [24] use the RNG k-e model for different curvature angles of vortex tubes to investigate flow field and energy separation and shown that vortices are produced at the end of inlet nozzle. Vortices increase number and size with curvature angle, they play an important role in mixing of inner and peripheral flows inside the vortex tube. Thermal separation is caused by diffusion of the mean kinetic energy. As a refrigerator straight and 150Deg curved vortex tube performed highest. Liew et al. [25] studied the droplet behavior in the RHVT with the model developed in MATLAB for inlet humidity varied from 0 to 50%. It has been found that the high humidity at inlet leads to higher liquid concentration and separation process take place in the starting of RHVT and it may increase the separation efficiency as droplet separator in RHVT. Saha et al. [26] studied the RHVT efficiency to separate droplet from saturated humidified N2 gas. It has been concluded that separation efficiency is independent from different types of swirl generator and wobbling. As the liquid concentration increased the separation efficiency increased at the cold side of RHVT.

The pressure, velocity and temperature distribution in a vortex tube can be studied using the conservation laws for mass, momentum and energy. The following is a summary of the results from the literature:
(1) Vortex momentum transfer theory: some experiments were conducted to analyze the temperature separation effect of a vortex tube, in the process of forming the free vortex, kinetic energy exchange occurs in the radial direction, which induces a temperature gradient along the radial direction.
(2) Theory of expansion work: Based on the analysis of the three dimensional energy equation some researches think that the key factor of energy separation of vortex tube is the fluid compressibility: a compressible fluid must expand in order to cool the fluid. The turbulence shear power between the forced vortex in the central part of the tube and free vortex at outer layer makes the largest contribution to the temperature separation effect. Turbulence shear power can be divided into a diffusion term, a kinetic energy term and a pressure term. In the free vortex layer, the total temperature rises because of the diffusion term. However, in the central forced vortex zone, the total temperature drops because of the kinetic energy term and the pressure term.
(3) Theory of acoustic streaming: A very unique proposition was put forth by few, they believes that the acoustic movement caused by orderly disturbance in the vortex tube is the reason for the occurrence of energy separation effect. After the high speed airflow entering vortex tube, helix traveling wave is formed in the tube,

which stimulates Stokes wave near the tube wall, then the Stokes wave stimulate acoustic wave, and finally causing the resonance of acoustic wave, making the Ranque vortex with small vortex core becomes a rotating solid type of forced vortex filled in the tube (except the boundary layer), which causing the radial separation of temperature. If one installs muffler in the vortex tube with downstream structure, adjusting the basic tangential wave to discrete frequency, with smaller amplitudes, then the temperature separation effect will be weaken.

According to the noise produced by vortex tube, known as "vortex howling", it is believed that the airflow in the tube is oscillatory in nature. Thus, when the sound intensity is increased, the effect of energy separation is enhanced. The energy separation effect is produced by the pressure on the pulsating wave-like flow lines, while the viscosity plays a supporting role. This theory is becoming more and more accretive to researchers in the field.

Table-1: Summary of theories on Vortex Tube

SNO	Theory	Remarks
1.	Adiabatic expansion and compression of working fluid	The coldest temperature measured in the experiment conducted by the Xue [27] was −1 °C which is much higher than the theoretical calculations based on adiabatic expansion.
2.	Transfer of kinetic energy from the higher angular velocity axial region to the lower angular velocity peripheral region with free and forced vortex flow inside the RHVT	The explanation of radial pressure gradient of forced vortex remains debatable.
3.	Heat transfer between layers of fluid	Is in contrast with the hypothesis that temperature increase near hot end is due to partial stagnation of the axial flow.
4.	Internal friction and turbulent shear work	Theoretical and experimental investigations by Linderstorm-Lang [28] on strong rotating incompressible flow showed the possibility of the temperature separation in the vortex tube without the effect of pressure variation.
5.	Compressibility of the working fluid	Experimental study showed that temperature separation existed when high pressure water was used as working media in the tube.
6.	Acoustic streaming model	This hypothesis cannot be accepted due to the lack of compression inside a vortex tube.
7.	Turbulent transfer of thermal energy in an incompressible flow	The kinetic energy of the turbulent component of flow was experimentally found to be minimal.

2.2 Components of Vortex Tube:

RHVT tube is a simple device, the major components which form a vortex tube is shown in the Fig-3 which comprises of: 1 – air inlet; 2 – hot exit; 3 – control valve; 4 – main body; 5 – vortex chamber; 6 – generator; 7 – cold exit; 8 – threaded ring nut; and 9 – brass bush.

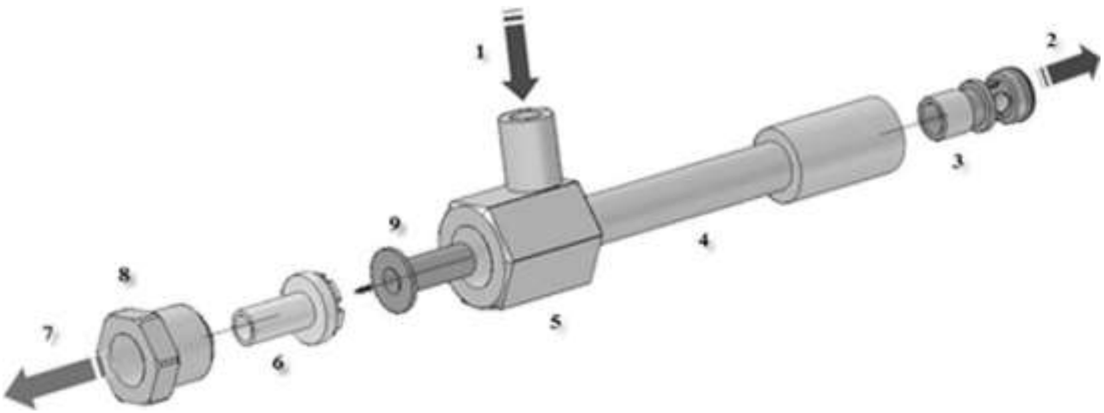

Fig-3: Components of RHVT

The sectional view in Fig-4 discribe the internal components, a blown up view of Vortex generator and Vortex stopper is shown.

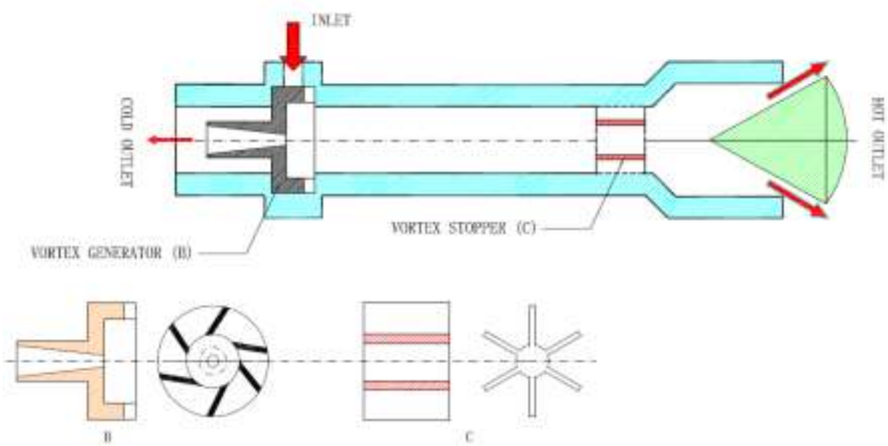

Fig-4: A Typical sectional view of RHVT

2.3 Design criteria for vortex tubes

Many variables influence the flow and performance of RHVTs: geometrical parameters, mass flows, reservoir conditions, gas properties, internal flow parameters, and other factors:

• Geometrical parameters: hot and cold tube length, internal diameter of tube, effective diameter of inlet nozzles, number of inlet nozzles, orientation of inlet nozzles, cold orifice diameter, shape and length of hot end valve, effective diameter of hot flow exit restriction, vortex chamber etc.

• Mass flows: cold mass fraction, overall mass flow rate.

• Reservoir conditions: inlet (reservoir) pressure, inlet (reservoir) temperature, gas density at tube inlet etc.

• Gas properties: gas viscosity, gas thermal conductivity, heat capacity of gas at constant pressure, gas isentropic exponent, gas coefficient of thermal expansivity, mole fraction of gas component i in any mixture, at the inlet etc.

• Internal flow parameters: static pressure at cold exit, static pressure at hot exit, swirl velocity at tube inlet etc.

• Other factors: material of tube, internal roughness, gas molecular mass etc.

As seen, in order to design a good RHVT, the inlet nozzle, the vortex chamber, the cold orifice, the hot and cold tube length, the tube geometry, the tube material, the fluid properties, the cold mass fraction etc., are all relevant design parameters. In Table-2 some of the considerations required in refrence to the design of RHVT is sumarized.

Table-2: The design criteria for RHVT.

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Group Name	Parameter/Variable name	Important Results
Geometrical Parameters	Tube Length	The length of the vortex tube affects performance significantly. An efficient tube of either design should be many times longer than its diameter. Optimum L/D is a function of geometrical and operating parameters. The magnitude of the energy separation increases as the length of the vortex tube increases to a critical length, however a further increase of the vortex tube length beyond the critical length does not improve the energy separation. L/D has no effect on performance beyond L/D > 45
	Tube Diameter	Different vortex tube diameters have been used in experimental RHVT investigations, from diameters as low as 4.4 mm and as high as 800 mm. The vortex tubes used for gas liquefication and separation can have much greater diameters. In general smaller diameter vortex tubes provide more temperature separation than larger diameter ones. A very small diameter vortex tube leads to low diffusion of kinetic energy which also means low temperature separation. A very large tube diameter would result in lower overall tangential velocities both in the core and in the periphery region that would produce low diffusion of mean kinetic energy and also low temperature.
	Diameter/Area of inlet nozzles	Increasing nozzle diameter, generally, increases the performance. The optimum nozzle diameter is about to be 0.25 Dvt.
	Type and number of nozzles	For maximum temperature drop the inlet nozzles should be designed so that the flow be tangentially into vortex tube. The increase of the number of inlet nozzles leads to higher temperature separation. The inlet nozzle location should be as close as possible to the orifice to yield high tangential velocities near the orifice.
	Cold orifice	Using a small cold orifice (dc/D = 0.2, 0.3, and 0.4) fields higher backpressure while a large cold orifice (dc/D = 0.6, 0.7, 0.8, and 0.9) allows high tangential velocities into the cold tube, resulting in lower thermal/energy separation in the tube. Dimensionless cold orifice diameter should be in the range of 0.4\dc/D\0.6 for optimum results. Coaxial orifices have greater temperature separation in compared to the other orifice configurations such as eccentric orifices, diaphram nozzles, and diaphrams with cross sections other than cylindrical configurations
	Hot Flow Control Valve	The hot-end plug is not a critical component in the RHVT. Optimum value for the angle of the cone-shaped control valve is approximately 50 degree C.
	Tube Geometry	Tapering the vortex tube contributes separation process in vortex tubes used for gas separation. In divergent vortex tubes, there exists an optimal conical angle and this angle is very small (*3).

		Rounding off the tube entrance improves the performance of the RHVT. With the muffler the performance of the system is better than that of without muffler.
Mass Flows	Cold mass fraction	The cold and hot temperature changes significantly with cold fraction. Higher temperature drops are obtained in vortex tube made of minimum cold flow temperature design, whereas, more cold fraction and higher adiabatic efficiency are obtained with maximum cooling capacity design. Maximum refrigeration occurs when a RHVT operates at 60–70% cold fraction. Minimum cold temperature occurs when a RHVT operates at 30 percent cold fraction.
	Overall mass flow rate	The inlet or overall mass flow rate of the working gas supplied into the vortex tube is one of the important factors affecting the performance.
Reservoir Conditions	Inlet (Reservoir) pressure	The increase of inlet pressure enhances temperature separation. Rather than depending on the absolute inlet pressure, the temperature separation is a linear function of the normalised pressure drop between the inlet and the cold end of the vortex tube. The normalised maximum temperature is a function of normalised inlet pressure and it approaches an asymptotic value as the normalised inlet pressure increases. The maximum temperature drop increases very slightly beyond the value of pin/pc = 11 or 12. Vortex tubes behave identically in the above and below atmospheric pressure regimes.
	Inlet (Reservoir) temperature	Inlet temperature does not affect significantly the temperature differences and performance.
Gas properties	Gas Prandtl Number	Maximum temperature drop is proportional to Prandtl number.
	Gas isentropic exponent	Specific heat ratio (k) is the inlet gas characteristic that affects the amount of energy separation in the vortex tube. Cold temperature difference increases with increasing k.
	Moisture content	The cold temperature difference and efficiency decrease by increasing the air moisture content of air.
Other factors	Tube material	Using materials with more smooth surfaces and lower thermal conductivities results in better temperature separation and performance. Using the vortex tube with insulation to reduce energy loss to surroundings gives a higher temperature separation in the tube than that without insulation. For all feasible operations of the vortex tube, choice of a durable material for the manufacture of the tube is quite important.
	Internal roughness	The roughness of the inner surface of the tube has influence on its performance. Any roughness element on the inner surface of tube will decrease the performance

		of the system. Using materials with more smooth surfaces results in better temperature separation and performance.
	Gas molecular mass	The lighter the molecular weight, the higher the temperature separation. Inlet gas with helium gives higher temperature difference than those found from the oxygen, methane, and air. Performance of RHVT with steam and hydrocarbons is similar to that of air. When the inlet pressure is high the energy separation process exists in incompressible vortex flow. For water very high pressures, 20–50 MPa, are required.

2.4 Calculations involved in Vortex Tubes:
Cold mass flow ratio: e = mc/mi
where mc is flow rate of cold stream, and mi is inlet or total mass flow rate
The value of e will be in 0<e<1
Cold temperature difference (Del Tc) =Tin - Tc
Hot temperature difference (Del Th) = Th - Tin
Where Tin is air inlet temperature and Tc is cold air exit temperature, and Th is hot air exit temperaure
Isentropic Efficency = Mu = hin – hc / hin – hs
Where hin is the air inlet enthalpy and hc is cold air enthalpy and hs is enthalpy after isentropic process.
For Ideal gas Muis = Tin – Tc / Tin – Ts
For isentropic expansion, the exhaust temperature is Ts = Tin (Pc/Pin) power (k-1)/k
After Muis = Tin – Tc/(Tin [1-(Patm/Pin) power (k-1)/k])
Qc = mc cp (Tin-Tc)

3. Applications

Vortex tubes are used for cooling of cutting tools (lathes and mills, both manually-operated and CNC machines) during machining. The vortex tube is well-matched to this application: machine shops generally already use compressed air, and a fast jet of cold air provides both cooling and removal of the "chips" produced by the tool. This completely eliminates or drastically reduces the need for liquid coolant, which is messy, expensive, and environmentally hazardous.
The vortex tube are also used in many applications such as

1. Cooling electronic controls
2. Cooling machining operations
3. Cooling CCTV cameras
4. Setting hot melts
5. Cooling soldered parts
6. Cooling gas samples
7. Electronic component cooling
8. Cooling heat seal
9. Cooling environmental chambers

It is also used in Gas and Chemical Industries:
Gas Industry: The classical problem solved in the gas industry by using VTs is that of removing higher hydrocarbons from natural gas (NG). With the VT, the removal of gas condensate from the cold stream was increased to 79% and that of sulfur, to 55–60%. The latest technologies for the production of liquefied natural gas (LNG) at the gas distributing stations (GDSs) of gas mains without using electricity have also been made possible by the use of VTs. This substantially cuts the consumption of gas compressed in the preheaters to raise the temperature of the gas being reduced.
Chemical Industry: Modern chemical plants often have various waste gases under high pressure, which as a rule are throttled down and burned in furnaces or in a flare. They contain the target products of the plant as well as other components formed during combustion of environmentally hazardous substances. It is desirable to have the available pressure drop occur in a VT, to produce cold, and to condense the indicated products. This has a good ecological effect and increases the productivity of the units and eliminates the problem of transporting the waste gases to the combustion site.
In conclusion, we must note that few vortex tubes are used in various branches of industry today. At the same time, vortex tubes could enhance the efficiency in many technologies of the chemical, gas, and gas and oil industries and could bring additional savings.

4. Available Results

Below are some results from the researches summarized in Table-4

Table-4: Experimental results conducted by other reserchers.

SNo	Reference	Inlet Pressure (Bar)	Length of VT (mm)	VT dia (mm)	VT inlet dia (mm)	Cold mass flow fraction	Drop in cold outlet temp K	Raise in hot outlet temp K
1.	Hilsch [3]	7.1	230	4.6	1.1	0.23	45	13
2.	Scheper [29]	2.02	914	38.1	6.35	0.26	11.7	3.9
3.	Scheller & Brown [30]	6.18	1092	25.4	-	0.506	23	15.6
4.	Stephan et al [31]	6.08	352	17.6	4.1	0.3	38	18
5.	Promovonge & Eiamsa-ard [32]	4.56	720	16	2.0	0.38	18	8
6.	Hamoudi et al [33]	5.07	100	2	0.8	0.57	18.5	11
7.	Eiamsa-ard et al [34]	4.05	720	16	2.0	0.3	17	4
8.	Im & Yu [35]	2.02	280	20	8.1	0.5	17	12
9.	K Kiran Kumar [36]	4.0	175	13	8	0.23	12	25

5.Conclusion

A vortex tube can separate a compressible air into a hot and a cold air stream. It has a simple structure with no moving parts; it is easy to manufacture and assemble, and it is easy to operate with no maintenance required. Vortex tube is a reliable and inexpensive device generating cooling and heating at the same time from a compressed gas source. If a cheap source of compressed gas is available, it has the potential to generate useful thermal energy for a lot of processes and applications. To date, the lack of a fast and reliable design method slows down the large spreading of this technology since the design of vortex tubes still relies on long and expensive experimental characterizations.

The purpose of this review paper is to overview of the past investigations of the design criteria of vortex tubes, to draw together the mass of literature, and to provide detailed information on the design of vortex tubes. Thus it will be possible to access the results of available experimental/theoretical investigations on vortex tubes. It will be possible also to make generalization about design of vortex tubes. First the classification of vortex tubes is presented and the types of vortex tubes are described. Then all criteria on the design of vortex tubes are given in detail using experimental and theoretical results from the past until now.

The findings of this study to investigate the performance of the vortex tube under several design parameters mainly; (1) inlet pressure, (2) cold mass fraction, (3) number of inlet nozzles, (4) vortex stopper location and (5) insulation. The following were concluded from the review of papers:

1. Inlet pressure is a key parameter for the vortex tube performance. Increasing the inlet pressure improves the energy separation effect in general. However, when the inlet pressure to the cold outlet pressure ratio becomes large, the rate of drop in the cold outlet temperature levels off. Furthermore, when this pressure ratio exceeds certain value so that shock waves appear, the temperature drop starts to decreases, corresponding to a transition from subsonic to supersonic flow at the tube inlet.
2. The cold air fraction is another key factor influencing the performance of the energy separation in the vortex tube and there is an optimum value to obtain maximum temperature difference and it is not the same for maximum energy load separation.
3. The effect of number of nozzle is very important. For constant inlet pressure test, it is clear that increasing number of nozzle increase the temperature difference between inlet and outlets. Also the study indicates that there could be optimum number of jet for maximum load that require further investigation.
4. The vortex tube length (vortex stopper location) has direct effect on the performance of the vortex tube. The data shows that as vortex stopper moves far from the vortex generator the energy separation performance increase which is true as long the distanced moved is below 14 times the vortex tube diameter (which was the investigated range).

5. Insulation has minimal effect on vortex tube cooling or heating capabilities.

By reviewing most of the theory predicting the vortex tube performance and showing the common features and promising add-ons, this review paper could set the basis for the development of the first commonly accepted design model of counterflow vortex tubes working with perfect gas for spot cooling application.

6. References:

[1] Ranque GJ. Experiments on expansion in a vortex with simultaneous exhaust of hot air and cold air. J Phys Radium (Paris) 1933;4:112–4 S-115, June. Also translated as General Electric Co., Schenectady Works Library 1947; T.F. 3294.
[2] Ranque GJ. Method and apparatus for obtaining from a fluid under pressure two outputs of fluid at different temperatures. US patent 1:952,281, 1934.
[3] Hilsch R. The use of expansion of gases in a centrifugal field as a cooling process. Rev Sci Instrum 1947;18(2):108–13.
[4] Westley R. A bibliography and survey of the vortex tube. College of Aeronautics. Cranfield note, UK, 1954.
[5] Curley W, McGree Jr R. Bibliography of vortex tubes. Refrig Eng 1951;59(2):191–3.
[6] Kalvinskas L. Vortex tubes (an extension of Wesley's bibliography). Jet Propulsion Laboratory, California Inst of Technology Literature Search, 56, Part 2, 1956.
[7] H. Takahama, Studies on vortex tubes, Bull. JSME 8 (1965) 433–440.
[8] B. Ahlborn, S. Groves, Secondary flow in a vortex tube, Fluid Dyn. Res. 21 (2) (1997) 73–86.
[9] C.M. Gao, K.J. Bosschaart, J.C.H. Zeegers, A.T.A.M. de Waele, Experimental study on a simple Ranque-Hilsch vortex tube, Cryogenics 45 (3) (2005) 173–183.
[10] K. Dincer, Y. Yilmaz, A. Berber, S. Baskaya, Experimental investigation of performance of hot cascade type Ranque-Hilsch vortex tube and exergy analysis, Int. J. Refrig. 34 (4) (2011) 1117–1124.
[11] K. Dincer, A. Avci, S. Baskaya, A. Berber, Experimental investigation and exergy analysis of the performance of a counter flow Ranque-Hilsch vortex tube with regard to nozzle cross-section areas, Int. J. Refrig. 33 (5) (2010) 954–962.
[12] J.R. Simoes-Moreira, An air-standard cycle and a thermodynamic perspective on operational limits of Ranque-Hilsch or vortex tubes, Int. J. Refrig. 33 (4) (2010) 765–773.
[13] P.A. Ramakrishna, M. Ramakrishna, R. Manimaran, Experimental investigation of temperature separation in a counter-flow vortex tube, J. Heat Transfer 136 (8) (2014) 082801–1-6.
[14] B. Ahlborn, J.U. Keller, R. Staudt, G. Treitz, E. Rebhan, Limits of temperature separation in a vortex tube, J. Phys. D: Appl. Phys. 27 (3) (1994) 480.
[15] V.A. Arbuzov, Yu.N. Dubnishchev, A.V. Lebedev, M.Kh. Pravdina, N.I. Yavorski, Observation of large-scale hydrodynamic structures in a vortex tube and the Ranque effect, Phys. Lett. 23 (12) (1997) 938–940.
[16] D.T. Williams, Ranque-Hilsch Vortex Tube for Refrigeration in Developing Communities, dissigno, San Francisco, CA USA, 2005.
[17] B. Ahlborn, J.M. Gordon, The vortex tube as a classical thermodynamics refrigeration cycle, J. Appl. Phys. 88 (6) (2000) 3645–3653.
[18] T. Amitani, T. Adachi, T. Kato, A study on temperature separation in a large vortex tube Trans JSME 49 (1983) 877–884.
[19] C.U. Lindstr/m-Lang, The three dimensional distribution of tangential velocity and total temperature in vortex tubes, J. Fluid Mech. 45 (1971) 161–87.
[20] I. Erdélyi, Effect of the centrifugal force field on the heat state of the gases, explanation of the Ranque phenomenon, Res. field Eng. 28 (1962) 181–186.
[21] M. Bovand, S. Rashidi, J.A. Esfahani, New design of Ranque-Hilsch vortex tube: helical multi-intake vortex generator, J. Thermophys. Heat Transfer (2016) 608–613.
[22] R. Westley, Vortex Tube Performance Data Sheets, College of Aeronautics, Cranfield, 1967.
[23] R. Shamsoddini, A.H. Nezhad, Numerical analysis of the effects of nozzles number on the flow and power of cooling of a vortex tube, Int. J. Refrig. 33 (4) (2010) 774–782.
[24] M. Bovand, M.S. Valipour, S. Eiamsa-ard, A. Tamayol, Numerical analysis for curved vortex tube optimization, Int. Commun. Heat Mass Transfer 50 (2014) 98–107.
[25] R. Liew, W.R. Michatek, J.C.H. Zeegers, J.G.M. Kuerten, Droplet behaviour in a Ranque-Hilsch vortex tube, J. Phys: Conf. Ser. 318 (052013) (2011) 1–10.
[26] D. Saha, J.C.H. Zeegers, J.G.M. Kuerten, Experiments on water droplet separation in a Ranque-Hilsch vortex tube (RHVT), WIT Trans. Eng. Sci. 89 (2015) 117–126.
[27] Xue Y, Arjomandi M, Kelso R (2011) Visualization of flow structurein a vortex tube. Exp Thermal Fluid Sci 35(8):1514–1521.
[28] Linderstrom-Lang CU (1971) Gas separation in the Ranque-Hilsch vortex tube model calculations based on flow data. Riso report, Denmark
[29] Scheper GW (1951) The vortex tube–internal flow data and a heat transfer theory. J. ASRE Refrigeration Eng 59:985–989

[30] Scheller WA, Brown GM (1957) The Ranque-Hilsch vortex tube. Ind Eng Chem 49(6):1013–1016.
[31] Stephan K, Lin S, Durst M, Huang F, Seher D (1983) An investigation of energy separation in a vortex tube. Int. J. HeatMass Transf 26:341–348.
[32] Promvonge P, Eiamsa-ard S (2005) Investigation on the Vortex Thermal Separation in a Vortex Tube Refrigerator. Sci Asia 31: 215–223
[33] Hamoudi AF (2006) An investigation of micro-scale Ranque-Hilsch vortex tube Master's thesis. Dissertation, University of Windsor
[34] Eiamsa-ard S, Wongcharee K, Promvonge P (2010) Experimental investigation on energy separation in a counter-flow Ranque–Hilsch vortex tube: effect of cooling a hot tube. Int Commun Heat Mass Transf 37:156–162.
[35] Im SY, Yu SS (2012) Effects of geometric parameters on the separated air flow temperature of a vortex tube for design optimization. Energy 37:154–160.
[36] K. Kiran Kumar Rao, Dr. A. Ramesh, M. Rajesh, Dr.G.Naga Malleswara Rao (2016), Performance of Vortex Tube with Comparing by CFD Ananlysis, IJRE, Vol. 03 No. 06, June 2016, ISSN 2348-7852.

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