The Development of Ranque-Hilsch Vortex Tubes: Computational models

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Abstract

The Ranque - Hilsch vortex tube, RHVT, is well-known for its unique function. This can be observed when a compressed air passes through the tube inlet. The thermal separation effect results in hot and cold streams which could be produced simultaneously. Many researchers investigated the RHVT mechanism and performance using computational method. There are a number of computational models presented as to explain the driving mechanism of the RHVT and to predict the RHVT performance. In this article, the development of the RHVT based computational method is reviewed. The important results from those models are presented for the benefit of future research in this field.

Keywords – RHVT, Computational Method, thermal separation effect, Efficiency

Introduction

A Ranque-Hilsch Vortex Tube, RHVT is a device that can produce hot and cold streams simultaneously. The RHVT was named after the two explorers and the flow pattern in the tube which is liked a vortex. It was first discovered by Ranque, a French physicist, in 1933 (Ranque, 1933). He discovered the dividing of stream by passing a pumped air into a cylindrical tube via a nozzle at the tube inlet. He observed the lower temperature steam at one tube outlet and the higher temperature steam at the other outlet. His invention was granted the US patent in 1934 (Ranque, 1934). The device was not widely known until Hilsch published his experimental and theoretical finding results (Hilsch, 1947). Valuable information regarded the RHVT operating condition and performance was presented. It became clear that the device could be useful for some specific cooling application. This was attracted by many researchers who interested in making their contribution to this subject. There are several names for this device e.g. Ranque tubes, Hilsch tubes, Ranque-Hilsch tubes, Ranque-Hilsch vortex tubes or vortex tubes. The last two are referred the most in publication. In this article, the name of Ranque-Hilsch Vortex Tubes (RHVT) is mainly used. Followed research works have been published on the theoretical study of Thermodynamics, Fluid Dynamics and Heat Transfer for explaining the separation phenomenon inside the RHVT (Fulton, 1950; Martynovskii and Alekseev, 1956; Eckert and Robert, 1972, Ahlborn and Gordon, 2000) . A computational method has been employed in order to study the characteristics of fluid flow in the RHVT. Recently, the simulation based computational fluid dynamic codes has been widely adopted to investigate the RHVT performance and thermal separation effect. A number of publication works referred the actual dimension of the RHVT in their simulation which aimed to predict its performance at various operating condition. The model was validated by comparing the computational results with either the measuring data available in the literature or with their own measurement. Furthermore, the models can be employed to determine the influenced parameters on the tube performance such as tube diameter, tube length, exit area and etc. The computational method seems having several advantages over the experimental method which mentioned by researchers in this field. That included low investment due to no requirement of the experimental equipments, measuring instruments and human work. However, the computation of three dimensional model could be a hard work which required more effort. The calculation process was also time consuming; particularly, in the computational fluid dynamic, CFD, model (Rattanongphisat, 2008).

There are two types of the Ranque - Hilsch vortex tube, RHVT. It is classified by the character of fluid flow as the counter-flow type and the uni-flow type. In the counter flow vortex tube, the inlet compressed air splits into two streams which leave the tube at the different two outlets as shown in Figure 1. A low temperature stream found at the central region exits the tube via an orifice at one end while a high temperature stream is throttled to leave at the other end. The second type is called either a uni-flow or a parallel flow vortex tube. It is seen that both low and high temperature streams leave the tube at different outlets in one side of the tube as shown in Figure 2. The separation mechanism of these two RHVT type is the same. The counter flow vortex tube is widely used in the industries; therefore, many investigators paid more attention on this type than the other one.

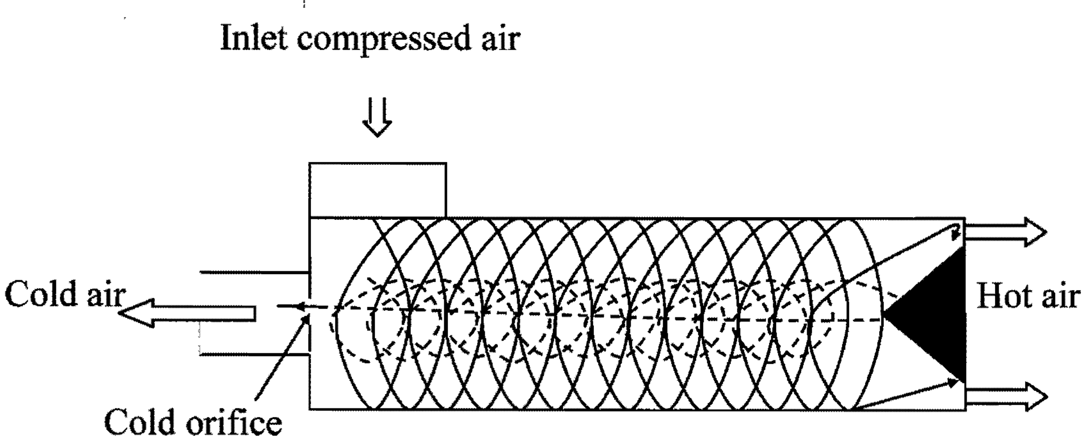

Figure 1 Schematic of a counter flow vortex tube

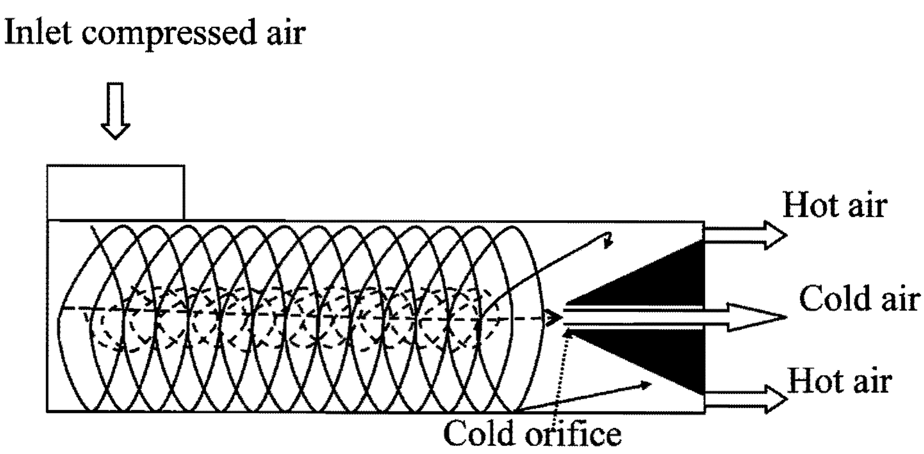

Figure 2 Schematic of a uni- flow vortex tube

In this article, the development of the RHVT based on the computational method is reviewed. This is involved the theory of energy separation and the impact of tube geometry and operating conditions on a RHVT performance. The important finding results from each research work are summarized.

COMPUTATIONAL MODEL

Energy/ Temperature Separation

Prior investigators paid attention on the mechanism of the separation effect and dimension of the Ranque-Hilsch Vortex Tube, RHVT. The explanation of the phenomenon proposed by Hilsch that a gradient of radial velocity generated by the expansion of air inside the tube from the high pressure near the wall to the low pressure at the center. Consequently, the kinetic energy transfers from the inner fluid layer to outer. Similar explanation was presented by several investigators (Martynovskii and Alekseev, 1956; Fulton, 1950; Negm 1988). In addition, pressure variation caused by acceleration and viscous resistance have an important role in temperature variation. Linderstrom-Lang was also emphasis on the centrifugal field and proposed the significant of the secondary flow and its interaction to the tangential velocity distribution (Linderstrom-Lang, 1966). The model of the transport of mass and energy in the vortex tube was developed to describe the tube performance in terms of work and availability as for gas separation and temperature separation processes respectively. It can be deduced from the discussion that the RHVT showed less impressive in mass separation. Deissler and Perlmutter (1960) studied the theoretical of the RHVT involved the velocity, temperature and pressure distribution in a turbulent vortex flow. It was found that the shear work made by the core flow on the outer flow has caused the energy separation. Gulyaev (1966) proposed that only the heat transfer process due to the conduction in a gas rotating as a rigid body is caused the transfer of heat from the axis region to the outer. Similar theory was presented by Eckert and Robert (1972). A fluid rotating in a tube provides a flow field that can be divided into an outer layer and inner layer, where the fluid acts like a solid-body rotation. The flow at the inner region has no shear stresses, so no viscous dissipation exists in a solid rotation flow. Energy is therefore transported merely by conduction. The difference between the total temperature at the radius R, T_R^o, and at the centre of the tube, T_0^o, is written as, $T_R^o - T_0^o = v_R^2 / c_p$ where V_R is the circumferential velocity in a function of tube radius and cp is a specific heat at constant pressure. Gutsol (1997) proposed another hypothesis on the energy separation in the RHVT that the centrifugal separation of turbulent elements in tangential velocity was actually the cause of this phenomenon. The strong turbulence with a tangential velocity difference in a centrifugal field was elevated the radial temperature distribution. Shannak (2004) reported that acceleration and viscous resistance caused the pressure of the fluid inside the tube to vary and resulted in temperature variation.

A different hypothesis is proposed by Kurosaka (1982) that the acoustic streaming induced by orderly disturbance in the swirling flow was the cause of the vortex effect. The sound emission was a discrete frequency of a spinning wave in swirling flows or the vortex whistle that proportional to the flow rate. The tangential velocity added into the steady swirl was transformed to a forced vortex and contributing to the total temperature separation in the radial direction. Furthermore, a vortex tube was proved that it can be used as a gas separation device. Regarding Cohen's theory of centrifuge, Linderstrom-Lang (1966, 1977) has adopted the mathematical equation from Cohen and validated with their experiment. The results confirmed the capability power of gas separation of vortex tubes. Centrifugal force is the cause of the separation effect where the important parameter is the hot to cold flow ratio.

An energy separation effect in a vortex tube with the use of air as a refrigerant was studied (Stephan et al, 1984). It was concluded that the temperature difference between the hot exit air and the inlet air, , and the temperature difference between the inlet air and the cold exit air, , were the function of the cold air mass fraction, the cold air mass flow rate divided by total air mass flow rate. A similarity relation for energy separation in a RHVT which could be written as . The ratio of ΔT_c to (ΔT_c)max was not depending on either the operating condition or the working fluid in the RHVT. Cockerill (1998) developed a computer based Navier-Stokes solver to simulate a turbulent flow in the RHVT. The developing code was sufficient to calculate the fluid flow for learning the mechanism of the energy separation. Kazantseva et al (2005) employed Navier-Stokes equations for solving an intense swirling flow in the RHVT numerically. The patterns of flow, velocity and temperature fields were obtained. Tarunin and Alikina (2006) showed their calculation to solve the hydrodynamics of compressible gas in complex geometry. It was suggested that only the calculation is enough to explain the effect inside the RHVT. Ahlborn et al. (1994) presented the conversion of kinetic energy into heat and a reverse process in the vortex tube. A mathematical model was developed and the calculation results were compared with experimental data. Mathematical equations were set up from the momentum and energy balances. The cylindrical coordinate system (r,Φ,z) was referred in order to describe the fluid profile in the tube. The limit of temperature separation in both hot and cold streams at the different ends of a vortex tube was given from the analysis. A limit of the hot air temperature can be calculated from .
A limit of the cold air temperature is , where is . The experimental result showed that the upper limit of hot exit air temperature and the lower limit of cold exit air temperature were dependent on the pressure drop between inlet and cold exhaust air. The inlet velocity was predicted by the model as high as a sound speed. Gao (2005) presented the modification model which developed from the secondary circulation model offered by Ahlborn et al (1998, 2000). The simulation results showed better agreement with the measurement than the original model. Plotnikov et al (2002) suggested a gas dynamics of a swirling flow in the RHVT to predict the temperature gradient. The results showed that the measurement offered greater effect than what obtained from the model. This might be caused by the cyclic loss of flow stability due to the appearance and disappearance of vortex structures at the axis.

Frohlingsdorf and Unger (1999) using the finite volume program from AEA Technology, the compressible and turbulent flow in a vortex tube were studied. Equation setup was based on mass, momentum and energy conservation. According to the transfer of mechanical work from the cold to the hot gas hypothesis, the shear stress-induced mechanical work has been considered as an extension term. The simulation result showed the transfer of energy from the cold to the hot stream by mechanical work. The friction of inner gas layer near the tube wall caused the mechanical energy transfer from cold to hot gas; therefore, the cold gas was cooled down while the temperature of hot gas increased. Rattanongphisat et al (2008) published the flow characteristic of fluid inside the RHVT. The visualized of flow provided from the computational fluid dynamics model using Fluent code was reported. The temperature gradient along the RHVT is shown in Figure 3. The temperature separation and secondary flow could be observed. The simulation results agreed well with the author own measurement. Lewins and Bejan (1999) reported a simplifying mathematical model for a RHVT from the optimization theory. The first optimization involved an energy balance and a minimization of the entropy rate. The second optimization considered the inside of a RHVT, as a heat exchanger, where the energy is exchanged between cold and hot airstream. The results showed the optimum refrigeration load at nearly half of maximum load in any given cold fraction. The optimum cold fraction at a half of a total gas masses was suggested by the second optimization. However, this optimization theory could not predict the actual performance. More accurate results mentioned by the investigators could be obtained from the use of computational fluid dynamics.

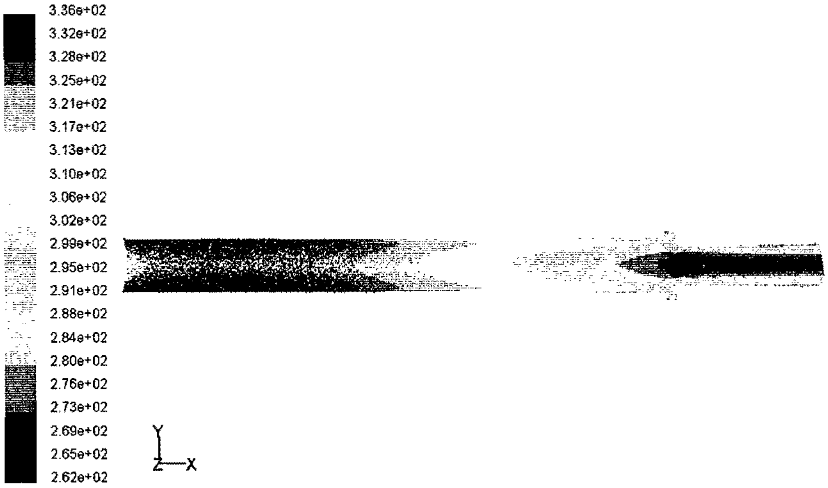

Figure 3. Total temperature profile in the vortex tube (Rattanongphisat et al, 2008)

A number of published works explained the mechanism behind based on heat transfer and turbulent model Lin et al (1990), Tarunin and Alikina (2005), Plotnikov et al (2002) and Dutta et al (2010). The overview of Ranque-Hilsch effect is also available (Eiamsaard and Promvong, 2008b). The first and second laws of Thermodynamics are employed to indicate the RHVT performance (Ahlborn et al, 1994; Ahlborn and Gordon, 1997; Saidi and Allaf-Yazdi, 1999; Simoes-Moreira, 2010). Saidi and Allaf-Yazdi (1999) applied a thermodynamic model for determining an energy separation in a vortex tube. The exergy analysis was presented in which the flow condition inside the RHVT assumed adiabatic. The entropy generation rate can be written $(\dot{S}_g)_{vortex-tube} = \dot{m}_i\left[C_p \ln \frac{(T_h/T_c)^{(1-y)}}{1+(1-y)(T_h/T_c-1)} + R\ln\frac{P_i}{P_c}\right]$, where S_c, S_h, and S_i are the entropies of the cold steam, The hot steam and the inlet air respectively, C_p is specific heat at constant pressure, mi is a mass flow rate of an inlet air, T_c and Th are cold and hot air temperatures respectively, y is the cold mass fraction, R is the universal gas constant, P_i is inlet pressure and P_c is pressure of cold air.An exergy analysis was used to optimize the dimensions and operating conditions of a vortex tube. The term of exergy destruction was minimized at the cold mass fraction about 0.7. Considering the RHVT as a refrigeration device, the tube effect was explained in terms of a thermodynamic cycle (Ahlborn et al, 2000). A vortex tube refrigerator has many things in common with a thermodynamic refrigeration cycle that both were driven by mechanical work input and the two systems have expansion, compression, and heat exchange process. Like a typical refrigeration cycle, the input work drives the heat engine which removes the heat from a room to environment. Therefore, the amount of heat from hot and cold fluids in both refrigerant and coolant loop can be calculated by the model. Moreover, the coefficient of performance, COP, of a vortex tube device is also assumed by the model. However, the model could not predict well when compared with the experimental measurement data and the manufacture data. In this case, it might be better to rethink whether or not to assume the cooling process in a vortex tube as same as a typical refrigeration cycle then apply thermodynamics for explanation a phenomenon in a vortex tube. The model of internal angular momentum for examining a physical effect in vortex tubes has studied (Trofimov, 2000). The model employs an angular-momentum distribution to sketch a real flow in vortex tubes which was useful to understand the physical effect by observation the temperature separation and other flow properties from experimentation. It was simplified the change of total enthalpy by the reasonable approximation on equilibrium and non-equilibrium thermodynamics. The model described the cause of temperature increase which is related to the action of angular velocity, Ω, on the strengthening of the angular momentum field, M, in the tube while the destruction of this field from the decrease of rapidity at the near axial region of the tube was caused to the temperature decrease.

The Ranque-Hilsch Vortex Tube Performance

In the literature study, the dimension of the RHVT significantly affected the performance of the RHVT. These parameters are the tube diameter, cold orifice diameter, hot and cold tube length, diameter and area of nozzles, type and number of nozzles. The design criteria for the RHVT was presented (Yilmaz et al, 2009). An optimum of tube length and diameter indicated in the ratio of tube length to tube diameter between 25 and 35 was suggested by Behera et al (2005). He also proposed that the configuration of nozzle with six numbers of convergent nozzle was offered higher total temperature difference compared to two numbers of nozzle. The nozzle design provided that the ratio of an inlet nozzle area to a cross section area of the RHVT approximately 0.11 suggested by Soni (1973). Cockerill (1998) presented the optimum cold orifice diameter in the ratio of the orifice diameter to the tube diameter in the range of 0.4 and 0.6.

The RHVT performance is also affected by the operating condition which mostly could be observed from the experimental work. It was found that the cold fraction is influenced to the RHVT efficiency which can be seen from the exergy destruction, Saidi and Yazdi (1999). Regarding to inlet pressure, this found significantly impacted the RHVT performance and the higher the inlet pressure the greater the tube performance, Hilsch (1947) and Ahlborn et al (1994). It has been seen that the irreversibility rate and inlet exergy were increased with the increase of inlet air pressure and independent of the nozzle numbers (Saidi and Yazdi, 1999; Kirmaci, 2009).

The RHVT efficiency can be calculated in terms of the coefficient of performance, COP, and the isentropic efficiency which employed in research work reported by Fulton (1950), Gao (2005) and Rattanongphisat (2008).

The summary of the computational results are shown in Table 1 which indicates both the capability of the model in predicting the separation effect, visualized the flow patterns and indicated the optimum tube geometry.

Table 1 Summary of the simulation finding based computational models

Authors	CFD code	Turbulence model	Validate with measurement	Results
Aljuwayhel et al. (2005)	Fluent	● 2 D ● S k- ε and RNG k- ε	Own experimental data	The length and diameter of the RHVT affect the energy separation.
Fröhlingsdorf and Unger (1999)	CFX	● k- ε	Bruun (1969)	The mechanical work transfer, due to friction, cause the vortex effect
Behera et al. (2005)(2008)	Star-CD	● 3 D ● RNG k- ε	Own measurement	The tube geometry for a good performance obtained
Skye et al.(2006)	Fluent	● 2 D ● S k- ε and RNG k- ε	Own measurement	● S k- ε gave better result ● The model can predict power separation
Sohn et al. (2006)	CFD-ACE	● 3 D ● S k- ε	Harnett and Eckert (1957)	Flow phenomena inside the RHVT is visualized
Eiamsa-ard et al (2008)	-	● Two dimension ● S k- ε	-	Results agree with measuring data
Rattanongphi-sat et al (2008)	Fluent 6.0	● 3 D ● S k- ε	Own measurement	● The characteristics of temperature distribution and energy separation obtained

Table 1 Summary of the simulation finding based computational models (continued)

Authors	CFD code	Turbulence model	Validate with measurement	Results
Farouk and Farouk 2007	CFD-ACE+	LES	Skye et al (2006)	• Performance curve obtained
Farouk et al 2009	CFD-ACE+	LES	-	• Performance curve obtained and gas separation is observed
Dutta et al.2010	FLUENT 6.3.26	S k- ε, RNG k- ε, S k- ω, SST k- ω	Behera et al (2005)	• Performance curve obtained • S k- ε better than others
Secchiaroli et al 2009	FLUENT 6.3.26	• RANS and LES	-	• Flow patterns and velocity profile obtained
Piralishvili and Fuzeeva 2005	CFX-TASCFlow	SST then k- ε	Own measurement	• Coefficient of hydraulic drag is a function of the process and the RHVT geometrical parameters
Ricci, et al 2009	FLUENT 6.3.26	• RNG k- ε, RSM • 3 D, LES	-	• Flow patterns are observed
Secchiaroli, et al 2009	FLUENT 6.0	• 3 D • RNG k- ε	Aljuwayhel 2003 thesis	• The cooling power increase with the increase of nozzle numbers

Noted: Two dimensional model (2 D); Three dimensional model (3D)
Re-Normalisation Group (RNG) methods; Large Eddy Simulation technique (LES);

The Shear Stress Transport Model (SST); Reynolds Stress differential Model (RSM)
An Algebraic Stress Model (ASM); Standard k- ε (S k- ε)

CONCLUSION

The computational models presented here benefits for the studying of the mechanism of energy/thermal separation effect in the Ranque-Hilsch Vortex. Particularly, a computational fluid dynamic model can also provide a visualize flow profile inside the RHVT which is very useful for understanding the thermal separation effect. The computational results were compared with the measuring data and showed good agreement. The good model is practicable to be use for prediction and designing of the high performance RHVT.

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