



Experimental study of vortex tube energy separation under different tube design

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ARTICLE INFO

Keywords:

Ranque-Hilsch tube
Vortex tube performance
Vortex tube geometry
Choked flow
Secondary circulation

ABSTRACT

Through experimental investigation, this study offers a closer look into the performance of the vortex tube energy separation under different geometrical parameters; mainly tube length, diameter and internal tapering angle. Also the study evaluates the effect of inlet pressure on the performance of the vortex. The data shows that the tested vortex tube has an optimum length between 66 mm and 158 mm, an optimum diameter between 9 mm and 26 mm and a tapering angle smaller than 4°. Finally the experimental data show that the higher the inlet pressure, the greater the temperature difference however there is a maximum value where performance starts to deteriorate due to inlet nozzle choking.

1. Introduction

Vortex tube is a thermal static device that produces cold and hot gases flow from room temperature compressed gas and is widely known as Ranque-Hilsch Vortex Tube (RHVT). The compressed gas enters the vortex tube tangentially forming a vortex flow which later exits from the vortex tube through two outlets known as cold end and hot end. At the hot end, the gas discharges at temperature higher than the inlet compressed gas temperature while at the cold end the gas discharges at temperature lower than the inlet compressed gas temperature. The vortex tube phenomenon was discovered by Ranque [1,2] in 1933 and re-evaluated by Hilsch [3] in 1974. The physical phenomena or physical mechanism that describes the energy separation inside the vortex tube is not well understood and is not resolved until now [4].

Vortex tube is covered extensively in literatures [5–7] through experimental and numerical analysis. Recently more focus is given to address the effect of geometry such as inlet nozzles size and orientation [8–10] and vortex tube geometry [11].

Westley [12] experimentally investigated the effect of different geometric parameters on the RHVT performance. He found that the optimum performance is manipulated by a relationship between five different geometric parameters which are the injection area, the tube length, the vortex tube cross-sectional area, the cold end orifice area and the inlet pressure. Westley [12] concluded that optimum RHVT is achieved by using the following parametric relations:

$$\frac{A_c}{A_{vt}} = 0.167, \quad \frac{A_{in}}{A_{vt}} = 0.156 + \frac{0.176}{\tau_p}, \quad \text{and} \quad \tau_p = \frac{p_{in}}{p_c} = 7.5$$

where A_c is the flow area of the cold exhaust, A_{vt} is the flow area of the vortex tube, A_{in} is the flow area of the inlet nozzle, p_{in} is the inlet pressure and p_c is the cold exhaust pressure. Parulekar [13] investigated the RHVT by testing a short conical tube and examined the conical angle effect on the vortex tube performance. He concluded that optimum RHVT performance is achieved when $\frac{L_{vt}}{D_{vt}} = 3$ where L_{vt} is the vortex tube length and D_{vt} is the diameter of the vortex tube. He also reported that RHVT performance is affected by tube roughness. He concluded that the performance of the RHVT system decreases due to the roughness element by inner surface of the tube. Parulekar [13] suggested that the tube cross section should be slotted and inlet nozzle should have a spiral shape. Borisenko et al. [14] reported that the optimum performance is achieved at tube conical angle of 3 degree. The conical vortex tube was further investigated for chemical applications by different researchers [15–17]. It can be finally said that there is an optimal conical angle and this angle should be very small as possible based on agreements between all researches.

Ting-Quan et al. [18] investigated the performance of temperature separation under different inlet pressure. They concluded that the inlet pressure has major effect on the temperature separation while keeping the inlet temperature at constant value. They noticed that when inlet pressure increases, the temperature separation increases for all cold volume fraction based on the work of Poshernev and Khodorkov [17]. Shannak [19] measured both cold and hot temperatures in RHVT and

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Nomenclature*List of symbols*

C_p	specific heat constant (kJ/kg K)
COP	coefficient of performance (-)
$\dot{m}_c$	mass flow rate for cold stream (kg/s)
$\dot{m}_h$	mass flow rate for hot stream (kg/s)
$\dot{m}_{in}$	inlet mass flow rate (kg/s)
$\dot{Q}_c$	cooling power gained via the system (W)
$\dot{Q}_h$	heating capacity of hot exhaust gasses (W)
RHVT	Ranque-Hilsch Vortex Tube
T_c	cold outlet temperature (K)
ΔT_c	temperature difference between the inlet and the cold outlet, $\Delta T_c = T_{in} - T_c$
T_h	hot outlet temperature (K)

ΔT_h	temperature difference between the inlet and the hot outlet, $\Delta T_h = T_h - T_{in}$
T_{in}	inlet temperature (K)

Greek symbol

ε	cold mass fraction = $\dot{m}_c / \dot{m}_{in}$ (-)
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Subscripts

c	cold
h	hot
HP	heat pump
R	refrigerator

found that the hot air outer temperature increases, as cold mass fraction increases until reaching maximum at $\varepsilon = 0.82$ and that the cold outlet temperature decreases when the cold air mass fraction decrease until reaching minimum value at $\varepsilon = 0.3$. The cold air mass fraction, between 0.82 and 0.3, reversely affects the outlet temperatures, so the hot temperature decreases and cold temperature increases in this region. Promvonge and Eiamsa-ard [20] studied the effect of number of inlet nozzles and the cold outlet diameter on the temperature separation. The results show that when the number of inlet nozzles increases the temperature separation increases. They also reported that the larger the cold outlet area, the lower the temperature separations is produced which results from the low back pressure. Singh et al. [21] reported that the cold mass fraction and the efficiency of RHVT depend on the size of the cold outlet more than on the size of the inlet nozzles. Furthermore, they found that the temperature separation increases when the length of the tube reach beyond 45 times the diameter. Xue et al. [22] reported three different parameters that have strong effect on RHVT performance which are the three dimensional velocity, the turbulent intensity and the pressure-temperature distribution. The experimental results show a relation between the formation of hot and cold streams and the vortex transformation along the tube.

This study presents experimental findings for vortex tube performance in achieving energy separation under different vortex tube geometrical parameters, namely: tube length, tube diameters and the tube tapering angle. Also the study reports the effect of inlet pressure that is widely reported in literature, on the vortex tube performance. In literature many study have reported the temperature separation as function of non-dimensional parameter L/D which is length-to-diameter ratio. However this study focuses on each parameter separately (length and diameter) to clearly show the importance of optimum diameter and optimum length.

2. Problem statement

The focus of this study is to find the effect of vortex tube geometry on the RHVT. As shown in Fig. 1, the RHVT can be divided to two sections which are vortex tube (right side) and inlet nozzles section (left side). The inlet nozzles are arranged in tangential form causing the flow to rotate in vortex when it enters the inlet nozzle section. The vortex tube is used to allow bigger region for secondary flow circulation which promotes energy separation. In this study the focus is on the vortex tube geometry including the vortex tube length (L), diameter (D) and tapering angle (θ) which are shown in Fig. 1.

3. Mathematical analysis

The vortex tube can be used for heating through the use of hot outlet

stream and the thermal heating load is calculated as follow:

$$\dot{Q}_h = \dot{m}_h C_p (T_h - T_{in}) \quad (1)$$

Also the vortex tube can be used for cooling through the use of cold outlet stream and the thermal cooling load is calculated as follow:

$$\dot{Q}_c = \dot{m}_c C_p (T_c - T_{in}) \quad (2)$$

Using conservation of mass, one can relate the hot stream to cold stream as follow:

$$\dot{m}_t = \dot{m}_h + \dot{m}_c \quad (3)$$

Following the work of Simões-Moreira [23], coefficient of performance (COP) of vortex tube is defined as follow:

$$COP_R = \varepsilon \frac{k}{k-1} \frac{(1 - T_c/T_{in})}{\ln(P_{in}/P_o)} \quad (4)$$

$$COP_{HP} = (1 - \varepsilon) \frac{k}{k-1} \frac{(T_h/T_{in} - 1)}{\ln(P_{in}/P_o)} \quad (5)$$

where $k = 1.4$ is the ideal gas heat capacity ratio.

4. Experimental setup

A schematic diagram of the experimental setup used in this study is shown in Fig. 2. As shown in the figure, the vortex tube is supplied with compressed gas using air compressor. To insure that the inlet temperature of the compressed gas does not change while operating, a 1 m³-size storage tank is used to ensure suppressing any pressure and possible temperature fluctuations in the supply air. The practice followed while conducting the experiments is to run the compressor for half an hour before conducting any test, in order (as highlighted above) to stabilize the tank pressure and temperature and to minimize any possible transient effects due to the compressor. The maximum

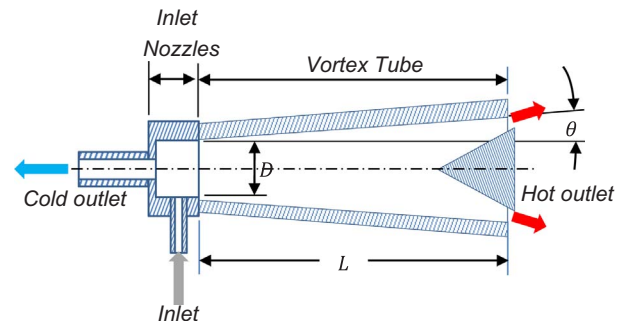


Fig. 1. Schematic diagram shows detail of the vortex tube with main geometric parameter, namely; tube length (L), diameter (D) and tapering angle (θ).

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