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Improving vortex tube performance based on vortex generator design

Mahmood Farzaneh-Gord*, Meisam Sadi

The Faculty of Mechanical Engineering, Shahrood University of Technology, Shahrood, Iran

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ABSTRACT

The effect of vortex generator parameters (Cold orifice angle, Cold orifice diameter and Nozzle area) on vortex tube performance is investigated experimentally. Vortex tube is connected to a natural gas pipeline with constant pressure of 4 bars. To improve vortex tube efficiency, six generators with different cold orifice angle, five generators with different cold orifice diameter and three generators with different nozzle area are studied for each experiment part. Results show variation of nozzle area has no effect on optimum cold mass fraction while cold mass angle and cold mass diameter move this point. Increment in cold orifice diameter increases optimum cold mass fraction and decreases cold temperature. As the angle of cold orifice increases, more mass flow passes through cold outlet and optimum cold mass fraction also increases. The expansion of the gas in the diffuser type cold orifice is investigated as the dominating reason for the different vortex tube performance. These mentioned designing parameters of vortex generator affect the flow pattern and efficiency of vortex tube as a consequence. For cold orifice angle of 4.1°, cold orifice ratio of 0.64 and nozzle area ratio of 0.14, highest efficiency is achieved.

1. Introduction

The VT (vortex tube) is a simple device without a moving part which is capable of separating a high pressure gas into hot and cold gas streams. The VT, also known as RHVT (Ranque–Hilsch Vortex Tube) was first discovered in 1933 by Ranque. The German physicist Hilsch [1] worked on the vortex tube and improved the designing parameters, provided comprehensive experimental and theoretical studies intend to improve the efficiency of the vortex tube. He methodically inspected the effect of the inlet pressure and the geometrical parameters of the VT on its performance and presented a possible explanation of the energy separation process. There have been a lot of researchers since then which studying vortex tube aiming to explain the reason of energy separation or enhance its performance. These studies could be divided into two categories as experimental and theoretical study.

Many researchers studied experimentally vortex tube and tried to demonstrate in what dimensions the best performance achieved. Thermophysical parameters and geometrical parameters are important factors affecting the VT performance (Saidi and Valipour [2]). They have classified the parameters affecting vortex tube performance as the thermophysical parameters such as inlet gas pressure, type of gas and cold mass fraction, moisture of inlet gas and the geometrical parameters, i.e., diameter and length of main tube and diameter of the outlet orifice were designated and studied. Xue and Arjomandi [3] studied the effect of the angle of rotating flow on the performance and efficiency of the vortex tube. To find best vortex angle, they used different vortex angle generators. A smaller vortex angle presented better performance for the heating efficiency of the vortex tube. Dincer et al. [4] have also experimentally studied the influences of the position, diameter, pressure and number of nozzles and angle of a mobile plug on the RHVT performance. The most efficient combination of parameters is obtained for a plug diameter of 5 mm, tip angle of 30 °C or 60 °C, by keeping the plug at the same position, and letting the air enter into the vortex tube through 4 nozzles. A series of experiments have carried out by Aydın and Baki [5] to study effects of the length of the pipe, the diameter of the inlet nozzle, and the angle of the control valve on the performance of the counter flow vortex tubes for different inlet pressures. Experiments demonstrated that the higher the inlet pressure, the greater the temperature difference of the outlet streams. It is also shown that the cold fraction is an important parameter influencing the performance of the energy separation in the vortex tube. Optimum values for the angle of the control valve, the length of the pipe, and the diameter of the inlet nozzle are obtained. Farzaneh-Gord and Kargaran [6] proposed the possibility of using vortex tube instead of throttling valves in natural gas pressure reduction points. They have studied VT performance with low pressure natural gas stream experimentally.

* Corresponding author. Tel.: +98 273 3330040x3353; fax: +98 273 3330258.
E-mail addresses: mahmood.farzaneh@yahoo.co.uk (M. Farzaneh-Gord), meisam.sadi@gmail.com (M. Sadi).

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Nomenclature

$A_{\text{Hot Tube}}$	hot tube area
A_{Nozzles}	nozzle area
d	cold orifice diameter (m)
D	vortex tube diameter (m)
h	enthalpy (kJ/kg)
h_c	cold enthalpy (kJ/kg)
h_{in}	inlet enthalpy (kJ/kg)
h_{cs}	cold enthalpy in isentropic process (kJ/kg)
Δh	enthalpy difference (kJ/kg)
Δh_{cs}	enthalpy difference in isentropic process (kJ/kg)
$\dot{m}_c$	cold mass flow rate (kg)
$\dot{m}_{in}$	inlet mass flow rate (kg)
P	pressure (MPa)
p_a	atmosphere pressure (MPa)
p_{in}	inlet pressure (MPa)
R	universal gas constant (kJ/kmol K)
s	entropy (kJ/kg K)
T	temperature (K)
T_c	cold temperature (K)
T_h	hot temperature (K)
T_{in}	inlet temperature (K)
ΔT_c	cold temperature difference (K)
ΔT_h	hot temperature difference (K)

Greek letters

α	cold orifice angle
β	ratio of cold orifice diameter to vortex tube diameter
γ	specific heat ratio
η_{isen}	isentropic efficiency
μ_c	cold mass fraction
ζ	nozzle area ratio

Farzaneh-Gord et al. [7] studied natural gas temperature behaviors in a VT and investigated the effects of hot tube length on VT efficiency. Further, the amount of cooling capacity created by natural gas as it passes through a VT has been calculated.

In parallel with experiments, researchers have carried out many theoretical activities, most are based on results obtained from the related experimental work and some are based on numerical simulations. A few attempts of applying numerical analysis tried to demonstrate the separation phenomena. Some other works tried to study vortex tube from a thermodynamic aspect view. Lewins and Bejan [8], Saidi and Allaf Yazdi [9], Farzaneh-Gord et al. [10] and Xue et al. [11] used the second law of thermodynamics to show temperature separation effect and measured losses in terms of exergy destruction, which provide direct measure of thermodynamic inefficiencies then resulted in several formulas for estimating the performance and efficiency of VT under different operating conditions, which induced the optimum ratios of VT dimensions corresponding to the highest efficiency. Different modeling technics are also used to optimize vortex tube dimensions. For example, by using 81 experimental data sets in the training step, heating and cooling performances of vortex tubes were experimentally investigated and modeled with Fuzzy modeling (Berber et al. [12]).

According to numerical and experimental attempts, various theories have been proposed in the literature to explain the "temperature separation" effect. These studies discuss the different theories to describe why this phenomenon happens in RHVT. Xue et al. [13] presented a critical review of explanations on the working concept of a vortex tube. They discussed hypotheses of pressure, viscosity, turbulence, temperature, secondary circulation and acoustic streaming. Based on the observed velocity, turbulence intensity, temperature and pressure distributions, Xue et al. [14] proposed multi-circulation as the main reason for thermal separation. They demonstrated that kinetic energy transformation outwards from the central flow contributes to the temperature separation. Briefly, the aim of all studies can be considered in three viewpoints; firstly, to find empirical expressions for geometrical/thermophysical parameters which can be used for improving the VT performance; secondly, to apply the VT for wide application purposes, like cooling and heating, cleaning, purifying and separation. In one application, vortex tube is used as a spot cooling device for a tractor cabinet (Kabeel et al. [15]).

Due to low efficiency of a vortex tube with natural gas as working fluid in previous studies (Farzaneh-Gord and Kargaran [6], Farzaneh-Gord et al. [7] and Farzaneh-Gord et al. [10]), the current research has been carried out to improve the performance of VT with natural gas as the working fluid. Study concentration focuses for vortex generator dimensions and designs. Different designing parameters of vortex generator (cold orifice angle, cold orifice diameter and nozzle area) affect the flow pattern in the vortex generator and consequently have an effect on efficiency of vortex tube. Different vortex generators have been considered. Six generators with different cold orifice angle, five generators with different cold orifice diameter and three generators with different nozzle area are examined. The natural gas from a pressure line extracted and directed into the vortex tube. It should be pointed out that the effects of cold orifice angle on the vortex tube performance have not been investigated in all previous researches. Also, cold orifice diameter and nozzle area effects on vortex tube performance for natural gas as working fluid are not studied yet. The variation of cold mass fraction at maximum temperature separation point is of our interest.

2. Theoretical issue

In order to study the performance of a VT, some terms (e.g. cold temperature difference, hot temperature difference, cold mass fraction and isentropic efficiency) should be defined firstly as follow:

a) The cold temperature drop (or difference) and the hot temperature difference of the vortex tube are defined as follows respectively:

$$\Delta T_c = T_{in} - T_c \tag{1}$$

$$\Delta T_h = T_h - T_{in} \tag{2}$$

b) Cold mass fraction is defined as the ratio of cold mass flow rate to inlet mass flow rate. By using a valve at the hot tube end, the passing mass of two ends is controlled.

$$\mu_c = \frac{\dot{m}_c}{\dot{m}_{in}} \tag{3}$$

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