1. Introduction

1.1 Introduction of vortex tube

A vortex tube (VT) is a simple and useful fluid dynamic device, used to obtain both cold and hot flows from a compressed gas at room temperature. It can produce a cold flow measuring around −30°C, and a hot flow of up to around 130°C. In 1930's, Ranque was the first to have discovered the energy/temperature separation phenomenon [1]. The first invented vortex tube by Ranque is shown in Fig. 1.1. Later in 1947, the flow mechanism of the vortex tube was investigated by Hilsch[2]. Since then, the vortex tube is also known as The Ranque-Hilsch Vortex Tube (RHVT).

There are a lot of advantages to VT, such as being light, small, with no moving parts, no need for maintenance, and an instant supply of cold flow. But, VT has low thermal efficiency and low coefficient of performance (COP), which is defined by the following equation;

$$\mathrm{COP}=\frac{\varepsilon c_p\left(T_{in}-\bar{T}_{t,cold}\right)}{\frac{\gamma}{\gamma-1}RT_{in}\left[\left(\frac{p_{in}}{p_{atm}}\right)^{\frac{\gamma-1}{\gamma}}-1\right]} \tag{1.1}$$

where ε is the cold fraction, c_p is the specific heat at constant pressure, T_{in} is the inlet temperature, $\bar{T}_{t,cold}$ is the mixing temperature of cold flow, γ is the specific heat ratio, R is the gas constant, p_{in} is the inlet pressure, and p_{atm} is the atmospheric pressure.

Figure 1.2 shows the comparison of COP between VT and other conventional cooling devices. As shown in the figure, the COP of VT is much lower compared to other cooling devices. But, compared to other conventional cooling devices, VT has a lot more merits to overwhelm the disadvantage, such as being small, lightweight, cheap, environmentally-friendly (no need for refrigerant), maintenance free (no moving part), and using a non-explosive device (no need of electrical power input). The VT has been mainly used as a device to cool small area, for example, electrical devices, thermal sensors, controlling cabins, cutting tools and areas under thermal stresses [3]. In addition to that, VT is also expected to be used as an oxygen collector of aero-propulsion engine for a subsonic-to-supersonic vehicle in in-flight condition [4], or as a device to clean exhaust gas of an internal combustion engine [5] as shown in Figs. 1.3 and 1.4, respectively.

There are 2 types of VT as shown in Fig. 1.5. Figure 1.5(a) is Uni-flow VT which consists of a vortex chamber, multiple or a single inlet nozzle, a control valve, and a tube. The center of the control valve at the end of the tube is an exit where a cold flow is discharged (cold exit). The peripheral area of the control valve is another exit where a hot flow is discharged (hot exit). Figure 1.5(b) is Counter-flow VT which consists of a vortex chamber, multiple or a single inlet nozzle, a control valve, and a tube. The cold exit is located at the center of the tube near inlet nozzle and hot exit is located at the peripheral of control valve at the other end. According to previous researches [6-7], the performance of counter-flow VT is better than the uni-flow VT. Therefore, in this research, I focus on counter-flow VT.

Next, a generally thought to occur flow pattern inside the Counter-flow VT is explained. As was shown in Fig. 1.5(b), compressed air enters a VT through a single or multiple tangential nozzles, and a high-speed vortical flow is generated in the vortex chamber. A part of the rotational flow follows the tube wall towards the opposite end; hot end. Then, this flow exits as a hot flow at the hot exit. The core flow, is forced back towards the vortex chamber by a control valve, and exits as a cold flow at the cold exit. The temperatures of cold and hot flows can be changed by adjusting a cold fraction ε, which is a ratio of the mass flow rate of a cold flow, $\dot{m}_{cold}$, to the inlet mass flow rate, $\dot{m}_{in}$;

$$\varepsilon = \frac{\dot{m}_{cold}}{\dot{m}_{in}} \tag{1.2}$$

The cold fraction is adjusted by axially moving the control valve left or right. From the definition of Eq.(1.2), the cold fraction value varies from 0 to 1. Cold fraction $\varepsilon = 0$ means, no flow exits from the cold exit, and $\varepsilon = 1$ means all flow inside the tube is discharged from the cold exit. A smaller value of the cold fraction produces a lower temperature of the cold flow, and a larger value of the cold fraction produces a higher temperature, closer to inlet temperature, of the cold flow [8]. For the hot flow, lower value of cold fraction produces a lower temperature of the hot flow, closer to inlet temperature, and higher value of cold fraction produces higher temperature of the hot flow [8]. Therefore, to obtain a lower temperature of cold flow, the value of cold fraction should be smaller, and to obtain a higher temperature of hot flow, the value of cold fraction should be larger.

The performance of VT is affected by the parameter of inlet nozzle, tube, control valve etc. Nowadays, many researchers are focusing on improving the performance of VT by changing geometrical parameters of VT. According to research works conducted in the past [6, 9-11], there are several ways to evaluate the performance of energy separation of the VT, in addition to COP in Eq.(1.1). For example, temperature difference $\Delta T_{t,cold}$, $\Delta \overline{T}_{t,cold}$ and $\Delta \overline{T}_{t,hot}$, total temperature difference $\Delta \overline{T}_t$, cooling capacity $\dot{Q}_c$, energy separation efficiency η_{sep} [9], energy separation flux energy η_{flux} [10], exergy efficiency η_{ex} [6], and isentropic efficiency η_{is} [11] defined by the following equations;

Temperature difference (inlet-cold)

$$\Delta T_{t,cold} = T_{in} - T_{t,cold} \quad \text{; Center temperature} \tag{1.3}$$

$$\Delta \overline{T}_{t,cold} = T_{in} - \overline{T}_{t,cold} \quad \text{; Mixing temperature} \tag{1.4}$$

Temperature difference (hot-inlet)

$$\Delta \overline{T}_{t,hot} = \overline{T}_{t,hot} - T_{in} \tag{1.5}$$

Total temperature difference (hot-cold)

$$\Delta \overline{T}_t = \overline{T}_{t,hot} - \overline{T}_{t,cold} \tag{1.6}$$

Cooling capacity

$$\dot{Q}_c = \dot{m}_{cold} c_p \Delta \overline{T}_{t,cold} \tag{1.7}$$

Energy separation efficiency

$$\eta_{sep} = \frac{T_{in} - \overline{T}_{t,cold}}{\frac{v_{in}^2}{2c_p} + T_s} \tag{1.8}$$

Energy flux separation efficiency

$$\eta_{flux} = \frac{\dot{m}_{cold}}{\dot{m}_{in}} \times \frac{c_p\left(T_{in} - \overline{T}_{t,cold}\right)}{\frac{\gamma}{\gamma-1} R T_{in}\left[\left(\frac{p_{in}}{p_{atm}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} = \text{COP} \tag{1.9}$$

Exergy efficiency

$$\eta_{ex} = \frac{\sum \dot{E}_{out}}{\sum \dot{E}_{in}} = \frac{\sum \dot{E}_{out,cold} + \sum \dot{E}_{out,hot}}{\sum \dot{E}_{in}} \tag{1.10}$$

where,