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AN INVESTIGATION OF THE EFFECT OF THE HOT END PLUGS ON THE EFFICIENCY OF THE RANQUE-HILSCH VORTEX TUBE

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Abstract

The phenomenon of temperature distribution in confined steady rotating gas flows is called Ranque-Hilsch effect. The simple counter-flow vortex tube consists of a long hollow cylinder with tangential nozzle at one end for injecting compressed air. The flow inside the vortex tube can be described as rotating air, which moves in a spring-shaped vortex track. The peripheral flow moves toward the hot end where a hot end plug is placed and the axial flow, which is forced back by the plug, moves in the opposite direction toward the cold end.

This paper focuses on the effect of the size of hot nozzle on the performance of the Ranque–Hilsch vortex tube. Series of plugs were used in the experiment in order to find the relationship between the diameter of hot end plug and the performance of the vortex tube.

Keywords: Vortex Flow, Vortex Tube, Ranque-Hilsch.

1. Introduction

The Ranque-Hilsch Vortex Tube is a device that generates separated cold and hot gases from a single compressed gas. The Ranque-Hilsch tube was invented by Ranque in 1933 and improved by Hilsch in 1947. The vortex tube is made of a cylinder in which gas is injected tangentially at several atmospheres, through a nozzle of a smaller area than the tube. Passing through the vortex chamber, injected gas forms strong vortical flow in the tube, which moves toward the hot end. The tube exit ports allow the gas to escape: the cold nozzle port is on the axis

Nomenclatures

A	Area
P	Power input
p	Air pressure
$\dot{Q}$	Heat rejected per unit time
T	Air temperature

Greek Symbols

ε	Cold mass fraction
Γ	$(\gamma-1)/\gamma$
γ	Specific heat ratio
η	Thermal efficiency

Subscripts

c	Cold air conditions
in	Inlet air conditions
p	Plug
t	Tube

of the tube near to the inlet and the hot nozzle port is at the periphery of the plug on the opposite side of the cold end.

Compressed air is injected into the device tangentially to create a vortex flow as shown in Fig. 1. When the vortex flow reaches the hot end, part of the flow is reflected by a plug which is placed at the hot nozzle. The plug adjusts the balance of the amount of air which is allowed to escape and the amount which is forced back through the axis of the vortex. This part of the flow leaves the tube from the cold end and is known as the cold fraction. These two separated hot and cold flows are shown in the CFD model of the Ranque-Hilsch Vortex tube in Fig. 2.

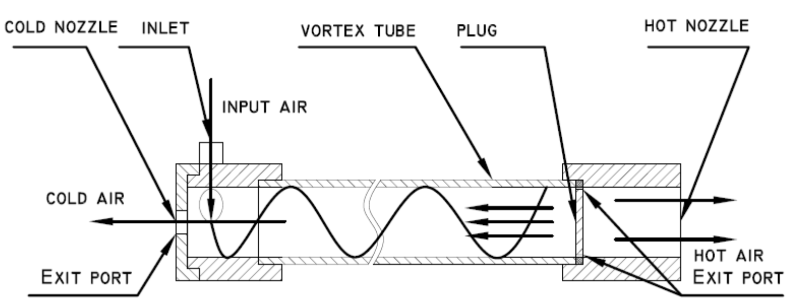

Fig. 1. Air Flow in the Vortex Tube.

The temperature drop between the hot and cold air streams is a function of the input parameters and geometrical characteristics of the tube. Hilsch [1] was the first one who investigated the effect of the geometrical parameters on the performance of the Ranque-Hilsch vortex tube, in 1947. Later on, further research has been performed in order to explain this phenomenon. However, the physical mechanism of the temperature separation is still not completely resolved.

Pongjet and Smith [2] investigated the vortex thermal separation in a vortex tube refrigerator, using two different tubes, insulated and non-insulated. Later, the air velocity inside of the tube was measured by Gao et al. [3] and the performance of the vortex tube with different parameters like cold fractions, pressures of the injected air and shape of the vortex tube was investigated.

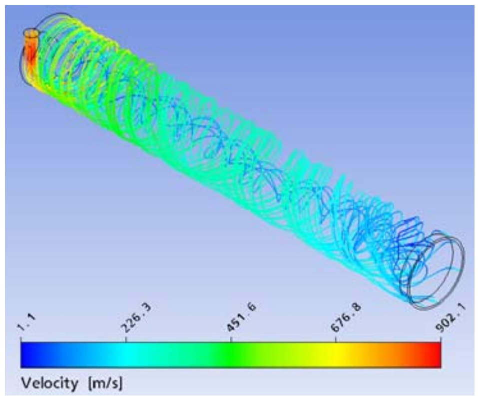

Fig. 2. CFD Model of the Ranque-Hilsch Vortex Tube.

This work focuses on the influence of the dimension of the plugs placed at the hot end on the vortex tube efficiency. To ignore the influence of the shape of hot-end plugs, all the plugs used in the experiments have similar shapes with different diameters. Similar investigations on testing the different shapes of plugs were done by Takahama [4], Linderstrom-Lang [5], Guillaume and Jollys [6], and Smith [2]. Gao [3] and Pongjet [2] used conical valves to control the cold mass fraction. In their work the shape of the conical valve at the hot nozzle changed when it was moved to adjust the balance of the mass flow rate.

In the experiments done in the current research, plugs with different diameters have been used while the shape and all other geometrical parameters of the tube have been kept the same. The tube thermal efficiency has been used as the parameter describing the tube performance for the different hot end plugs. Also the experiments for measurement of temperature and pressure have been done for total blockage of the hot end. The results of these experiments have been used for calculation of the tube efficiency in the extreme condition.

2. Experimental Procedures

The setup of the experimental apparatus and the main sizes of the vortex system are shown in Fig. 3. In these tests the tube was positioned horizontally. A large tank of compressed air was used as the source of the working material. A pressure regulator was placed before the inlet nozzle, which was used to control the input pressure of the air and maintain constant input pressure. The replaceable plugs were fixed at the hot end and cold air nozzle diameter was kept constant during the experiment.

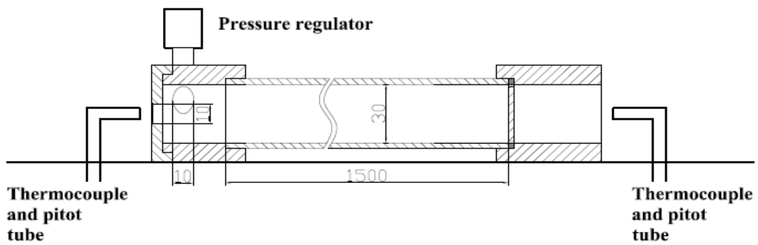

Fig. 3. Experimental Apparatus.

To reduce the influence of the humidity, ambient pressure and temperature, all tests were done in the similar weather conditions. During the experiments temperature was measured by a thermocouple and the exhausting air pressure was measured by a Pitot tube, which were fixed at the distance of 50mm from the exhaust nozzle and along the centreline of the tube.

3. Results and Discussion

The thermal efficiency of the tube has been used for comparing the different hot end plugs. To calculate the thermal efficiency Eq. (1), presented by Fulton [7], has been used

$$\eta = \frac{\dot{Q}}{P} = \frac{1}{\Gamma} \frac{\varepsilon \Delta T}{T_{in} \ln \frac{p_{in}}{p_c}} \tag{1}$$

where η is the vortex tube thermal efficiency, $\Gamma=(\gamma-1)/\gamma$, γ is the specific heat ratio$=1.4$, ε is the cold mass fraction and is defined as the cold mass flow rate divided by the input mass flow rate, ΔT is the temperature difference, T_{in} is the input temperature, p_{in} and p_c represent the air pressure at the inlet and at cold air nozzle, respectively.

Figure 4 shows the cold mass fractions when different plugs were tested. In this figure, A_p/A_t is the ratio between plug area and tube cross section area. As it is seen the cold mass fraction increases from 0.17 to 1 when A_p/A_t changes from 0.75 to 1 which is the result of varying the plug diameter from 26mm to 30mm.

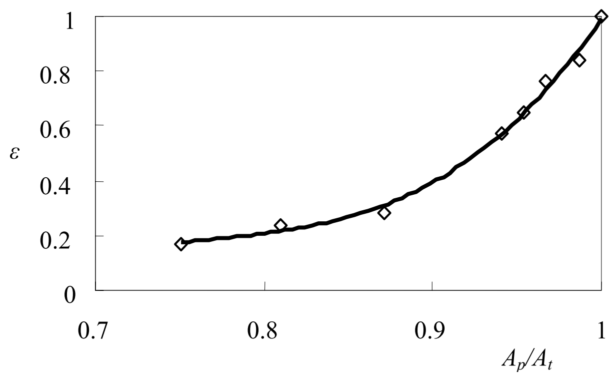

Fig. 4. Cold Mass Fraction versus the Size of the Plugs.

Figure 5 shows the temperature changes for different cold mass fractions. Highest temperature occurs at the cold mass fraction of 0.84 and lowest temperature occurs at the cold mass fraction of 0.57.

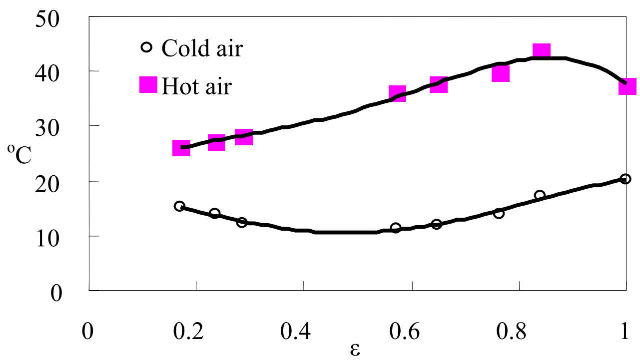

Fig. 5. Temperature of the Air versus Cold Mass Fraction.

Figure 6 shows the thermal efficiency of the vortex tube. The cooling efficiency reaches to its peak value of 16% when the cold mass fraction is 0.76 and the heating efficiency gains its highest value which is 9.2% when the cold mass fraction is 0.65. The tube thermal efficiency at cold mass fraction of 0.3 is 5%, which is similar to the results reported by Gao [3], where he found that at the cold mass fraction of 0.3 the thermal efficiency of the tube is about 4%. The difference between the cooling and heating efficiency could be explained by the heat transfer between the tube and ambient air. The heat transfers from the hot tube to the ambient air which is resulted in the loss of heating efficiency, when the temperature of the tube is higher than the ambient temperature. Oppositely, the heat transfers from the ambient air to the hot air via the wall of the tube which increases the heating efficiency, when the temperature of the hot air is lower than the ambient temperature. Figure 7 shows the thermal efficiency of the tube versus the plug sizes. In this figure A_p/A_t is the area ratio between the plugs and the tube. It is seen in this figure that the plug size has large effect on the tube efficiency when the area ratio is between 0.9 and 0.98, and the best performance occurs at the area ratio of 0.96.

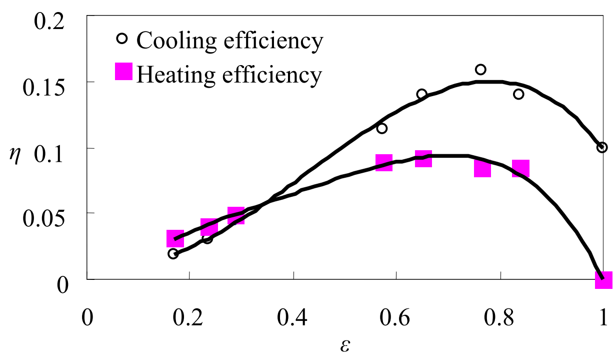

Fig. 6. Thermal Efficiency of the Tube versus the Cold Mass Fraction.

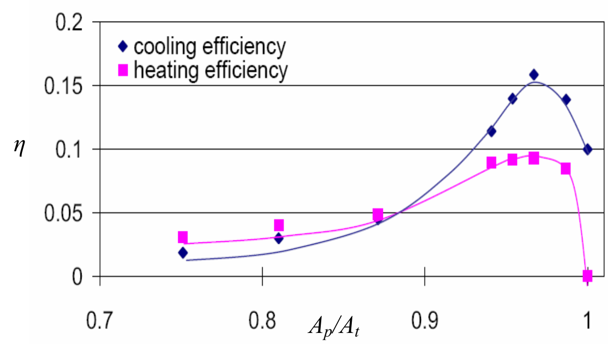

Fig. 7. Thermal Efficiency of the Tube versus the Plug Size.

When the 30mm plug was installed at the hot end, all the air escaped from the cold nozzle and consequently the cold mass fraction was 1. For this extreme condition the air temperatures of 20.2 and 37.5 were recorded for the cold nozzle and tube wall respectively. The heat generation in the tube can be explained by the friction between vortex flow inside the tube and tube wall. Also due to sudden expansion the temperature at the cold nozzle is less than input temperature. This point does not support the secondary circulation modelled by Ahlborn [9], which presents the cumulative mass flow over the cross section of the vortex tube in the cold end is larger than the cold exhaust flow.

4. Conclusions

Experiments were conducted to find the relationship between the hot-end plug diameter and the efficiency of the Ranque-Hilsch vortex tube. The results show that the size of plug determining the cold mass fraction results in different efficiencies. It was also shown that the efficiency of the tube is maximised when the area ratio is between 0.9 and 0.98.

The geometrical parameters of the tube which is designed for achieving the maximum temperature are different from those of the tube designed for cooling purposes. Generally, Ranque-Hilsch vortex tube is more efficient as a cooling device rather than an air heater.

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