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Experimental study of the thermal separation in a vortex tube

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ABSTRACT

A vortex tube, a simple mechanical device capable of generating separated cold and hot fluid streams from a single injection, has been used in many applications, such as heating, cooling, and mixture separation. To explain its working principle, both experimental and numerical investigations have been undertaken and several explanations for the temperature separation in have been proposed. However, due to the complexity of the physical process in the vortex tube, these explanations do not agree with each other well and there has not been a consensus.

This paper presents an experimental study of the flow properties in a vortex tube focusing on the thermal separation and energy transfer inside the tube. A better understanding of the flow structure inside the tube was achieved, based on the observed three-dimensional velocity, turbulence intensity, temperature and pressure distributions. The gradual transformation of a forced vortex near the inlet to a free vortex at the hot end is reported in this work. The calculated exergy distribution inside the vortex tube indicates that kinetic energy transformation outwards from the central flow contributes to the temperature separation. Experimental results found in this research show a direct relationship between the formation of hot and cold streams and the vortex transformation along the tube.

1. Introduction

From a single injection of compressed air, a Ranque-Hilsch vortex tube generates instant cold and hot streams at the opposite ends of the tube. Fig. 1 shows the structure of a counter-flow vortex tube, which consists of a straight tube with a port for tangential injection and exits at each end. With the tangential injection of compressed gas, the cold stream is exhausted from the central exit near the inlet, and the hot stream is exhausted from the peripheral exit at the other end of the tube. Xue et al. [1] summarised different explanations for the thermal separation in a vortex tube. The critical analysis of these explanations reveals that there has not been a well-accepted explanation for the temperature separation in a vortex tube so far.

To identify the mechanism of thermal separation in a vortex tube, understanding of the physical process inside the tube is essential. Xue et al. [2] conducted a qualitative analysis of the flow behaviour in a vortex tube using flow visualization techniques, in which a flow recirculation, named the multi-circulation, was identified, whereby part of the central flow moved outwards and returned to the hot end. Hence, they suggested that flow streams separate with different temperatures because of the sudden expansion near the inlet to generate the cold flow, and partial stagnation of the multi-circulation near the hot end to generate the hot flow.

The flow properties inside the vortex tube have been studied by many researchers, in order to validate the internal flow behaviour. It was reported by Takahama [3] that the flow inside a vortex tube behaves as a forced vortex based on measurements of the swirl velocity. To explain the existence of the secondary flow in a vortex tube, Ahlborn and Groves [4] measured both azimuthal velocity and axial velocity. Their results suggested that the flow consisted of a Rankine vortex, with a forced vortex in the centre and free vortex in the periphery. Detailed measurements of the flow in a counter-flow vortex tube, including the 3-D velocity distribution, temperature and pressure gradients, were conducted by Gao et al. [5]. However, due to difficulties in obtaining experimental measurements inside the vortex tube, there has not been a consistent understanding of the flow behaviour, so further clarification of the flow properties is required.

Energy transfer between different layers of flow inside the vortex tube is believed to be the main reason for the thermal separation as discussed previously [1]. Therefore, an energy analysis needs to be included in a thorough investigation of the vortex tube. Saidi and Allaf Yazdi [6] derived a equation based on the thermodynamic principles to calculate the rate of entropy generation in a vortex tube and provided a new method to optimize the tube's dimensions and operating conditions. Moreover, in their numerical study, Frohlingsdorf and Unger [7] reported that it is possible to analyse the energy separation by calculating the work done on fluid due to viscous shear. Dincer et al. [8,9] performed an analysis of the exergy performance of a vortex tube, in which the effects of

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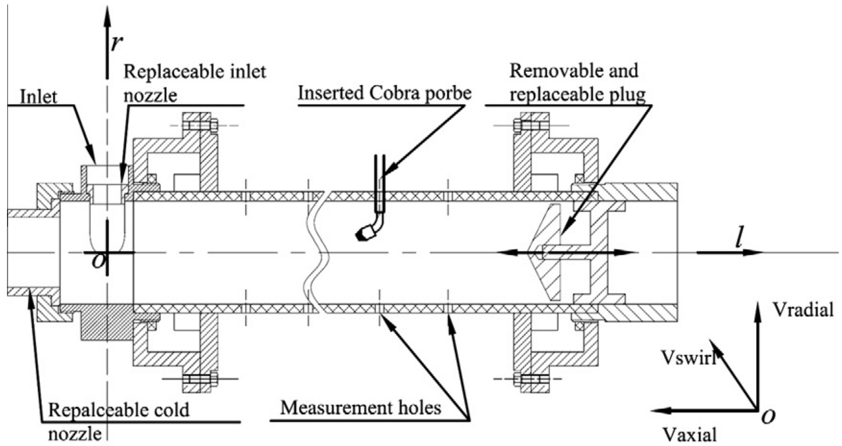

Fig. 1. Structure of a counter-flow vortex tube.

different nozzles and working fluids were investigated. Energy transfer between different layers of flow has also been simulated by Aljuwayhel et al. [10] and Behera et al. [11], in which energy transfer due to viscous shear and heat transfer were given as the main reasons for the thermal separation. However, inconsistent distributions of shear work and heat transfer along the tube indicate the need for further verification of the energy analysis.

In order to identify the dominant factors in the generation of separate cold and hot streams in a vortex tube, this paper presents an energy analysis of the internal flow based on the measurements of the flow properties and velocity distributions. In a specially designed large-scale vortex tube, three-dimensional velocity distributions, static temperature and static pressure inside the tube were measured and used to perform the energy analysis. It is found that the kinetic energy transferred from the central stream to the peripheral stream is not the dominant reason for the temperature drop in the vortex tube but contributes to the temperature rise near the hot end. Instead, the sudden expansion near the inlet and partial stagnation of the multi-circulation in the rear part of the vortex tube are the main factors in generating cold and hot streams respectively.

2. Experimental apparatus

Due to the strong swirling motion of the flow, the high turbulence intensity inside the vortex tube and the small dimensions of the tube, it is difficult to conduct high fidelity experimental investigations. The experimental study becomes more complicated when the measurements are taken by intrusive probes causing vortex shedding and stronger turbulence. In order to obtain accurate quantitative observations of the flow in a vortex tube, a large-scale tube with a length of 2000 mm and diameter of 60 mm was employed in this work as shown in Fig. 1. To allow the measurements of flow properties at different locations of the tube, 35 inline holes were drilled along the acrylic tube with a distance of 50 mm from each other. The tube length in this experiment was fixed at 21 times of the tube diameter, i.e. $L/D = 21$ from the inlet. A round inlet nozzle with a diameter of 6 mm, a cold exit with a diameter of 14 mm and a hot exit of 1 mm gap, formed by inserting a 58 mm plug into the 60 mm tube, were chosen based on an optimization of the temperature difference [12]. Compressed air was injected through the inlet nozzle at 2.6 bar and 297.15 K. During the experiments the vortex tube was positioned horizontally on a table and measurement devices were inserted into the tube through the holes along the tube.

A Turbulent Flow Instrumentation brand Cobra probe was used to obtain 3-D velocity, static pressure and turbulence intensity profiles at different locations along the tube. The small dimension of the probe head ensured a minimum disturbance introduced to the internal flow. The probe was mounted on a manual traverse vertically with a positioning accuracy of 0.01 mm in the radial direction. By adjusting the angular position of the tube, the cobra probe was inserted through the centre of the tube, so the flow profiles were measured in the radial direction of the tube. A useful feature of the cobra probe software was its provision of a measure of acceptable data. Fig. 2 shows the results of a typical measure-

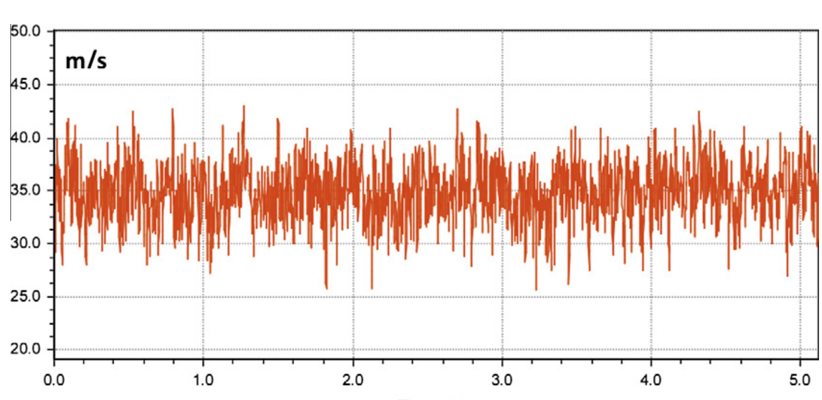

Fig. 2. Typical measurement result of the total velocity using the cobra probe.