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Energy analysis within a vortex tube

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ABSTRACT

The generation of separated cold and hot streams from a single injection in a vortex tube is known as the Ranque effect. Since its invention, several explanations concerning the phenomenon of thermal separation in a vortex tube have been proposed, however there has not been a consensus, due to the complexity of the physical process inside the tube.

This paper proposes an explanation for the temperature separation in a vortex tube based on an experimental study focusing on the flow structure and energy analysis inside the tube. Using the measured flow properties inside the tube, the exergy density distribution along the vortex tube was calculated, from which the reasons for the temperature separation were identified. The good agreement of the exergy density analysis with findings from other experimental work supports the validity of the proposed hypothesis.

1. Introduction

Invented by Ranque in 1933, the vortex tube has been used in many industrial applications, due to its simplicity and ability to generate separated cold and hot streams from a single injection. 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 of the tube ends. A control plug, with a smaller diameter than the tube diameter, is positioned inside the tube away from the injection end to allow the gas to escape from the small gap between the control plug and the tube wall. When compressed air is injected into the tube from the tangential inlet, it forms a highly vortical flow as it moves to the other end of the tube. The peripheral part of the airflow escapes at a temperature higher than the inlet temperature from the peripheral gap, which is also known as the hot exit. While, the core part of the airflow, which is turned back by the plug in a counter-flow vortex tube, escapes from the central exit near the injection, i.e. the cold exit, at a temperature lower than the temperature of the fed air. Thus, with a single injection, the injected flow is divided into two streams with different temperatures, which is known as the phenomenon of temperature separation or the Ranque effect. As demonstrated in Fig. 1, a vortex tube does not have any internal or moving parts. Hence, the temperature separation effect in a vortex tube can be explained solely using fluid dynamical theories.

Xue et al. summarized [1] different hypotheses describing the main process of thermal separation in a vortex tube based on experimental, theoretical and numerical work. The critical analysis of the presented theories reveals that a well-accepted explanation for the temperature separation in a vortex tube has not been proposed. Recently, an explanation [2] was reported that the separation of energy within a vortex tube was achieved by the turbulent eddies, which carry the heat from the core to the periphery. The similarity between this explanation and the secondary circulation [3,4] and the lack of new evidence provided in the manuscript indicate the unclear mechanism within a vortex tube and requirement of a new hypothesis.

To identify the dominant factors of the thermal separation in a vortex tube, an understanding of the physical processes inside the tube is required. In another work, Xue et al. [5] conducted a qualitative analysis of the flow behavior in a vortex tube using visualization of the flow inside a transparent tube. They showed that in an operating vortex tube, a portion of the central flow moved outwards and returned to the hot end in a flow pattern, termed multi-circulation. Hence, they hypothesized that the generation of two flow streams with different temperatures is due to the expansion of the injected gas near the inlet and partial stagnation of the multi-circulating flow near the hot end.

This paper proposes a new explanation for the temperature separation in a vortex tube based on an analysis of the internal exergy density distribution along the vortex tube. To identify the governing factors affecting the temperature separation, clarification of the energy transfer between different layers of the internal flow is required. According to detailed measurement results, the exergy density gradient inside the vortex tube can be used to show and verify the energy transfer between flow layers. It is found that in the front part of the vortex tube, i.e., also known as the cold part,

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Nomenclature

θ	exergy density ratio
ρ	density (kg/m^3)
C_p	specific heat at constant pressure (kJ/kg K)
D	diameter of the vortex tube (mm)
dh	change of enthalpy (J)
dp	pressure change (Pa)
ds	entropy change (J)
E	energy of the control volume (J)
ex	exergy density (J/m^3)
Ex	exergy of the control volume (J)
g	gravitational acceleration
H	enthalpy of the control volume (J)
I_{uvw}	overall turbulence intensity
l	axial location (mm)
L	effective length of the vortex tube from inlet to the plug (mm)
m	mass (kg)
P	pressure (Pa)
δQ	infinitesimal transfer of heat to the control volume (J)
r	radial location (mm)
R	radius of the vortex tube (mm)
R	universal gas constant
S	entropy of the system (J)
ΔT	temperature difference (K)
T	temperature (K)
v	velocity (m/s)
$\bar{v}$	time-averaged overall velocity (m/s)
v'	time-varying velocity fluctuating component (m/s)
V	volume (m^3)
z	net height (m)

Subscripts

g	gravitational
i	instantaneous conditions
in	input parameter
k	kinetic energy
$k, Mean$	average kinetic energy
$k, Turbulence$	kinetic energy of turbulent component
o	reference conditions
t	total

the exergy density in the central region drops dramatically. This is associated with the process of injecting gas to the central region of the tube and indicates the effect of the pressure gradient. The slightly changed exergy density of the peripheral flow in the rear part of the vortex tube, i.e., also known as the hot part, suggests that there is small amount energy transferred outwards and the temperature rise in the vortex tube is mainly caused by the partial stagnation and mixture due to the multi-circulation in the rear part of the tube.

2. Experimental apparatus

To investigate the exergy density, the flow properties inside a large-scale vortex tube with a length of 2000 mm and a diameter of 60 mm were measured (Fig. 2). The large diameter of the vortex tube is selected to ensure accurate measurement and to minimize the turbulence induced by the intrusive equipment. A round 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 the optimization of the tube performance as reported in [6].

A Cobra probe was used for the measurement of the flow properties inside the vortex tube, including 3-D velocity, static pressure and turbulence intensity of the flow. Data from the Cobra probe was logged and processed using the Turbulent Flow Instrumentation control software. The cobra probe was inserted into the vortex tube through the drilled holes along the tube and the small dimension of the probe head, i.e. 1.4 mm width, ensured minimum disturbance to the internal flow.

Due to measurement range limitations, the cobra probe could only be used for the measurements of 3-D velocity when the flow velocity was between 2 m/s and 50 m/s. For velocities higher than 50 m/s, the acceptance of data collected by the cobra probe was reduced to less than 80%. Therefore, a rotatable pitot tube (RPT) was employed for validation of the pressure and velocity measurements beyond the range measurable by the cobra probe. The structure and working principle of the rotatable pitot tube are presented in Fig. 3, which depicts a 1 mm tube with a 0.2 mm hole on one side and a pressure sensor connected at the other end. The RPT was rotating at a constant velocity (0.2 rad/s) during the measurement, and the measured surface pressure of the tube (0–50 kPa) was recorded continuously. The direction and magnitude of the total velocity were calculated using the surface pressure distribution.

The total temperature distribution along the vortex tube was measured using a T-type thermocouple inserted into the tube through the available holes. Due to the tube dimensions and construction of the vortex tube, the temperature difference in this experiment was not as significant as it is in a commercial vortex tube. Considering this relatively small temperature change and the low Mach number of the flow in the tube, a recovery factor of 1 was assumed for the static temperature calculation.

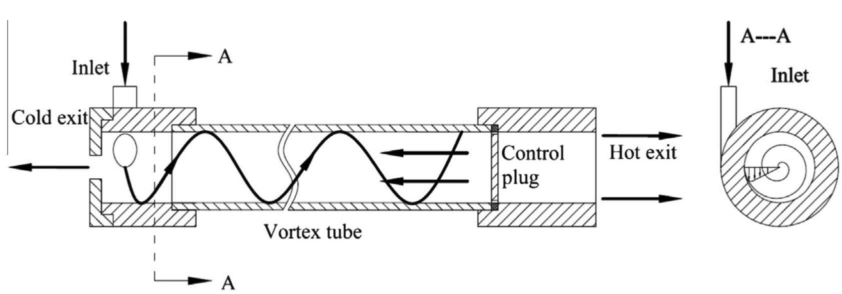

Fig. 1. Schematic of a counter-flow vortex tube.