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Analysis on the fluid flow in vortex tube with vortex periodical oscillation characteristics

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ABSTRACT

To reveal the energy transferring mechanism in the vortex tube, which is an interesting phenomenon in the area of heat and mass transfer, numerical simulation and analysis of the dynamic fluid flow were employed. In contrast to the previous static study, the focus of this paper is the dynamic process, or the oscillation, of the secondary circulation layer. Based on the fluid flow results derived from the unsteady 3-D computation, the existence of the forced or Rankine vortex was confirmed, which also verified the certainty of reverse flow in the cold end of the vortex tube. Then, the oscillation of the boundary layer of the central recirculation zone was emphasized and the periodical vibrating of the fluid flow within the secondary circulation zone, varying of its boundary, and the typical frequencies of points on a cross section were provided. Based on these results, a novel energy transferring mechanism in the vortex tube was proposed, under the condition that stable oscillation of the boundary layer is the dominant mechanism for the heat and mass transfer process.

1. Introduction

Though the configuration of a vortex tube is simple, it exhibits a unique phenomenon of energy (or temperature) separation with a single source of pressurized gas to instantly generate cold and hot streams simultaneously. Fig. 1 shows the structure of a counter-flow vortex tube, which contains a main tube with tangential injection in the vortex chamber, a cold exit near the inlet, and a hot exit far from the inlet containing a control valve to change the flowrate proportion between both exits and achieve different effects of energy separation. The instant cooling or heating effects are produced without any moving parts or chemical reactions inside the vortex tube, which lowers the amount of maintenance necessary and increases the service life. Due to the high swirl velocity caused by the tangential injection, gas separation and undesired condensable component removal from a gas stream have become areas of research interest. The cooling effects have made vortex tube advantageous for use in liquefaction of natural gas.

Since the vortex tube was invented by Georges J. Ranque [1] in the 1930s, the quantitative analysis and mathematical model of energy separation have not been fully developed due to the intense turbulent swirling flow in the vortex tube. A better description of the flow structure and more reasonable explanation of the energy separation have limited broader use and higher thermal efficiency of the vortex tube. Studies of the vortex tube have been chronologically reviewed by Gutsol [2], Eiamsa-ard [3], Xue [4] and Thakare [5] in recent decades. Among the different explanations or hypothesis models, the secondary circulation, resulting from part of the cold air that is forced back by the plug must return to the hot end, has been experimentally and numerically confirmed. It has been suggested that the thermal energy transferred from the inner flow to the outer flow is a refrigeration cycle or heat pump, as proposed by Ahlborn [6,7]. Xue [8–10] also concurred with the presence of secondary circulation and attributed the energy separation to partial stagnation.

Although there have been intensive studies on fluid flow and heat transfer within the vortex tube, a clear explanation of the process in which heat is transferred from the low-temperature region in the center to the outer higher-temperature region has not been provided. Most of the previous research is based on static gradient analysis, such as pressure, temperature or velocity.

Other interesting investigations analyzing fluid flow and energy transfer within the vortex tube lead to another research direction. Acoustic streaming in the core-flow was studied by Kurosaka [11], who believed the streaming induced by orderly disturbances in the swirl flow deforms the Rankine vortex into a forced vortex, which leads to energy separation in the radial direction. Liew [12,13] established a model similar to Maxwell's demon with adiabatic compression and expansion caused by turbulent eddies. In Liew's

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Nomenclature

u	velocity (m/s)
T	temperature (K)
t	time (s)
p	pressure (Pa)
$\dot{m}$	mass flow rate (kg/s)
S	swirl number
w	length of vortex tube inlet (m)
h	width of vortex tube inlet (m)
A_{inlet}	area of vortex tube inlets (m^2)
A_{tube}	section area of main tube (m^2)
D	diameter (m)
R, r	radius (m)
G_{ϕ}	the axial flux of angular momentum ($N \cdot S$)
G_x	the axial flux of linear momentum ($N \cdot S$)
Ω	angular velocity (s)
Γ	circulation (m^2/s)

Greek symbols

ξ	cold mass fraction
ρ	density (kg/m^3)
τ	time (s)
φ	phase angle (rad)
ω	vorticity (s^{-1})

Subscripts

c	cold gas
h	hot gas
t	tangential direction
x,z	axial direction
i,in	inlet gas
e	main tube

model, the gas pocket was moved back-and-forth between the wall and axis to exchange energy with the flow in the core and periphery, resulting in the temperature separation. From their work, evidence of swirl dynamics and analysis on the vibration of swirl flow was introduced.

In this paper, the fluid flow is analyzed with the knowledge of swirl flow. From simulation and calculation, it is clear that reverse flow within the vortex tube is a natural feature of the strong swirl flow. The vortex breakdown and leakage of partial pressurized gas to the cold exit is not taken into consideration. In addition, the important inherent characteristic of vortex breakdown cannot be considered time-stable, and the precessing vortex core (*PVC*) phenomenon is studied. There was some evidence of *PVC* contributing to the energy separation in Kurosaka's experiment [11], where acoustic suppressors were used to weaken the *PVC* and resulted in distinct deterioration of the temperature separation effect. Based on these ideas, a new energy transfer model within the vortex tube is presented in this paper.

In addition to providing analysis on the energy separation phenomenon of the vortex tube, we theorize that the combination of pulsation flow structure and energy transfer may contribute to the common studies of fluid flow and heat transfer.

2. Numerical model and verification

To analyze the swirl flow and its dynamic features, the unsteady computation fluid dynamic method was implemented to acquire fluid field data.

2.1. Geometry model

In this paper, the vortex tube used by Dincer et al. [14] in experimental studies and by Baghdad et al.[15,16] in steady-state numerical investigations was used to make comparisons and verification. The geometry of the vortex tube is shown in Fig. 1.

2.2. Governing equations of numerical model to the fluid flow

The mass, momentum, energy conservation and state equation solved for compressible turbulent flows in the vortex tube are as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho \overline{u_i}) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho \overline{u_i}) + \frac{\partial}{\partial x_i}(\rho \overline{u_i u_j}) = \frac{\partial}{\partial x_j}\left(\mu \frac{\partial \overline{u_i}}{\partial x_j} - \rho \overline{u_i' u_j'}\right) - \frac{\partial p}{\partial x_i} \tag{2}$$

$$\frac{\partial}{\partial t}(\rho H) + \frac{\partial}{\partial x_i}(\rho \overline{u_j} H) = \frac{\partial p}{\partial t} + \frac{\partial}{\partial x_j}\left(\frac{k}{c_p}\frac{\partial H}{\partial x_j} - \rho \overline{u_i'} H\right) \tag{3}$$

$$p = \rho R T \tag{4}$$

where ρ is the fluid density, u is the fluid velocity, p is the static pressure, H is the total enthalpy, k and c_p are the thermal conductivity and specific heat of the fluid, respectively, R is the ideal gas constant, and T is the gas temperature.

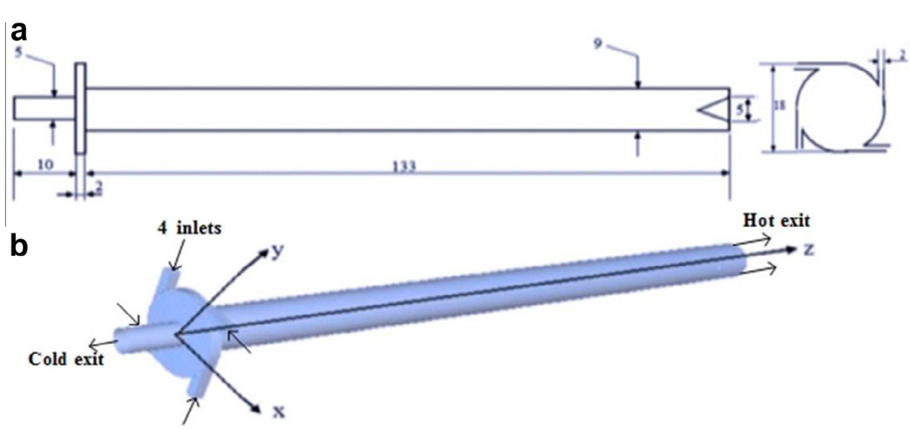

Fig. 1. Geometry model: (a) schematic representation and dimensions (in mm); (b) axis system from Baghdad et al.