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Numerical analysis of the curvature effects on Ranque–Hilsch vortex tube refrigerators

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In this paper, the effect of curvature on the performance of vortex tubes is investigated numerically. The study was conducted on curvature angles of 0 and 110°. The model is three dimensional and utilizes the RNG k–ε turbulence model for determining the flow and temperature fields. The CFD model is verified through comparison with experimental data reported by the authors previously. The code was then utilized to study the effects of radius and angle of curvature on the performance of vortex tube. The results show that the efficiency of straight vortex tube is higher than the curved vortex tube with angle of 110°. The actual values and CFD model results indicated that CFD model can be successfully used for the determination of heating and cooling performances of curvature effects on Ranque–Hilsch vortex tube.

1. Introduction

A vortex tube is a device which can separate an incoming uniform temperature compressed gas (air) stream into two streams at different temperatures, i.e., one warmer and one colder than the inlet stream. Thus, vortex tubes can be considered as refrigerators with no moving parts; schematic of a typical vortex tube is shown in Fig. 1 [1]. The operating mechanism of a vortex tube, which is also known as Ranque–Hilsch tube, was first reported by Ranque [2]. Later, Hilsch [3] inspected the effects of the inlet pressure and the geometrical parameters of the vortex tube on its performance and presented a possible explanation for the separation process. Since then, scientists have utilized various experimental, analytical and numerical techniques to study the transport phenomena in vortex tubes.

Several experimental studies have been devoted to the investigation of the effects of geometric characteristics such as vortex generator, inlet nozzles, length of main tube, cold orifice diameter and other parameters on temperature separation and refrigeration capacity [4–7]. In addition, the flow and temperature fields have been determined experimentally to understand the operation mechanism of vortex tube and consequently determine techniques for improving their performance [5–15].

Analytical studies have been undertaken to explain the operation mechanism of the vortex tube. For example, Kurosaka [16] suggested that separation inside a vortex tube is the result of acoustic streaming effects. Ahlborn and Groves [17] proposed the secondary circulation theory to explain energy separation within a vortex tube.

Despite the various experimental and analytical investigations that have been carried out on the vortex tube, the fundamental mechanism of the temperature separation effect is still in question. So in the last decade, some efforts have been made to successfully utilize computational fluid dynamics (CFD) modeling to explain the fundamental principle behind the energy separation in a vortex tube. Frohlingsdrof and Unger [18] by using CFX code along with the k–ε model investigated fluid flow and energy separation inside the vortex tube. Promvong [19,20] introduced a mathematical model for simulation of strongly swirling compressible flow in a vortex tube by using the algebraic Reynolds Stress Model (RSM) and k–ε turbulence model. Behera et al. [21] presented a three dimensional CFD model for analysis of energy separation using the STAR-CD software with the RNG k–ε turbulence model. They investigated the effects of different types of nozzle profiles and their number on the temperature separation in a counter-flow

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Nomenclature

CFD	computational fluid dynamics
COP	coefficient of performance
C_p	Specific heat at constant pressure (J kg^{-1} k^{-1})
$C_{\varepsilon i}$	coefficients (i = 1,2) used in ε equation
C_μ	constants in Eq. 14
D	diameter of vortex tube (mm)
E	total energy (kJ)
G_k	generation of turbulence kinetic energy
k	turbulence kinetic energy (m^2 s^{-2})
k	thermal conductivity (Wm^{-1} k^{-1})
L	length (mm)
Ma	Mach number
P	pressure (bar)
Pr_t	turbulent Prandtl number
Ra	radius of curvature (mm)
R	specific constant of an ideal gas (J/kg mol-K)
r	radial distance (mm)
T	temperature (K)
u_i	absolute fluid velocity component in i-direction (m/s)
Y_M	contribution of the fluctuating dilatation
Y_c	cold mass fraction

Greek symbols

α_k	inverse effective Prandtl numbers in Eq. 11
α_ε	inverse effective Prandtl numbers in Eq. 12
β	constants in Eq. 14
δ_{ij}	Kronecker delta
τ	shear stress (N m^{-2})
$(\tau_{ij})_{eff}$	deviatoric stress tensor (N m^{-2})
θ	angle of curvature (°)
ε	turbulence dissipation rate (m^{-2} s^{-3})
η_0	coefficient used in Eq. 13
μ	dynamic viscosity (kg m^{-1} s^{-1})
ρ	density (kg m^{-3})

Subscripts

c	cold gas
eff	effective
h	hot gas
in	inlet gas
is	isentropic
i,j,k	cartesian indicates
n	nozzle
st	static
t	turbulent

vortex tube. Aljuwayhel et al. [22] studied the mechanism of stream separation inside a vortex tube using Fluent code. They observed that the standard k–ε turbulence model was sufficient to predict the velocity distribution and temperature separation inside the vortex tube better than the RNG k–ε turbulence model. Skye and Nellis [23] conducted a similar research. Farouk and Farouk [24] used large eddy simulation to predict the energy separation in the vortex tube. They compared the predicted results with the published experimental result of Skye et al. [23]. Bramo and Pourmahmoud [25,26] also numerically studied the effect of length to diameter ratio (L/D) of tube and the importance of stagnation point occurrence in flow patterns. Dutta et al. [27] compared the influence of different Reynolds-Averaged Navier–Stokes (RANS) based turbulence models in predicting the temperature separation in a Ranque–Hilsch vortex tube. They used standard k–ε, RNG k–ε, standard k–ω and SST k–ω turbulence models in their study. They found that standard k–ε model has better prediction for energy separation in Ranque–Hilsch vortex tube.

A curved vortex tube was, for the first time, investigated by Valipour and Niazi [6], experimentally, where the curvature played a major role in the overall performance of the system. However, the detailed understanding of the flow properties within the curved vortex tube and its refrigeration capacity remained unclear. Hence, in this study, a detailed analysis of the curved vortex is carried out using CFD techniques to simulate the internal flow profiles. The simulations are verified through comparison with the experimental data reported by the authors in Ref. [6]. The code is then utilized to investigate the effect of curvature on the performance of vortex tubes.

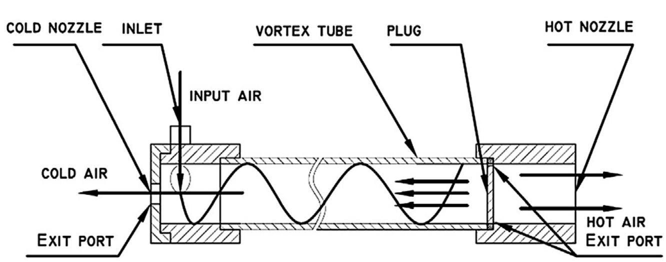

Fig. 1. Schematic of a counter-flow vortex tube system [1].

2. Numerical modeling and procedure

2.1. Geometrical model description

The vortex tubes of Valipour and Niazi [6] are chosen as the model and its flow and energy characteristics were determined. The geometrical features of the model are listed in Table 1. The schematic diagram of the models is shown in Fig. 2. The models have an inside diameter of D = 19.05 mm brass tube and same length of 400 mm. Air enters the tube tangentially through two nozzles with an inner diameters of d_n = 4 mm. The flow rate of hot stream is regulated by a hot control valve. Vortex tubes are designed with constant parameters, inner diameter of cold end tube d_c = 0.5D.

2.2. Performance parameters

The key parameters that are usually used for describing the performance of vortex tubes include:

- Cold mass fraction:

$$Y_c = \frac{\dot{m}_c}{\dot{m}_{in}} \tag{1}$$

where $\dot{m}_c$ is the mass flow rate of the cold air stream and $\dot{m}_{in}$ is the mass flow rate of the inlet air.

Table 1
Geometrical characteristics of vortex tubes.

No	*Ra* (mm)	*θ* (°)	*L* (mm)	*D* (mm)	*L/D*	*Ra/D*
1	∞	0	400	19.05	21	∞
2	208.5	110	400	19.05	21	10.94