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International Journal of Heat and Mass Transfer 50 (2007) 4724–4735

International Journal of HEAT and MASS TRANSFER

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Large eddy simulations of the flow field and temperature separation in the Ranque–Hilsch vortex tube

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Received 22 October 2006; received in revised form 5 March 2007
Available online 27 June 2007

Abstract

A computational fluid dynamic model is used to predict the flow fields and the associated temperature separation within a Ranque–Hilsch vortex tube. The large eddy simulation (LES) technique was employed for predicting the flow and temperature fields in the vortex tube. A vortex tube with a circumferential inlet stream and an axial (cold) outlet stream and a circumferential (hot) outlet stream was considered. The temporal evolutions of the axial, radial and azimuthal components of the velocity along with the temperature, pressure and density fields within the vortex tube are simulated. Performance curves (temperature separation versus cold outlet mass fraction) were obtained for a specific vortex tube with a given inlet mass flow rate. Simulations were carried out for varying amounts of cold outlet mass flow rates. Predictions from the present large eddy simulations compare favorably with available experimental measurements.

Keywords: Ranque–Hilsch vortex tube; Modeling; Large eddy simulations; Temperature separation

1. Introduction

The vortex tube is a simple device with no moving parts that is capable of dividing a high pressure flow into two relatively lower pressure flows with temperatures higher and lower than that of the incoming flow. The device consists of a simple circular tube, with one or more azimuthal nozzles for flow inlet and two outlets for flow exits. High pressure air enters the tube azimuthally at one end and produces a strong vortex flow in the tube. The gas is separated into two streams having different temperatures, one flowing along the outer wall and the other along the axis of the tube. The gas streams leaving through the exits located along the outer wall and along the axis are at higher and lower temperatures, respectively, than the inlet gas temperature. This effect is referred to as the "temperature separation" and was first observed by Ranque in 1931 when he was studying processes in a dust separation cyclone [1]. Intense experimental and numerical studies of the Ranque–Hilsch vortex tubes began since then and continue even today [2–9]. Despite the simplicity of its geometry, the energy separation phenomenon is quite intriguing. Various theories have been proposed in the literature to explain the "temperature separation" effect since the initial observations by Ranque [1]. In his pioneering work on the vortex tube, Hilsch [10] suggested that angular velocity gradients in the radial direction give rise to frictional coupling between different layers of the rotating flow resulting in the migration of energy via shear work from the inner layers to the outer layers. Other investigators have attributed the energy separation to work transfer via compression and expansion. Several variations of this theory are described in the literature, differing according to the mechanism that drives the fluid motion. Harnett and Eckert [11] invoked turbulent eddies, Ahlborn and Gordon [12] described an embedded secondary circulation and Stephan et al. [13] proposed the formation of Görtler vortices on the inside wall of the vortex tube that drive the fluid motion. All these theories treat individual particles as small refrigeration systems, each undergoing thermodynamic cycles that are

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doi:10.1016/j.ijheatmasstransfer.2007.03.048

Nomenclature

c_p	specific heat at constant pressure (J/kg K)
C_s	Smagorinsky constant
H	total enthalpy (kJ/kg)
k	thermal conductivity (W/m K)
m	mass flow rate (m s^{-1})
p	pressure (Pa)
R	universal gas constant (J/mol K)
S	strain rate
t	time (s)
T	temperature (K)
$\boldsymbol{u}$	velocity vector (m s^{-1})
u_x	velocity component in the x direction
u_r	velocity component in the r direction
u_θ	velocity component in the θ direction

Greek symbols

ΔT_{hc}	temperature difference between hot and cold ends
ν_t	eddy viscosity (kg/m s)
ρ	density (kg/m^3)
τ	shear stress (N/m^2)
τ_{ij}	stress tensor component

Subscripts

c	cold gas
h	hot gas
r	radial direction
x	axial direction
θ	azimuthal direction

powered by energy from the flow itself. Kurosaka [14] reported the "temperature separation" to be a result of acoustic streaming effect that transfer energy from the cold core to the hot outer annulus. Gutsol [15] hypothesized the energy separation to be a consequence of the interaction of micro volumes in the vortex tube. Despite all the proposed theories, none has been able to explain the "temperature separation" effect satisfactorily.

Recent efforts have utilized modeling to explain the fundamental principles behind the energy separation produced by the vortex tube. Ahlborn et al. [4] showed the dependence of vortex tube performance on normalized pressure drop with a numerical model. Frohlingsdorf and Unger [6] used a fluid dynamics model that included the compressible and turbulent effects. Their numerical predictions qualitatively matched the experimental results of Bruun [2]. Aljuwayhel et al. [8] utilized a fluid dynamics model of the vortex tube to understand the process that drive the power separation phenomena. They report that the energy separation exhibited by the vortex tube is due to the work transfer caused by a torque produced by viscous shear acting on a rotating control surface that separates the cold flow region and the hot flow region. Skye et al. [9] used a model similar to that of Aljuwayhel et al. [8]. They also measured the inlet and outlet temperatures of the vortex tube and compared with the predictions from the fluid dynamics model. The temperature separation predicted by their model for a commercially available vortex tube was found to be in reasonable agreement to the experimental measurements. Behera et al. [7] conducted both numerical and experimental studies towards the optimization of the Ranque–Hilsch vortex tube. Their numerical study resulted in obtaining the optimum parameters (cold end diameter, length to diameter ratio) for the maximum temperature separation. All of these models used the compressible form of the Navier–Stokes equation, and the turbulence effects were included using either the standard k–ε or the renormalization group (RNG) k–ε model.

In the present study, a compressible form of the Navier–Stokes equation together with the large eddy simulation (LES) technique has been used to simulate the phenomenon of flow pattern and temperature separation in a Ranque–Hilsch vortex tube with a circumferential inlet port, and a cold axial and a hot circumferential outlet ports (as shown in Fig. 1). This arrangement is a bit different from the geometry used by Aljuwayhel et al. [8] where the flow enters the tube from the top surface with axial and angular components of velocities rather than the circumferential outer wall (as considered in the present study) with radial and angular components of velocities.

The Reynolds averaged Navier–Stokes simulations (RANS) method attempts to model the turbulence by performing time or space averaging. The averaging process wipes out most of the important characteristics of a time-dependent solution. The direct numerical simulation (DNS) technique on the other hand attempts to solve all time and spatial scales in the velocity field. As a result, the solution is accurate but numerically very intensive. LES is considered somewhere in between DNS and RANS with respect to both physical resolution and computational costs. LES inherits the universality of DNS, allowing accurate prediction of the coherent structures in turbulent flows. The computational cost for LES is lower than that for DNS because the resolution requirements for LES are of the same order as those for RANS.

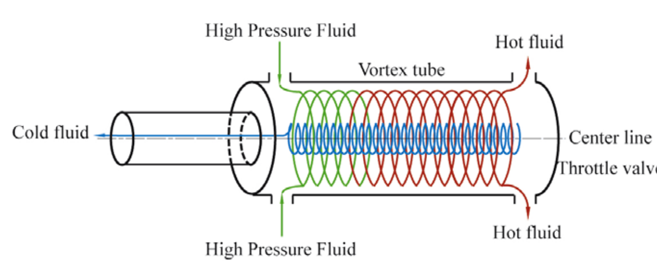

Fig. 1. Schematic diagram of the Ranque–Hilsch vortex tube with simplified representation of the flowlines for the hot and cold gas.