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Numerical analysis of the effect of helical nozzles gap on the cooling capacity of Ranque–Hilsch vortex tube

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ABSTRACT

In this article, the effect of helical nozzles on both energy separation and refrigeration phenomena in the Ranque–Hilsch Vortex Tube (RHVT) was investigated by CFD techniques. The radial gap of inlet of helical nozzle from the vortex chamber (GPL) stands as a significant designing parameter. The standard $k-\varepsilon$ turbulence model was introduced to the governing equations for analyzing highly rotating complex flow field. The studied helical nozzles have the same profile shape but their radial distance from the chamber distinct them from each other. Presented numerical results show that operating the vortex tube with GPL = 0.034 leads to the maximum cooling effect and swirl velocity. Furthermore, by keeping GPL value constant, the effect of number of nozzles is studied in more detail. Present results in this article, show increasing of temperature separation due to increase of nozzle numbers, however the coefficient of performance (COP) does not change very significantly.

Analyse numérique de l'effet de l'écart entre les tuyères hélicoïdales sur la puissance de refroidissement d'un tube vortex Ranque-Hilsch

Mots clés : tube vortex ; tuyères hélicoïdales ; simulation numérique ; séparation d'énergie

1. Introduction

The Ranque–Hilsch vortex tube (RHVT) is known as a simple device with having no moving parts that produces hot and cold gas streams simultaneously at its two ends. The two streams are supplied from this machine, only due to feed of a compressed gas source. The vortex generated through the vortex chamber, that is located at the inlet of the RHVT, causes the creation of strong rotating flows. Indeed, the operating principle of the vortex tube is based on the formation of unbelievable high counter rotating vortices. At the most of applications, the working inlet gas is taken arbitrary compressed air. This apparatus is utilized in the vast industrial branches such as gas purifying, spot cooling and most commonly in refrigeration processes. This device was accidentally invented many years ago, when a French physicist

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Nomenclature

D	diameter of vortex tube [mm]
k	turbulence kinetic energy [$m^2\,s^{-2}$]
L	length of vortex tube [mm]
Z	axial length from nozzle cross-section [mm]
r	radial distance measured from the centerline of tube [mm]
s	radial gap of nozzle inlet from vortex chamber [mm]
l	length of helical nozzle
T	temperature [K]
GPL	dimensionless ratio of radial gap of nozzle inlet from vortex chamber per nozzle length (s/l)
$V_{\theta,max}$	maximum swirl velocity
COP	coefficient of performance
R	radial of vortex tube

Greek symbols

α	cold mass fraction
ε	turbulence dissipation rate [$m^2\,s^{-3}$]
$\Delta T_{c,h}$	temperature difference between cold and hot end [K]
$\Delta T_{i,c}$	temperature difference between inlet and cold end [K]
$\Delta T_{i,h}$	temperature difference between hot end and inlet [K]
ρ	density [$kg\,m^{-3}$]
μ	dynamic viscosity [$kg\,m^{-1}\,s^{-1}$]
μ_t	turbulent viscosity [$kg\,m^{-1}\,s^{-1}$]
τ_{ij}	stress tensor components

named Ranque (1933) was conducting a research over vortex tube in the field of dust separation. He noticed the emitting of hot air from one side and cold air from another one. A few years later, German physicist, Hilsch (1947) worked on the vortex tube, consequently. He developed the vortex tube principles and worked on its designing parameters. He finally published the results of his works in an article in 1947. In Fig. 1 a vortex tube and its components is schematically displayed. In the recent years, the techniques of CFD modeling have been developed for more surveys and clarification. Since the publication of Hilsch's (1947) studies, the vortex tube has been the subject of much interest and many studies have been conducted in an attempt to explain its physical principles and thermodynamical mechanism. However, the hot and cold temperature differences that are denoted by $\Delta T_{i,c}$ and $\Delta T_{i,h}$ respectively, are the main quantities in this system and are commonly called "temperature separation" criterion.

Stephan et al. (1983) proposed the formation of Gortler vortices on the inside wall of the vortex tube that drives the fluid motion. Ahlborn and Gordon (2000) described an embedded secondary circulation. Aljuwayhel et al. (2005) utilized a fluid dynamics model of the vortex tube to understand the process that drives the temperature separation phenomena. Skye et al. (2006) used a model similar to that of Aljuwayhel et al. (2005). Akhesmeh et al. (2008) made a 3D CFD model in order to study the variation of velocity, pressure and temperature inside a vortex tube. Their results obtained upon numerical approach emphasized comprehensively on the mechanism of hot peripheral flow and a reversing cold inner core flow formation. Bramo and Pourmahmoud (2010, 2011) studied numerically the effect of length to diameter ratio (L/D) of tube and the importance of stagnation point occurrence in flow patterns.

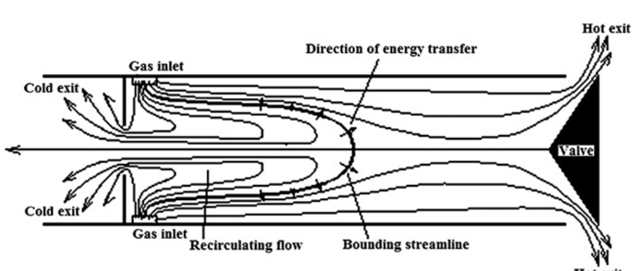

Fig. 1 – Flow pattern and schematic drawing of a vortex tube (Cockerill, 1995).

Until now, complete understanding of the physical mechanisms occurring in the vortex tube has been one of the most scientific challenges in theoretical and experimental researches. Recent efforts that have successfully benefited from CFD techniques, can almost explain the basic principles behind the energy separation produced by the vortex tube. More designing parameters such as tube length and its geometry, cold and hot exit area and number of nozzles can govern on the flow field behavior in a vortex tube. Nevertheless, among them, the nozzles types including straight or helical shape are a specific case because they can significantly enhance the high velocity for gas at the exit end just at the location of entrancing to vortex chamber. Singh et al. (2004) carried out experimental investigations to understand the heat transfer characteristics in a vortex tube with respect to various parameters like mass flow rates of cold and hot air, nozzle area of inlet compressed air, cold orifice area, hot end area of the tube, and L/D ratio. They concluded that cold mass fraction as well as adiabatic efficiency is more influenced by the size of the cold orifice rather than the size of the nozzle. Saidi and Valipour (2003) performed an experimental investigation to realize the behavior of a vortex tube system. They investigated the effect of geometrical parameters, including diameter and length of main tube, diameter of outlet orifice, shape of entrance nozzle and thermo-physical parameters such as inlet gas pressure, type of gas, cold gas mass ratio and moisture of inlet gas. To study the effect of type of inlet nozzles, they designed and fabricated two shapes of nozzle having 3 and 4 intakes with constant inlet cross-sectional area. Their results were that the nozzle with three intakes shows better performance than the four intakes nozzle from the point of view of refrigeration efficiency. Behera et al. (2005) performed the most comprehensive research only on the shape and number of inlet nozzles among CFD researchers, but they did not focus on the helical nozzles' radial arrangement respect to vortex chamber. Their study revealed that in