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Effects of variable thermophysical properties on flow and energy separation in a vortex tube

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ABSTRACT

A numerical study has been conducted to investigate the effects of variable fluid properties on the prediction of a basic tube vortex design. Beforehand, a literature review is presented to highlight some of the recent advances in the enhancements of the device design and its efficiency. The three-dimensional computations with constant and variable properties revealed that the constant thermophysical assumption might not have a dramatic effect if the aim is to predict global values only, but extra caution should be taken for an in-depth flow assessment. The exergy analysis conducted suggests that the highest exergy efficiency, for the current device design, ranges from 38% to 46% depending on the inlet pressure value. Based on the current numerical analysis; rather large exergy losses are due to irreversibility occurring at either; the lowest or the highest cold mass fraction boundary conditions.

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Effets de propriétés thermophysiques variables sur l'écoulement et la séparation d'énergie dans un tube vortex

Mots clés : Tube vortex ; Analyse exergétique ; Reynolds Stress Model

1. Introduction

Vortex tubes are an attractive means for producing cold and hot streams from a compressed gas. Due to their simplicity, ease of manufacturing and their potential low cost, vortex tubes could become viable candidates for partly replacing the conventional cooling systems. In recent years, tremendous advances have been made in increasing the efficiency of vortex tubes. Many research efforts have been focused on the optimal geometry that maximizes the COP. In particular, the number of inlet nozzles and their relative locations has been the subject of a number of theoretical, experimental and numerical studies. For instance, some of the early proposals aiming at increasing the device performance by: increasing the number of inlet nozzles, changing the tube diameter, varying the cold and hot outlet diameters, and/or changing the working fluid are the ones due to Deissler and Perlmutter, 1960, Linderstrbm-Lang, 1964, Yu and Tankel, 1974, Marshall,

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Nomenclature

A	Area (m^2)
a	Speed of sound ($m\ s^{-1}$)
D	Vortex tube diameter (mm)
E	Total internal energy ($J\ kg^{-1}$)
Ex	Exergy (W)
h	Enthalpy ($J\ kg^{-1}\ K^{-1}$)
k	Turbulence kinetic energy ($m^2\ s^{-2}$)
L	Vortex tube length (m)
m	Mass flow rate ($kg\ s^{-1}$)
p	Pressure (Pa)
R	Vortex tube radius (mm)
r	Radial distance from axis
T	Temperature (K)
u_i	Absolute fluid velocity component in direction x_i
x_i	Cartesian coordinate ($i = 1, 2, 3$)
ΔT_{ch}	Temperature difference between cold and hot end

Greek symbols

γ	Adiabatic exponent
ξ	Cold gas fraction
η	Efficiency
λ	Thermal conductivity ($W\ m^{-1}\ K^{-1}$)
μ	Dynamic viscosity ($kg\ m^{-1}\ s^{-1}$)
ρ	Density ($kg\ m^{-3}$)
τ_{ij}	Stress tensor components

Subscripts

o	Environmental state
c	Cold gas
ex	Exergetic
h	Hot gas
i	Vortex tube inlet
k	Kinetic
o	Outlet
p	Potential
ph	Physical
s	Static
t	Total

1977, Takahama et al., 1979, Collins and Lovelace, 1979, Stephan et al., 1983, Ahlborn et al., 1996 among others.

Since the beginning of the last decade, research is focussed more towards producing detailed data on the flow in different vortex tube configurations by both; experimental measurements and numerical predictions. For example, Fröhlingsdorf and Unger (1999) simulated numerically the compressible flow and energy separation phenomena using the CFD code *CFX*. They extended an axisymmetric model by integrating relevant terms for the shear-stress-induced mechanical work. Ahlborn and Gordon (2000) showed that the thermal and fluid dynamics of the vortex tube bear the signature of a classic cooling cycle. They developed simple analytical formulae for the temperature and pressure profiles within the tube and compared successfully the principal model predictions to experimental measurements. Saidi and Valipour (2003) performed an experimental investigation in order to provide information data on the classification of the parameters affecting vortex tube operation. They divided these parameters into two different types; geometrical and thermophysical ones. The Results showed that these parameters have a non negligible influence on the cold temperature difference, thus, the efficiency of the vortex tube. Behera et al. (2005) conducted numerically a detailed parameters analysis of a vortex tube. The velocity components and the flow patterns have been evaluated using the CFD code *Star-CD*. Optimal design parameters of the vortex tube, such as number of nozzles, nozzle profiles, cold-end diameter, length to diameter ratio and cold and hot gas fractions, have been also determined. Gao et al. (2005) manufactured a simple vortex tube in order to investigate pressure, temperature, and velocity distributions using nitrogen as the working fluid. Pressure and velocity were measured using a special Pitot tube while the temperature field was obtained using thermocouples. They reported result for different entrance conditions and their study was further strengthened by including a thermodynamic analysis. Aljuwayhel et al. (2005) investigated numerically the energy separation mechanism and flow phenomena within a counter-flow vortex tube. A two-dimensional axi-symmetric computational domain was used for their study. Then, the computational predictions were compared to experimental data obtained from a laboratory vortex tube operating with room temperature compressed air. The work also included a parametric study to investigate the effects of varying the diameter and length of the vortex tube. Promvonge and Eiamsa-ard (2005) analysed the effects of the number of inlet nozzles, the cold-end diameter, and the tube insulations on the temperature reduction and the isentropic efficiency of the vortex tube. Skye et al. (2006) presented a comparison between the performance predicted by numerical analysis and experimental measurements using a commercially available vortex tube. In their study, they considered a two-dimensional steady axisymmetric computational domain. They presented results obtained with both; the standard and renormalization group (RNG) $k-\varepsilon$ turbulence models. Wu et al. (2007) used three innovative technologies in order to improve the energy separation and the efficiency of vortex tubes. A new nozzle with equal gradient of Mach number and a new intake flow passage of nozzles with equal flow velocity have been designed and developed to reduce the flow loss. This newly invented diffuser by the authors has been installed to reduce friction loss of air flow energy at the hot tube-end, which has been shown to greatly improve the vortex tube performance. Eiamsa-ard and Promvonge (2007) presented a numerical analysis of flow field and temperature separation in a uni-flow vortex tube type. In particular, they studied the effects of the turbulence modelling ($k-\varepsilon$ model and ASM), effects of numerical schemes (hybrid, upwind and second-order upwind) and grid density; on the calculation of energy separation in the vortex tube. They argued that the use of the ASM improves slightly the accuracy of the predictions in comparison with those obtained with the $k-\varepsilon$ model. Farouk and Farouk (2007) used the large eddy simulation (LES) approach to predict the flow and temperature fields in a vortex tube. The temporal evolutions of the axial, radial and

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