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Effects of swirl intensity on heat transfer and entropy generation in turbulent decaying swirl flow

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HIGHLIGHTS

- Accurate numerical model of anisothermal turbulent swirl flow was built and validated.
- The swirl number is directly and inversely proportional to Nusselt and Stanton numbers, respectively.
- Numerical simulations revealed that a critical swirl number exists $S_n \approx 0.278$.
- A novel correlation for predicting entropy augmentation number in swirl flow is proposed.
- The entropy field in the flow core was found to be dominated by viscous irreversibilities.

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ABSTRACT

In the present work, numerical simulations of turbulent incompressible nonisothermal pipe flows were conducted to investigate the effect of inlet swirl intensity and streamwise swirl decay on heat transfer and local entropy generation in the flow. The RANS, energy and entropy equations along with Shih's realizable k–ε turbulence model were numerically solved using second order finite volume upwind discretization scheme. The CFD model results showed very good agreement with established LDV measurements. The streamwise trends of Nusselt and Stanton numbers were studied at different inlet swirl intensities. A new CFD-based empirical correlation for predicting the entropy augmentation number as a function of swirl number was proposed. It is shown that the swirl number radically affects the local entropy generation due to viscous dissipation in the inner core of the Rankine vortex structure.

1. Introduction

During the past decade, second law analysis and its subsequent thermal optimization procedures have produced well established methods for assessing and improving heat and mass transfer processes in different engineering applications. The concept of entropy generation minimization is the corner stone for a number of such procedures. This concept aims at reducing the irreversibility of thermodynamic systems to optimize their exergy. The Gouy–-Stodola theorem dictates that for a given thermodynamic system, the lost work is given by:

$$\dot{W}_{\text{rev}} - \dot{W} = T_o \dot{S}_{\text{gen}} \tag{1}$$

where $\dot{W}_{\text{rev}}$ is the reversible (i.e. available) work, $\dot{W}$ is the actual work, and $\dot{S}_{\text{gen}}$ is the total entropy generated in the system. In general, entropy is generated due to numerous factors depending on the system properties such as heat transfer, viscous dissipation and chemical reaction. By considering the heat and mass irreversibilities in a thermodynamic system, the local entropy generation can be expressed as [1,2]:

$$\dot{S}_{\text{gen}} = \frac{k}{T^2}\left(\frac{\partial T}{\partial x_j}\right)^2 + \frac{\mu}{T}\frac{\partial u_i}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_j}\right) \tag{2}$$

where the first and second terms on the RHS refer to entropy generation due to heat transfer$\dot{S}_{ht}$ and viscous dissipation $\dot{S}_{\text{V}}$, respectively (Fig. 1).

The minimization of the entropy generation results in reduction of the lost work, hence increase in the available work of the system. There are several methods for reducing $\dot{S}_{\text{gen}}$ in different

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Nomenclature

Greek symbols

ρ	density (kg m^{-3})
μ	dynamic viscosity (kg m^{-1} s^{-1})
δ_{ij}	second viscosity coefficient (kg m^{-1} s^{-1})
Ω	vorticity (s^{-1})
τ	shear stress tensor
ε	dissipation of turbulence kinetic energy

Latin symbols

$\dot{W}_{\text{rev}}$	reversible work (W)
$\dot{W}$	actual work (W)
$\dot{S}_{\text{ht}}$	entropy generation due to heat transfer (W K^{-1})
$\dot{S}_{\text{V}}$	entropy generation due to viscous dissipation (W K^{-1})
$\dot{S}_{\text{gen}}$	total entropy generated in the system (W K^{-1})
T	temperature (K)
p	pressure (pa)
S	strain rate tensor
k	turbulence kinetic energy
u	velocity (m s^{-1})

Dimensionless parameters

Re	Reynolds number
Be	Bejan number
σ_k	turbulent Prandtl number for k (dimensionless)
σ_ε	turbulent Prandtl number for ε (dimensionless)
S_n	Swirl number
Nu	Nusselt number
Pr	Prandtl number
$N_{S,a}$	entropy augmentation number

Abbreviations

PEC	Performance Evaluation Criteria
EGM	Entropy Generation Minimization
LDV	Laser Doppler Velocimetry

Superscripts

	Reynolds averaged quantity
$.'$	fluctuating quantity

engineering systems. In convective heat transfer applications (i.e. refrigeration, cooling, heat exchangers) one method is to use heat transfer promoting techniques to reduce the heat transfer irreversibilities [3]. These techniques include turbulators and swirlers, which aim at improving the mean flow thermal convection as well as the near-wall heat transfer coefficient. However, the admission of tangential velocity component to the flow via swirlers/turbulators may result in an increase of the entropy generation due to elevated viscous dissipation rates. Perhaps this could neutralize the exergy gain from heat transfer enhancement.

This article presents numerical investigations of the effect of swirl intensity on the local entropy generation in nonisothermal pipe flows undergoing fully developed isotropic turbulence. The main objective of this work is to investigate the relation between the reduction of entropy generation due to heat transfer enhancement and the augmentation of entropy generation due to turbulent viscous dissipation associated with swirling flow. In the present work, the term swirl refers to a vortex structure of the Rankine type [4], and the term intensity refers to the ratio between axial thrust of tangential momentum and the axial thrust of axial momentum [5,6]. A brief literature review presented hereafter, followed by a description of the mathematical model and numerical methodology. The results are presented and discussed in final section.

1.1. Literature review

Several attempts were made during the past decade to study the impact of heat transfer enhancement techniques on minimizing entropy generation in heat exchangers. Zimparov presented a series of remarkable studies [7–9] in which a novel method for assessing heat transfer enhancement techniques called the performance evaluation criteria (PEC) was proposed. The PEC method is basically an improvement to Bejan's entropy generation minimization (EGM) method. Both methods depend on integral (i.e. gross) relations and do not investigate local phenomena. Yakut and Sahin [10] investigated the effect of coiled-wire turbulators used for heat transfer enhancement on the entropy generation in channels. They analyzed the effect of pitch (i.e. frequency) variation of the wire coil on the entropy generation using experimental measurements. They concluded that the wire coils provided exergy improvement up to $Re = 1.3 \times 10^4$. Kurtbaş et al. [11] studied the effect of propeller-type swirl generators on the entropy generation in heat exchangers. They have conducted a series of experiments to examine different sets of propeller geometry as well as different flow regimes to explore possible exergy gains due to heat transfer enhancement. They concluded that possible exergy gains exist for $Re \le 3 \times 10^4$. Bilen and coworkers have conducted experiments to estimate the entropy generation in internally grooved tubes with different groove geometries [12]. The tests which were done for a range of Reynolds number ($1 \times 10^4 \le Re \le 3.8 \times 10^4$) revealed that the grooved tubes are thermodynamically advantageous for Re as high as 3×10^4 and optimally reduces exergy losses at $Re \approx 1.7 \times 10^4$. To that end, and to the best of the authors' knowledge, there is no study available in open literature, which investigates the relation between inlet swirl intensity and entropy generation in plain pipes.

The objective of the present work is to investigate the relationship between swirl decay in straight pipe flows and entropy generation due to heat transfer and viscous dissipation. There is a number of published studies which investigated entropy generation due to swirl pipe inserts used for heat transfer enhancement. However, to the best of the authors' knowledge, the present study is the first numerical work, which investigates the entropy augmentation due to swirl flow in plain pipes. In addition, the present study aimed at developing a novel preliminary correlation, which enables the prediction of entropy generation as a function of swirl decay. The significance of the present work is realized from the great importance of swirl flows in numerous industrial applications, which requires accurate prediction of thermal characteristics.

2. Mathematical model and numerical details

2.1. Mathematical model

The governing equations of the present turbulent nonisothermal flow are steady incompressible continuity and the Reynolds Averaged Navier Stokes (RANS) equations. The Reynolds stress term is closed using the well established realizable k–ε turbulence model of Shih [13]. This model has shown prevalence in modeling complex swirling flows, with and without chemical reactions, in comparison with the standard k–ε model [14–16]. These equations can be written as: