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An analysis of entropy generation through a circular duct with different shaped longitudinal fins for laminar flow

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Abstract

The present study focuses on the entropy generation analysis in a circular duct with internal longitudinal fins of different shape for laminar flow. Three different fin shapes are chosen for the analysis: Thin, triangular and V-shaped fins. Calculations are performed for various dimensionless lengths and number of fins, dimensionless temperature difference and fin angle for triangular and V-shaped fins. It is found that the number of fins and dimensionless length of the fins for both thin fins and triangular fins, and the fin angle for triangular and V-shaped fins have significant effect on both entropy generation and pumping power. Further, both entropy generation and pumping power also are influenced by dimensionless temperature difference.

Keywords: Entropy generation; Laminar flow; Circular duct; Longitudinal fins

1. Introduction

Pipes with internal or external longitudinal fins are used to enhance heat transfer as a passive method. The heat transfer across the stream to stream ΔT and the frictional ΔP experienced by each stream represent two different facets of one single aspect of the heat exchanger, namely, its degree of thermodynamic irreversibility [1]. From this point of view, the second law analysis is used to determine the optimum heat exchanger dimensions. Ducts with longitudinal fins of different shapes are also widely used in compact heat exchanger applications [2–5]. Such geometries are called internally finned tubes.

Bejan [6] investigated the concept of irreversibility for heat exchanger design in counter-flow heat exchangers. He illustrated a design approach for a heat exchanger by using the second law analysis of thermodynamics. It was found that the entropy generation unit method is more useful than the traditional heat exchanger design technique. In his another study, he obtained the entropy generation in fundamental convective heat transfer problems and provided some examples [7].

Sahin [8] made an analytical study of the second law analysis for laminar viscous flow through a duct subjected to constant wall temperature. It was found that entropy generation, ψ, increases with increasing the dimensionless temperature difference. However, pumping power ratio decreases with increasing temperature

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Nomenclature

A	cross-sectional area of duct (m^2)
C_p	specific heat capacity (J/kg K)
D	diameter of pipe
D_H	hydraulic diameter (m)
d	radius of tube
f	friction factor
$\bar{h}$	average heat transfer coefficient ($W/m^2 K$)
k	thermal conductivity (W/m K)
L	length of duct (m)
L_d	fin length (m)
L^*	non-dimensional fin length for thin fin, L/d
L^*_u	non-dimensional fin length for triangular fin, L/d
L^*_v	non-dimensional fin length for V-shaped fin, L/L_{max}
L_{max}	defined in Eq. (6)
m	mass flowrate (kg/s)
n	number of fins
$\overline{Nu}$	average Nusselt number (hD_H/k)
p	perimeter of duct (m)
P	pressure (N/m^2)
PPR	pumping power to heat transfer ratio ($A\,\Delta P\overline{U}/\dot{Q}$)
Pr	Prandtl number ($\mu C_p/K$)
$\dot{Q}$	total heat flux (W)
Re	Reynolds number ($\rho\overline{U}D_H/\mu$)
s	entropy (J/kg K)
$\dot{S}_{gen}$	entropy generation (W/K)
St	Stanton number $\bar{h}/(\rho\overline{U}C_p)$
T	temperature (K)
T_0	inlet fluid temperature (K)
T_w	wall temperature of the duct (K)
$\overline{U}$	fluid bulk velocity (m/s)
x	axial distance (m)
ΔP	total pressure drop (N/m^2)
ΔT	increase of fluid bulk temperature (K)
μ	viscosity ($N\,s/m^2$)
λ	non-dimensional axial distance (L/D_H)
Π_1	non-dimensional group ($4\overline{Nu}\lambda/Pr$)
Π_2	non-dimensional group ($\mu^2\lambda(fRe)/(2\rho^2D_H^2 C_pT_w)$)
ψ	non-dimensional entropy generation
ρ	density (kg/m^3)
τ	non-dimensional inlet wall-to-fluid temperature difference ($(T_0 - T_w)/T_w$)
ϕ	fin angle

difference. In the case of small value of the dimensionless temperature difference, the entropy generation due to viscous friction becomes dominant. For constant wall temperature condition, a thermodynamic optimization was performed by Nag and Mukherjee [9]. They observed that the initial temperature difference between fluid and the wall is an important design criterion. Entropy generation for a duct under constant heat flux boundary conditions was analyzed by Sahin [10]. For low heat flux boundary condition, it was found that the entropy generation due to viscous friction is dominant. Hydraulic diameter of the duct is found to be an effective parameter as a design criterion for second law analysis on both constant wall heat flux and constant wall temperature boundary conditions. In both cases, it is found that circular duct is the most feasible geometry.

A number of numerical and experimental studies on ducts with longitudinal fins can be found in the literature from the point of view of flow field and heat transfer rates. Due to space limitation in this paper only a few of them are mentioned here. Fabbri [11] made a numerical study by using a finite element code to solve optimization problem in a duct with longitudinal convective fins of both symmetrical and asymmetrical position. It was shown some optimized geometries and found that under particular conditions, noticeable improvements in the heat transfer have been observed for optimum fins with asymmetrical polynomial lateral profiles. In another study, the same author investigated the optimum internal fins of asymmetric shape in a circular tube [12,13]. Fins of polynomial shape have been used to enhance heat transfer in circular tube configuration. Ifhakhar and Ghoshdastidar [14] made a numerical study to solve heat transfer and fluid flow in circular tubes with internal longitudinal fins having tapered lateral profiles for laminar flow conditions. Braga and Saboya [15] performed an experimental study to determine average heat transfer coefficients and friction factors for turbulent flow through annular ducts with continuous longitudinal rectangular fins. Average Nusselt number and friction factor as functions of flow Reynolds number were obtained. Kumar [16] made a numerical study to obtain natural convection heat transfer rates and flow fields in a vertical annulus with longitudinal fins with various parameters. It was found that the heat transfer rates increase as the fin ratio and radius ratio increase. In addition, the heat transfer rates decrease if the aspect ratio and the fin thickness angle increase. Zeitoun and Hegazy [17] solved numerically the momentum and the energy equations to obtain heat transfer augmentation in laminar flow for internal longitudinal thick fins. Their study showed that the results obtained for different pipe-fin geometries show that the fin heights affect greatly the