International Journal of Thermal Sciences 50 (2011) 760–768

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Second law analysis of curved rectangular channels

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ARTICLE INFO

Article history:
Received 12 May 2010
Received in revised form
21 August 2010
Accepted 20 December 2010
Available online 28 January 2011

Keywords:
Curved rectangular channels
Entropy generation
Numerical simulation
Field synergy principle
Laminar flow
Heat transfer

ABSTRACT

The thermodynamic performance of the curved rectangular channels in laminar flow is numerically investigated in terms of entropy generation. The classical Navier–Stokes equations are adopted, and water is selected as the working fluid. The results show that the geometric parameters have important influences on the heat transfer performance of the channel flows. For the channels with the same cross-section, the Nusselt number increases significantly as the curvature ratio increases at the expense of slight increase of pressure drop; the dimensionless total entropy generation generally tends to reduce as Reynolds number grows, and decreases as the curvature ratio increases at the same Reynolds number. The dimensionless total entropy generation lessens with the reduction of cross-sectional area at the same Reynolds number in the channels with the same radius of curvature. Despite the rapid drop of the Bejan number, we have not found the optimal flow regime for curved rectangular channel laminar flows. The local heat transfer and fluid friction entropy generations mainly occur in the narrow region near the walls, especially the outer wall. The field synergy principle provides an alternative way to explain the heat transfer enhancement mechanism for the curved rectangular channel flows.

1. Introduction

The curved channel as a passive heat transfer enhancement device is widely used in heat transfer equipments. In a curved channel, centrifugal force is generated due to the curvature, which generates a secondary flow field, resulting in the heat transfer enhancement [1]. Dean [2,3] was the first to investigate the hydrodynamics of a curved channel flow, and a single parameter, the Dean number was defined to characterize the flow phenomena of Newtonian fluids in a curved channel. Itō [4] investigated the steady laminar flow in a curved channel with circular cross-section, and derived a formula for the friction factor of the curved channel. Berger et al. [5] comprehensively reviewed the study of the flow of Newtonian fluids in curved pipes. Ligrani et al. [6] investigated the heat transfer in transitional curved channel flow over a range of Dean numbers less than 300, and found that Nusselt number on the concave surface is higher than that on the convex surface for the curved channel. Yang et al. [7] numerically analyzed the laminar flow and heat transfer in a curved pipe with periodically varying finite curvature, and found that a decrease in the wave length of the periodic wavy pipe could enhance the heat transfer rate significantly. Kumar et al. [8] examined the influences of temperature-dependent properties on hydrodynamic and thermal performance of a curved tube in laminar flow regime under cooling and heating conditions, and reported that the Nusselt number markedly depends on the property variation in the curved tube. In [9], the pressure losses of laminar oil-flows in curved rectangular channels with various geometrical aspect ratios and curvatures were investigated, and an empirical equation based on experimental data for Dean numbers between 100 and 800 was developed. Yanase et al. [10] conducted a numerical simulation of the non-isothermal flows through a curved rectangular duct of aspect ratio 2 with the spectral method; the results showed that the Nusselt number on the outer side wall increases as the Dean number increases within the ranges of the Dean number and the Grashof number considered in [10]. Wang and Liu [11] numerically studied the fully developed laminar flow of viscous fluid in a slightly curved square microchannel, and they found that no matter how small the curvature ratio is the channel curvature always generates a secondary flow, which enhances the heat transfer significantly and increases the fluid friction slightly. Che et al. [12] analytically investigated plug flow in curved microchannels, they found that the flow pattern can be controlled by the geometric structure. Chu et al. [13] conducted an experimental investigation of the flow characteristics in curved rectangular microchannels at Reynolds number of 80–876, and found that the

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doi:10.1016/j.ijthermalsci.2010.12.011

Nomenclature

a	width (m)
b	height (m)
Be	Bejan number
c	constant
c_p	Specific heat (J kg^{-1} K^{-1})
d	tube diameter (m)
D_h	hydraulic diameter (m)
e	Relative error (%)
f	General solution variable
C_f	Friction factor
Fs	factor of safety for error estimators
GCI	grid convergence index
$\bar{h}$	Average heat transfer coefficient (W m^{-2} K^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
$\vec{n}$	outward normal unit vector
N	Number of mesh cells
N_{s1}	dimensionless entropy generation
Nu	Nusselt number
Pr	Prandtl number
q	spatial order of accuracy
p	pressure (Pa)
$\dot{Q}$	heat transfer rate (W)
r	grid refinement factor
R	radius of curvature (m)
Re	Reynolds number
$\dot{S}'''_g$	volumetric entropy generation rate (W m^{-3} K^{-1})
T	temperature (K)
u	velocity (m s^{-1})
$\bar{u}$	average velocity (m s^{-1})
$\vec{U}$	velocity vector (m s^{-1})
V	volume (m^3)

Greek symbols

ΔT	temperature difference (K)
ΔP	pressure drop (Pa)
α	aspect ratio
γ	curvature ratio
δ	Kronecker delta
θ	local intersection angle
λ	thermal conductivity (W m^{-1} K^{-1})
μ	dynamic viscosity (kg m^{-3} K^{-1})
ρ	density (kg m^{-3})
σ	degree of arc (rad)

Subscripts

ΔT	temperature difference
ΔP	pressure drop
hw	heated wall
i	inlet
m	average
w	wall
z	based on length x

parallel simulation results based on the classical Navier–Stokes equations are in good agreement with the experimental data. Naphon and Wongwises [1] reviewed literatures on heat transfer and flow characteristics of single-phase and two-phase flow in curved tubes, and presented the relevant correlations of single-phase heat transfer coefficients and single-phase, two-phase friction factors. The comprehensive reviews of the flow of Newtonian fluids in curved pipes can also been found in [14,15].

The curved channel flow and heat transfer have been studied extensively. However, most work focuses on the analysis based on the first law of thermodynamics. Although the energy is conserved in heat transfer processes, the useful energy (available work or exergy) is destructed, since heat transfer processes are inherently irreversible. Reducing lost available work is of great significance for energy saving, especially for the today's world where the available coal and petroleum (useful energy) becomes scarce in the visible future [16]. According to the Gouy-Stodola theorem, the lost available work is directly proportional to the irreversibility level (entropy generation) in the heat transfer processes, and the proportionality factor is simply the environment absolute temperature [17]. In order to minimize the lost available work in engineering systems and their components, the entropy generation minimization is required for the design of the systems and components [17]. The analysis of the lost available work and irreversibility are directly related to the second law of thermodynamics, so the second law analysis is very important for conserving useful energy. Bejan [16] stated that the second law (entropy generation) should play a central role in heat transfer analysis. However, very little work is devoted to the second law analysis of the curved channel flow and heat transfer. Therefore we attempt to conduct a second law analysis of the curved channel flow and heat transfer in the present work.

Since the curved channel usually works in a heat exchanger as a component, let us first look at the second law analysis for heat exchanger performance. The irreversible losses in a heat exchanger include two parts: the irreversible loss caused by heat transfer and the irreversible loss contributed by fluid friction [16]. Generally, the entropy generations caused by heat transfer and fluid friction have opposite tendencies with the variations of the parameters in heat transfer processes, the competition may lead to the existence of the total entropy generation extremum. The best balance point between the entropy generations caused by heat transfer and fluid friction is regarded as the optimal flow regime in convective heat transfer. This is one of the key points of the entropy generation minimization developed by Bejan [16,17]. When the hydraulic diameter of the channel is larger than the range of the so-called microchannel, the trade-off between entropy generations caused by heat transfer and fluid friction may not exist, the trade-off is more likely to occur for very small hydraulic diameters [18]. This view demonstrates the necessity of the second analysis of the microchannel flow and heat transfer.

Sekulić et al. [19] explored the existence of thermodynamic irreversibility extrema for straight ducts with various cross-sections in laminar flow, and found that the irreversibility extrema are very weak or do not exist in laminar flow. Richardson et al. [18] presented an analysis of the existence of an optimum laminar flow regime inside straight micro channels with irregular cross-sections, and found that the thermodynamic optimum flow regime rarely occurs in the laminar region of the straight ducts with irregular cross-sections; for very small diameters, the ones of an order of magnitude of O($\leq 10^{-3}$ m), the optimum flow regime appearance is more probable, if the optimum flow exists, it is close to the transitional region. Ko and Ting [20] numerically studied the entropy generation in the curved ducts with different aspect ratios and air as the working fluid under constant heat flux condition; the optimal aspect ratio can be obtained when the dimensionless heat flux and the Dean number are given, the optimal Dean number exists for each aspect ratio case, and increases as dimensionless heat flux increases.

In the present work we present the second law analysis of the laminar flow in the curved rectangular channels with equivalent diameters of an order of magnitude of O($\leq 10^{-3}$ m) and water as