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Second law analysis of water flow through smooth microtubes under adiabatic conditions

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ABSTRACT

In the study, a second law analysis for a steady-laminar flow of water in adiabatic microtubes has been conducted. Smooth microtubes with the diameters between 50 and 150 μm made of fused silica were used in the experiments. Considerable temperature rises due to viscous dissipation and relatively high pressure losses of flow were observed in experiments. To identify irreversibility of flow, rate of entropy generation from the experiments have been determined in the laminar flow range of Re = 20–2200. The second law of thermodynamics was applied to predict the entropy generation. The results of model taken from the literature, proposed to predict the temperature rise caused by viscous heating, correspond well with the experimental data. The second law analysis results showed that the flow characteristics in the smooth microtubes distinguish substantially from the conventional theory for flow in the larger tubes with respect to viscous heating/dissipation (temperature rise of flow) total entropy generation rate and lost work.

1. Introduction

The advances in the manufacturing technologies make it possible to build various microsystems such as micro-heat sinks, micro-pumps, micro-sensors, micro-biochips, micro-reactors, and micro-fuel cells [1–3]. Since microchannels are usually integrated in these microsystems, it is crucial to understand the fluid flow and heat transfer characteristics in the microchannels [4]. For effective design of fluid flow and heat transfer applications in industry, the second law analysis is an essential tool to determine energy losses and to identify the irreversibility. The irreversibility in a flow is primarily due to friction losses occurred between tube wall and flow, as well as heat transfer between flow and ambient which induces entropy generation in a thermodynamic system. Temperature and velocity gradients in microscale flows are much larger as compared to macro-sized channels and any change in the flow would result in larger impact and the second law analysis is inevitable. The concepts of irreversibility and entropy generation were extensively reviewed by Bejan [5]. He showed the fundamental importance of the entropy minimization for efficient processing.

Numerous experimental and theoretical studies were carried out to understand the fluid flow and heat transfer characteristic of microchannels [1–4,17–25]. The entropy generation due to steady laminar forced convection fluid flow between parallel plates microchannel was investigated numerically by Haddad et al. [6]. They found that the entropy generation within the microchannel decreased as the Knudsen number increases and increased as Reynolds, Prandtl, Eckert numbers and the non-dimensional temperature difference increased. Entropy generation has been numerically investigated for fully developed laminar flow forced convection in a micro-pipe by Özalp [7]. In his paper, the compressible and variable fluid property continuity, Navier–Stokes and energy equations were solved for various Reynolds number, constant heat flux and surface roughness cases; entropy generation was discussed in conjunction with the velocity and temperature profiles, boundary layer parameters and heat transfer-frictional characteristics of the pipe flow. Also he presented in a different paper [8] a computational study of the integrated effects of surface roughness, heat flux, and Reynolds number on the 1st and 2nd law characteristics of laminar-transitional flow in microtubes. Entropy generation of transient laminar forced convection in microtubes has been investigated numerically considering the micro scales in the region of Kn < 0.001 by Erbay et al. [4]. Their results showed that the entropy generation had its highest value at channel with the smallest aspect ratio at counter motion of the lower plate with the highest Re, Pr, and Br/Ω values. In addition, the exergy destruction of the laminar forced convective flow was numerically analyzed by Erbay et al. [9]. Their results indicated that the exergy destruction reached its highest value at the entrance region of microtubes. Öztop et al. [10] performed a second law analysis for rectangular ducts with semicircular ends. Entropy generation was obtained in the laminar flow considering two different conditions:

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Nomenclature

A	area (m^2)
Br	Brinkman number
c	specific heat ($J\,kg^{-1}\,K^{-1}$)
D	inner diameter (μm)
E	total energy (kJ)
Ec	Eccert number
f	Darcy friction factor
h	enthalpy ($kJ\,kg^{-1}$)
Kn	Knudsen number
L	length of tube (m)
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
N_T	temperature number
P	absolute pressure (Pa)
Pr	Prandtl number
Re	Reynolds number
$\dot{Q}$	heat transfer rate ($kJ\,s^{-1}$)
T	temperature (K)
ΔT_v	temperature increase due to viscous heating (K)
T_{ref}	reference temperature (K)
u	specific internal energy ($kJ\,kg^{-1}$)
U_m	mean velocity of fluid ($m\,s^{-1}$)
V	volume (m^3)
$\dot{V}$	volumetric flow rate ($m^3\,s^{-1}$)
$\dot{W}$	power ($kJ\,s^{-1}$)

Greek symbols

τ	shear stress ($N\,m^{-2}$)
β	entropy generation coefficient
μ	fluid viscosity ($N\,s\,m^{-2}$)
Φ	viscous function
Ω	dimensionless temperature difference

Subscripts

CV	control volume
in	inlet
out	outlet
gen	generation
ref	reference
v	viscous

i.e., constant wall temperature and constant heat flux at the wall for various cross-sectional areas. They found that the total entropy generation increased with increase in the aspect ratio for both constant wall temperature and constant heat flux. Khan [11] employed the entropy generation minimization procedure to optimize the overall performance of microchannel heat sinks using analytical and empirical correlations for heat transfer and friction coefficient. Also they performed a parametric study to show the effects of different design variables on the overall performance of heat sinks. Al-Zaharnah and Yilbas [12] examined the influence of fluid viscosity on the entropy generation due to pipe flow heated from the wall at constant temperature. They pointed out that the volumetric entropy generation rate in the region close to the pipe wall was higher for variable properties case and the total entropy generation rate in the pipe wall attained lower values for variable viscosity case as compared to that corresponding to the constant viscosity case. Makinde and Gbolagade [13] investigated the second law analysis of a laminar flow of viscous incompressible fluid through an inclined channel with isothermal walls. The velocity and temperature profiles were obtained analytically and used to compute the entropy generation number. Results showed that the heat transfer irreversibility dominates along the channel centerline while an increase in group parameter (Br Ω^{-1}) may cause fluid friction irreversibility to dominate near the tubes heated walls. The Reynolds number and wall effects on entropy distribution and total entropy generation in the tube were investigated by Al-Zaharnah [14]. His numerical results indicated that the increase in the Reynolds number enhanced the entropy generation rate. He also reported that the entropy generation caused by heat transfer dominated over the entropy generation due to fluid friction. Non-Newtonian flow in an annular-pipe was studied by Yilbas et al. [15] and Engin et al. [16]. Engin et al. [16] reported significant departures from the conventional laminar flow theory for the microtube flows with wall roughness effects. Mahmud and Fraser [17] investigated the second law analysis of steady-laminar flow of incompressible fluid inside channel with circular cross-section and channel formed by two parallel plates. They concluded that the viscous dissipation will be a heat source which caused a temperature increasing in flow. The effect of viscous force has an important role in the laminar heat transfer and fluid flow, and has been investigated by several authors [18–25]. The authors found that the effects became significant and influenced the temperature, pressure and velocity distributions in the flow. Therefore, the relationships between the average friction factor and the Reynolds number change when the hydraulic diameter of the microtubes is very small. The viscous dissipation effects are brought about by rises in the velocity. In addition, the results of studies showed that viscous dissipation was a strong function of geometric parameters and Reynolds, Prandtl and Eckert numbers, and the viscous dissipation cannot be ignored in micron-sized channels.

It is clearly seen from the literature survey that although there are many analytical and/or numerical studies that dealt with entropy generation in macro or micron-sized channels, the experimental studies are very scarce in the open literature. The experimental investigations in this regard are crucially important in order to validate the available analytical and computational models, and understand the physical aspects of the micro-sized heat transfer and fluid flows encountered in microsystems.

In this paper, experiments have been conducted to investigate the rate of entropy generation during incompressible laminar flows in microtubes. Experiments were carried out under the adiabatic conditions in order to discover the effects of viscous dissipation by means of the entropy generation occurred in the flow. The individual effects of microtube diameter, length, fluid inlet temperature, as well as the Reynolds number on entropy generation have been discussed The experimental data compared with the results of predictive model available in the literature (proposed by Morini [2]). The comparison showed that the measured data were consistent with the model predictions.

2. Mathematical formulations

The adiabatic microtube analyzed in this study is shown in Fig. 1. Water flows through the inlet of the tube with a mass flow rate of $\dot{m}_{in}$ at the inlet temperature of T_{in}. The flow is assumed to be laminar and fully developed with constant fluid properties.

For a steady flow, the conservation of mass for a control volume requires that the total rate of mass entering the control volume is equal to the total rate of mass leaving it.

$$\dot{m}_{in} = \dot{m}_{out} \tag{1}$$