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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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