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Modeling non-adiabatic parallel flow microchannel heat exchangers

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ABSTRACT

This article analyzes parallel flow microchannel heat exchangers with non-adiabatic thermal condition imposed on the wall separating the fluids and the ambient. For purposes of analysis, a thermal model comprising of two governing equations, one for each of the fluids, is developed and analytically solved to obtain equations for calculating the axial temperature and thereby the effectiveness of both fluids. Provision is provided in these equations for the temperature of the ambient interacting with the hot fluid to be different from that associated with the cold fluid. Analytical equations for determining the heat transfer between the individual fluids and the respective ambient as well as that between the fluids are also developed in this paper. The temperatures/effectiveness of the fluids depend on parameters such as NTU, fluid heat capacities, thermal resistance between the individual fluid and the respective ambient and ambient temperatures. In addition, under certain operating conditions the phenomenon of temperature-cross is observed. Depending on the ambient temperatures, increase in NTU will continuously improve the effectiveness of one the fluids; the effectiveness of the other fluid over the same NTU range increases before peaking and subsequent decrease. Equations for determining the NTU at which this peak value in effectiveness occurs are also provided. An unbalanced flow microchannel heat exchanger with the hot fluid having the lowest heat capacity has better effectiveness than when the cold fluid has the lowest heat capacity.

1. Introduction

Fluidic devices that employ channels with hydraulic diameter smaller than 1 mm are dealt with in the field of microfluidics [1]. Microfluidic devices have gained tremendous importance in recent times. This surge in interest is mainly due to the advantages associated with fluid flow at the microscale over macroscale flows such as: 1) increased functional integration, 2) miniaturization, 3) reduced residence time, 4) reduced working fluid inventory, 5) enhanced heat and mass transfer rates, and 6) increased surface area density [2].

Conventional ε–NTU relationships are used for designing both macro- and micro-sized two-fluid heat exchangers [3]. These equations are formulated based on the assumption that the thermal interaction in a heat exchanger is limited to that between the two fluids flowing through it [4]. This is a reasonable assumption as long as the heat exchangers are properly insulated. However, proper insulation of microchannel heat exchangers (MCHXs) can be a challenging task. It is difficult to insulate these microfluidic devices in a conventional way, i.e. by packaging them in insulating materials or vacuum, without affecting its overall size and weight. This is evident in the case of a two-stage microminiature refrigerator, developed at MMR Technologies Inc., which is packaged in a dewar [5]. The size of the packaged device is much bigger than the microminature refrigerator itself. Moreover, this approach can prevent MCHXs from being integrated with other micro devices on a single substrate. In recent years, several researchers have placed devices such as microreactors and microchannel fuel cells in vacuum packages for reducing their thermal interaction with the surrounding [6]. These researchers used very low pressure ($\sim$10–50 m Torr) inside the package to minimize heat loss. Even at such low pressure they were only able to reduce the heat loss by 60% of the heat loss that occurred without a vacuum package [6]. Moreover, Shah and Besser [6] expressed concern about the reliability of such packages, as it would become difficult to maintain such low pressure for a prolonged duration. Shah and Besser [6] thus suggested the use of materials of low thermal conductivity along with vacuum packages for minimizing heat loss from micro devices. The lack of proper thermal isolation can affect the thermal performance of MCHXs in several ways. Due to its small size (channel dimensions and wall thickness) the thermal resistance between the fluids is comparable to that between the individual fluid and its corresponding ambient. Moreover, for MCHXs that are currently being used in high temperature and cryogenic

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