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Optimization of micro heat exchanger: CFD, analytical approach and multi-objective evolutionary algorithms

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Abstract

Advances in miniaturization have led to the use of microchannels as heat sinks in industry. Studies have established that the thermal performance of a microchannel depends on its geometric parameters and flow conditions. This paper describes two approaches for determining the optimal geometric parameters of the microchannels in micro heat exchangers. One approach combines CFD analysis with an analytical method of calculating the optimal geometric parameters of micro heat exchangers. The second approach involves the usage of multi-objective genetic algorithms in combination with CFD.

Keywords: Computational fluid dynamics; Micro heat exchanger; Optimization; Multi-objective; Optimal shape; Evolutionary algorithms

1. Introduction

The trend toward miniaturization and the advances in microfabrication have led to the application of microchannels for thermal management in areas such as medicine, consumer electronics, avionics, metrology, robotics, process industry, telecommunication and automotive industries to mention just a few. Since the work of Tuckerman and Pease [1], microchannels have received considerable attention particularly in the areas of experimental [2–10], analytical [11–19] and numerical [10,20–23] studies. These studies revealed deviations in the heat transfer and fluid flow characteristics in microscale devices from those of conventionally-sized (or macro-scale) devices. The flow and heat transfer characteristics of fluids flowing in microchannels could not be adequately predicted by the theories and correlations developed for conventionally-sized channels. The studies [15,16] further showed that the performance of a microchannel heat exchanger depends very much on the aspect ratio (AR) of the channels. Bau [24] conducted optimization studies to minimize temperature gradient and overall thermal resistance in microchannels and concluded that reduction in overall thermal resistance could be achieved by varying the cross-sectional dimensions of a microchannel.

In spite of the widespread use of micro heat exchangers (μHEXs) in the process and automotive industries, there is limited published literature on attempts at designing them for optimal performance.

The objective of this paper is to present two methods for determining the optimal design parameters of the microchannels in μHEXs that maximize the heat transfer rate (or heat flux) subject to specified design constraints. The first is a simple approach that combines CFD with the analytical solution of a simplified transport equation for momentum and heat transfer. This approach optimizes the dimensions of a microchannel with predetermined geometry. The second approach, a more sophisticated method, not only determines the optimal dimensions of a heat exchanger but also determines the optimum shape

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Nomenclature

b	length scale as defined in Eq. (5)
c_p	specific heat capacity at constant pressure
d_h	hydraulic diameter
g	acceleration due to gravity
h	heat transfer coefficient, specific enthalpy (in Eq. (3))
H	height of microchannels
k	thermal conductivity
l	length of channel
Nu	Nusselt number
u_i	velocity component in tensor notation
p	pressure
ΔP (ΔP_h, ΔP_c)	pressure drop (hot, cold gas channel)
s	thickness of material separating channels (Table 2)
T	temperature
x_i	general coordinate direction
w	width of channel
Q	heat transfer

Greek symbols

α	ratio in Eq. (7)
β	bulk viscosity
δ_{ij}	Kronecker delta function
μ	dynamic viscosity
ρ	density
τ_{ij}	stress tensor

Subscripts

c	channel
f	fluid
s	solid

based on imposed operating conditions. This approach increases the degree of freedom of the geometrical variations by combining CFD analyzes with multi-objective evolutionary algorithms (MOEAs).

2. Mathematical model

The problem under consideration is the forced convection through μHEX. A schematic model of the μHEX is shown in Fig. 1. It consists of rectangular channels with hot and cold fluid flowing through alternate channels. The dimensions of the heat exchanger core are shown in the figure. The method described here applies to both co- and counter-flow configurations.

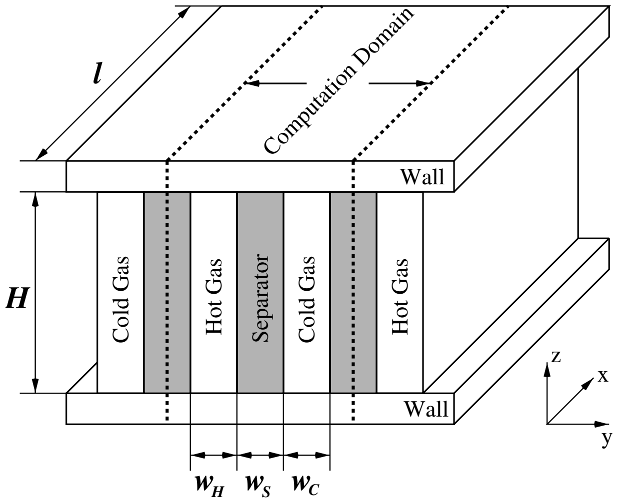

Fig. 1. A schematic model of the micro heat exchanger. The micro heat exchanger consists of three parts, i.e., a hot gas channel, a cold gas channel and a separator. The heat energy in the hot gas channel will be transferred to the cold gas channel via the separator.

For the studies reported in this paper, the hydraulic diameter of microchannels considered was between 100 μm and 1000 μm. The Knudsen number for all the flows considered was less than 0.001, a necessary condition for continuum flow. Therefore, the conservation equations based on continuum flow apply. The governing equations that describe the steady state momentum and heat are given in tensor notations below.

Continuity and momentum

$$\frac{\partial}{\partial x_i}(\rho v_i) = 0, \quad \rho u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \rho g_i + \frac{\partial \tau_{ij}}{\partial x_j}, \quad \text{where}$$

$$\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) + \left(\beta - \frac{2}{3}\mu\right)\frac{\partial u_k}{\partial x_k}\delta_{ij}. \tag{1}$$

Energy

$$\rho u_j \frac{\partial h}{\partial x_i} = u_i \frac{\partial p}{\partial x_i} + \phi + \frac{\partial}{\partial x_i}\left(k\frac{\partial T}{\partial x_i}\right), \quad \text{where } \phi = \tau_{ij}\frac{\partial u_i}{\partial x_j}. \tag{2}$$

In steady state the conservation equations are written in the general form

$$\frac{\partial}{\partial x_i}(\rho u_i \phi) = \frac{\partial}{\partial x_i}\left(\Gamma \frac{\partial \phi}{\partial x_i}\right) + S, \tag{3}$$

where ϕ represents a general dependent variable such as velocity or temperature, Γ is a diffusion coefficient and S is a source term. The partial differential equations represented in general by Eq. (3) were discretized over spatial coordinates by means of the control volume technique [25]. To predict the thermal performance of the μHEX the resulting finite difference equations were solved in three-dimensions using an iterative, segregated solution method wherein the