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Heat transfer and pressure drop characteristics of mini-fin structures

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Abstract

Forced convection heat transfer of air and water in bronze and pure copper mini-fin structures and mini-channel structures was investigated experimentally. The mini-fin dimensions were 0.7 mm × 0.2 mm and 0.8 mm × 0.4 mm. The tests included both staggered diamond-shaped and in-line square mini-fin arrangements. The tests investigated the effects of structures, mini-fin dimensions and arrangement, test section materials, and fluid properties on the convection heat transfer and heat transfer enhancement. For the tested conditions, the convection heat transfer coefficient was increased 9–21 fold for water and 12–38 fold for air in the mini-fin structures compared with an empty plate channel. The friction factor and flow resistance in the mini-channel structures and the in-line square mini-fin arrangement were much less than in the staggered diamond-shaped mini-fin arrangement. For the small channel width, $W_c = 0.2$ mm, the convection heat transfer with the in-line square array structure was more intense than with the staggered diamond-shaped structure, the mini-channel structure or the porous media. For the larger channel width, $W_c = 0.4$ mm, the convection heat transfer in the staggered diamond-shaped array structure was more intense than in the others systems while the in-line square structure had the best overall thermal-hydraulic performance.

Keywords: Mini-fin; Mini-channel; Experiment; Convection heat transfer

1. Introduction

Pin fins are cylinders or other shaped elements that are attached perpendicular to a wall. Various parameters characterize the pin fins, such as height, shape, diameter, and height to diameter ratio. Furthermore, pin fins may be positioned in either staggered or in-line arrangements with respect to the flow direction.

Sparrow and Ramsey (1978) and Sparrow and Kadle (1986) were among the first to investigate the heat transfer performance of in-line and staggered wall attached arrays of cylindrical fins, using fins 2.54 mm in diameter spaced 5.08 mm apart. Tanda (2001) analyzed the heat transfer and pressure drop in a rectangular channel equipped with arrays of diamond-shaped pin fins that were 5 mm wide with 20–40 mm between fins. The diamond-shaped elements were made of Plexiglas and, owing to their low thermal conductivity, the thermal boundary condition was considered to be adiabatic. Both in-line and staggered fin arrays were considered. Thermal performance comparisons with data for a rectangular channel without fins showed that the presence of diamond-shaped elements enhanced the heat transfer for equal mass flow rates and equal pumping power. Sara (2003) presented the heat transfer and friction characteristics and performance analysis of convective heat transfer through a rectangular channel with square cross-section pin fins attached to a flat surface. The pin fins were staggered and were 10 mm wide with 15–90 mm between fins. The experimental results showed that the square cross-section pin fins may provide better heat transfer enhancement. Bilen et al. (2001) did an experimental study on the heat transfer and friction loss characteristics of a surface with cylindrical fins in a rectangular cross-section channel with large diameter fins and different channel

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Nomenclature

d_p	particle diameter, m
D_e	mini-fin and porous plate channel hydraulic diameter, m
f	$\Delta p / \frac{1}{2}\rho u^2 \frac{L}{De}$, friction factor
h	average heat transfer coefficient, W/(m^2 K)
h_x	local heat transfer coefficient, W/(m^2 K)
j	$StPr^{2/3}$, Colburn factor
St	$Nu/RePr$, Stanton number
L	channel length, m
G	mass flow rate, kg/s
Nu	Nusselt number
Δp	pressure drop, Pa
Pr	Prandtl number
q	heat flux, W/m^2
Re	$\rho_f u_f D_e/\mu_f$, Reynolds number based on the plate channel hydraulic diameter
T	temperature, K
W_w	fin width, m
W_c	mini-channel width and distance between adjacent mini-fins, m
u_p	fluid velocity in the x direction, m/s
x, y	coordinates, m

Greek symbols

λ	thermal conductivity, W/(m K)
μ_f	fluid absolute viscosity, N s/m^2
ρ	fluid density, kg/m^3
ε	Porosity

Subscripts

e	effective
f	fluid
x	local
0	initial

geometries. The experiments were performed with in-line and staggered fin arrangements. The results indicated that the staggered array had a little better heat transfer enhancement than the in-line arrangement. The cylindrical fins were 17 mm in diameter and were spaced 30 mm apart, while the Reynolds number range was 3700–30 000.

In the past 20 years, convection heat transfer in micro-channel structures has been studied extensively both numerically and experimentally to enhance the heat transfer. Guo and Li (2003) reviewed and discussed the size effects on microscale single-phase fluid flow and heat transfer. A detailed numerical simulation of forced convection heat transfer occurring in silicon-based microchannel heat sinks was conducted by Li et al. (2004) using a simplified three-dimensional conjugate heat transfer model (2D fluid flow and 3D heat transfer).

A porous media in the flow channel intensifies mixing of the fluid flow and increases the contact surface with the coolant, so porous structures are an effective heat transfer augmentation technique (Lage et al., 1996; Ould-Amer et al., 1998; Jiang et al., 1999, 2004a,b; Alkam et al., 2001; Tzeng et al., 2006; Hetsroni et al., 2006). The porosity variation next to the solid wall has been analyzed by many researchers (Benenati and Brosilow, 1962; Vortmeyer and Schuster, 1983; Vafai, 1984; Vafai et al., 1985; Cheng et al., 1991; Chen et al., 1996; Jiang et al., 1996; Moise and Tudose, 1998; Fu and Huang, 1999). This non-uniform porosity distribution leads to a maximum velocity within the high-porosity region, which is recognized as the flow-channeling phenomenon. Experiments have demonstrated that to improve the heat transfer, the porosity in the vicinity of the solid boundary should be reduced. The mini-fin structure can be conceptualized as a pin fin structure with very small dimensions as a kind of constant porosity porous structure (Jiang et al., 2004c).

The mini-fin, mini-channel and porous media structures are all effective heat transfer enhancement methods. Jiang et al. (2004c) studied the heat transfer and fluid flow of water and air in constant porosity mini-fin structures and in sintered porous media. The results showed that the friction factor and flow resistance in the mini-fin structure with higher porosity were much less than in the other mini-fin structures and in the sintered porous media. The heat transfer coefficients in the mini-fin structure were larger than in the sintered porous plate channel with the same porosity and material and similar dimensions. However, this previous research was preliminary and did not include the mini-channel data in Jiang et al. (2004c).

This paper presents extensive experimental data for staggered diamond-shaped mini-fins, in-line square mini-fins, sintered porous media and mini-channel structures. The mini-fin width and the distance between adjacent fins were both less than 0.8 mm. The flow resistances and heat transfer coefficients in the staggered diamond-shaped mini-fin structures, in-line square mini-fins, sintered porous media and mini-channel structures were compared to analyze the influence of structure, fin shape and fin arrangement on the flow resistance and convection heat transfer.

2. Experimental system and test sections

The physical model and the test section geometry are shown in Fig. 1. The test section dimensions were 39.6 mm × 39.6 mm × 4 mm with a heated section 38.6 mm × 35.8 mm × 4 mm. The channel upper surface received a constant heat flux, q_w, while the bottom and side plates were adiabatic. The flow entered the channel with an average velocity, u_o, and constant temperature, T_{f0}.