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Effect of tip clearance on the heat transfer and pressure drop performance in the micro-reactor with micro-pin–fin arrays at low Reynolds number

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ABSTRACT

To optimize and improve the thermal and hydrodynamic performance of micro-reactors with micro-pin–fin arrays (MPFAR), the effect of tip clearance on the performance of the heat transfer and pressure drop at low Reynolds number was investigated by computational fluid dynamics (CFD). Unlike with high Reynolds number flow, it was found that the heat transfer and pressure drop performance in the case of low Reynolds number is quite sensitive to the tip clearance, and the introduced tip clearance can enhance the heat transfer and reduce the pressure drop effectively. Previous correlations were examined and found to overpredict the average Nusselt number and friction factor. New heat transfer and friction factor correlations accounting for the effect of tip clearance were developed, providing a valuable approach to the design and optimization of the tip clearance of the MPFAR. Finally, a series of experiments was carried out to validate the numerical simulation approach, and the experimental results agreed well with those from simulation.

1. Introduction

With the rapid application of micro-reactors and electronic microprocessors, there is an increasing need for greater availability of highly efficient technologies that can enhance heat and mass transfer. Among many possible micro-scale structures, micro-pin–fin arrays are commonly used to enhance heat and mass transfer in a variety of applications by increasing the heat transfer surface area and channel flow turbulence [1–3]. In our previous studies, a novel micro-reactor with micro-pin–fin arrays (MPFAR) was designed for hydrogen production, via methanol steam reforming due to the intensification of the heat and mass transfer [4,5]. To enhance energy density, a complete understanding of the performance of the flow characteristics, especially heat transfer, is essential for the design and optimization of micro-reactors [6,7].

Numerous studies have been carried out on the effects of pin–fins on the heat transfer and pressure drop performance in a channel, and a lot of experimental data and empirical correlations have been presented. Short et al. [8,9] studied heat transfer and pressure drop in macro/conventional-sized pin–fin arrays. They proposed new heat transfer and friction factor correlations for two flow regimes of low Reynolds number ($175 < Re < 1000$) and high Reynolds number ($Re > 1000$). Kosar et al. [10] experimentally investigated the pressure drop characteristics across four arrays of aligned and staggered circular and diamond-shaped micro-pin–fins over Reynolds numbers ranging from 5 to 128, and proposed a new friction factor correlation. Peles et al. [11] theoretically and experimentally analyzed heat transfer and pressure drop over a bank of cylindrical micro-pin–fin arrays. Their work focused mainly on the effect of geometrical and thermo-hydraulic parameters on the total thermal resistance. Kosar and Peles [12,13] studied heat transfer and pressure drop in an array of staggered circular pin–fins. Water and the refrigerant R-123 were used as working liquids. Previous correlations overpredicted the Nusselt number at low Reynolds number in their study, so they proposed a new heat transfer correlation based on the water and R-123 data. Qu and Siu-Ho [14,15] studied the heat transfer and pressure drop characteristics of liquid single-phase flow in an array of micro-pins. In their studies, two inlet temperatures and six maximum mass velocities were tested in an array of 1950 staggered square micro-pin–fins. New correlations were then developed to predict the heat transfer and pressure drop performance in the heat sink of the micro-pin–fin arrays. Tullius et al. [16] studied the effects of pin–fin shapes, channel clearances, fin material and the geometry of short micro-pin–fin arrays through numerical simulation using CFD. Correlations describing the Nusselt number and friction factor were obtained, which applied only to short fins in a laminar regime.

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Nomenclature

A_b	surface area of the heated base region
A_c	cross section area of a micro-pin–fin
A_{fin}	wetted surface area of a micro-pin–fin
A_{min}	minimum transverse flow area of the micro channel
A_t	total area of the micro-pin–fin arrays base
C	tip clearance
c, c_f	coefficient in heat transfer and friction factor correlations, respectively
c_p	specific heat
D_c	hydraulic diameter of the channel
D_f	hydraulic diameter of a micro-pin–fin
f	flow friction factor
$f_{ave,pred}$	predicted average flow friction factor
$f_{ave,sim}$	simulated average flow friction factor
h	heat transfer coefficient
h_{ave}	average heat transfer coefficient of the micro-pin–fin arrays
h_b	height of the base
h_{base}	heat transfer coefficient of the base
h_c	height of the channel
h_f	height of a pin–fin
h_{fin}	heat transfer coefficient of the micro-pin–fin
I, J	the exponents in fiction factor correlation
j, m, n	the exponents in fiction factor correlation
k	thermal conductivity
L	length of the micro-pin–fin arrays
L_c	length of the micro channel
l_d	distance between the four thermocouples and top surface
M	number of data points
m_{fin}	fin parameter
$\dot{m}$	mass flow rate
N	total number of micro-pin–fins
N_L	row number of micro-pin–fins
N_T	column number of micro-pin–fins
Nu	Nusselt number
Nu_{ave}	average Nusselt number
$Nu_{ave,pred}$	predicted average Nusselt number
$Nu_{ave,sim}$	simulated average Nusselt number
P_{fin}	cross section perimeter of a micro-pin–fin
P_{in}	inlet pressure
P_{out}	outlet pressure
Pr	Prandtl number
$Pr_{f,ave}$	Prandtl number at $T_{f,ave}$
Q	heat transferred to the micro-pin–fin arrays
Q_{loss}	heat loss
q	heat flux applied on the base of the micro-pin–fin arrays
Q_f	volume flow rate
Re	Reynolds number based on the pin–fin size
Re_c	Reynolds number based on the channel size
S_L	longitudinal pitch (center to center)
S_T	transverse pitch (center to center)
T	temperature
$T_{f,ave}$	average temperature of water
T_{in}	inlet temperature of water
T_{nw}	volume averaging temperature of near wall water
T_{out}	outlet temperature of water
T_w	wall temperature
$T_{w,ave}$	average temperature of channel bottom
u	flow velocity
u_{in}	inlet flow velocity
u_{max}	maximum flow velocity in the micro-pin–fin arrays
W	width of micro-pin–fin array
ΔP	pressure drop
Greek symbols	
Λ	interface between the solid and fluid regions
η_{fin}	fin efficiency
μ	viscosity
ρ	density

However, most of the studies mentioned above were focused mainly on the operating conditions and the geometry of micro-pin–fin arrays. Little attention has been paid to the effect of tip clearance. Reyes et al. [17] studied the effect of tip clearance in micro channels on the performance of heat transfer and pressure drop, and optimized the tip clearance accounting for both thermal and pressure drop performance based on the experimental results. Min et al. [18] found that when the tip clearance was about 40% of the channel height, the heat transfer and pressure drop performance was better. Moores et al. [19,20] studied the effect of tip clearance on the thermal and hydrodynamic performance of staggered pin–fin arrays. In their study, the tip clearance ranged from 0 to 25% of pin–fin height with a Reynolds number range of 200 to 1000. The introduction of a small tip clearance was found to enhance the heat transfer performance in some cases due to the additional surface area that was exposed to the fluid flow. More recently, Rozati et al. [21] studied heat transfer in shrouded pin–fin arrays with and without tip clearance through numerical analysis. Their study was focused mainly on the effects of tip clearance on the heat transfer performance. They found some reasonable values of tip clearance that provided the best performance under certain conditions.

Most of the previous studies about the tip clearance in micro-channels were carried out at high Reynolds number, while the Reynolds number of the reagent flowing into micro-reactors for chemical reactions is very small (normally $Re < 300$). Heat transfer is quite sensitive to the tip clearance at low Reynolds number. Previous correlations may not be suitable for describing the heat transfer and pressure drop performance in the MPFAR at low Reynolds number.

Therefore, the aim of this study was to investigate the effect of different tip clearances on the heat transfer and pressure drop performance of the MPFAR at low Reynolds numbers. A computational model of the MPFAR with a tip clearance range of 0 μm to 1000 μm was developed. The thermal and hydrodynamic performance was studied by numerical analysis at low Reynolds numbers, ranging from 20 to 350. A series of experiments was then carried out to validate the computational model in the numerical analysis. The average Nusselt number and friction factor data obtained were compared to the predictions of previous correlations. Finally, new heat transfer and friction factor correlations accounting for the effect of tip clearance were developed to provide a valuable approach for the design and optimization of the MPFAR.

2. Computational modeling

The computational model of the MPFAR is shown schematically in Fig. 1. The model is focused on forced flow passing through micro-pin–fin array reactors with or without tip clearance. Tip clearance (C) can be defined as the subtraction of the pin–fin height (h_f) from the channel height (h_c). The detailed dimensions of the models are listed in Table 1. In the present study, different tip