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Pressure drop and friction factor of a rectangular channel with staggered mini pin fins of different shapes

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ABSTRACT

Experiments were performed on de-ionized water as working fluid, flowing across staggered mini pin fins of the same height and transverse spacing but with different pin density and different shapes of circular, elliptical, square, diamond and triangle, in a rectangular channel. The volume flow rate, pressure difference and temperature at the inlet and outlet were measured for the channel with different pin fin shapes at various Reynolds number (*Re*) in the range of 50–1800 to obtain the friction factor. The results showed that the friction factor for all the fins decreased with the increase of *Re*. At low *Re* (<100), the influence of the endwall effect on the flow characteristics of the test section is obvious and the friction factor weighs more; while at high *Re* (>300), the friction factor caused by eddy dissipation is the main part. In the intermediate range of *Re* (100–300), there is a transition. At different flow regimes, the shape and the fin density affects f differently. For laminar flow, the channel with triangle pin fins of the smallest density has the minimum f value while the elliptical one of the largest density has the maximum f value. On the contrary, for turbulent flow the channel with triangle pin fins has the maximum f while the elliptical one has the minimum f. Comparisons were made between experimental data and existing correlations, and results showed that there were large deviations between them. The existing correlations for the friction factor cannot correctly describe the whole flow range including laminar, transitional and turbulent zones, and new correlations are needed.

1. Introduction

The flow and heat transfer in micro domains has received great attentions and has been used widely in many fields, such as biomedical science [1–3], micro reactors [4,5], micro engines [6,7], micro mixers [8–10], and electronics cooling [11–13]. Micro pin fins embedded in a mini/micro channel is one of the most important micro structures. The micro pin fins can greatly enhance the active area of heat sinks; moreover, the pin fins disturb the flow and break down the boundary layer, which promotes the early flow transition, boosts the flow mixing, and drastically raises the heat transfer. They might solve the problem of high heat flux and overcome the bottle neck for rapid development of ultra-large-scale integration of electronics and micro-electro-mechanical systems (MEMS). Over the years, a large amount of research work has been conducted on flow and heat transfer characteristics of micro pin finned channel. The focus of the current paper is on the hydraulic performance of the micro pin finned structures, so in the following, only the flow characteristics is surveyed.

Many researchers chose different definitions of Reynolds number when studying the micro pin finned channels. Reynolds number and minimum cross-sectional flow area are usually calculated using different approaches depending on the pin height-to-diameter ratio H/D [14]. In the first approach, for arrays with long fins ($H/D > 8$), "tube bundle" fins, the pressure drop is dominated by the fins while the endwall effects, i.e., thickening of boundary layer on the end walls, are secondary; the length scale for calculating Reynolds number is simply the fin hydraulic diameter D, and Reynolds number designated as Re here. In the second approach, for very short fins ($H/D < 1/2$) commonly used in compact heat exchangers, where the characteristic pressure drop is severely influenced by the top and bottom walls. These fin configurations are referred to as "compact heat exchanger" fins. The hydraulic diameter of the heat exchanger is used to calculate Reynolds number designated as Re_d. In the third approach, the minimum cross-sectional flow area has been adopted to define Reynolds

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Nomenclature

A_f cross-sectional area of the fin, m^2
a, b dimensional size of pin fin, m
D hydraulic diameter of pin fin, m
C tip clearance ($C = H - H_f$), m
f friction factor
H height, m
L length, m
N_x number of rows of pin fins
N_t number of total pin fins
ΔP pressure difference between channel inlet and outlet, Pa
Q flow rate, $m^3\ s^{-1}$
Re Reynolds number
$REER$ relative error
S_L longitudinal distance between pin fins
S_T transverse distance between pin fins, m
T_f characteristic temperature of the fluid, °C
T_1, T_2 temperature at channel inlet and outlet, °C
U velocity, $m\ s^{-1}$
W width, m

Geek symbols
μ dynamic viscosity, $kg\ m^{-1}\ s^{-1}$
ρ density, $kg\ m^{-3}$
ε density of pin fins

Subscripts
c channel
exp experimental
f fin
$pred$ predicted

number, and Re_c is assigned to it [15]. In the following literature survey, Reynolds number used will be stated as Re, Re_d and Re_c when mentioned, according to their original definitions.

Peles et al. [16] performed adiabatic tests for laminar flow over micro pin fin at $10 < Re < 80$. They found out that both conventional correlations and existing micro pin fin correlations fitted the experimental data fairly fell with a mean absolute error from 11.1% to 27.7%. They pointed out that for H/D smaller than some value between 1 and 2, the endwall effect is important. Later on, many researchers performed systematic studies on the flow characteristics of the micro pin finned channel. They found out that, height to diameter ratio, arrangement, pitch, endwall effect, flow regime and pin fin shapes all influenced the heat transfer and flow behavior to some extent.

Kosar et al. [14] studied laminar flow across micro circular and diamond pin fins with small H/D ratio of 1 and 2, and made comparison of their experimental data with a large amount of existing conventional correlations. They found out that those correlations had large prediction errors and concluded that this was because the conventional correlations did not include the end wall effect which occurred at the micro level and low H/D ratio. They proposed a new correlation for the friction factor. They also ascertained that the staggered micro pin fins experienced a greater pressure loss than the inline ones at low Re and the difference between them disappeared as Re increased. Further, they compared circular pin fins with diamond pin fins, and found out that the diamond ones had a higher friction factor. Kosar and Peles [17] investigated the flow and heat transfer across the heat sinks with circular micro pin fins of height 243 μm and $H/D = 2.43$ for effective heat fluxes ranging from 3.8 to167 W/cm^2 and Re from 14 to 112. The long tube correlations predicted their friction data well at high Reynolds number but over-predicted at low Reynolds number. The discrepancy of their data with the correlation from Kosar et al. [14] at low Reynolds number was attributed to the thickening of boundary layer (on the endwalls) which predominates over "flow separation delay" effects for $H/D = 1$ in Kosar et al. [14]. For $H/D = 2.43$ in their own case, "flow separation delay" prevails over boundary layer effects, resulting in a low friction factor. Prasher et al. [18] studied both staggered circular and square micro pin fins with dimensions (diameter for circular and sides for square) ranging from 50 μm to 150 μm and H/D ratio from 1.3 to 2.48, in the range of $10 < Re < 1000$; they found out that the square pins led to slightly higher friction factor than the circular pins. The friction factor varied more sensibly with Re at $Re < 100$ but less at $Re > 100$; they established different correlations of friction factors for these two zones. They also suggested to use a log–log scale for better observation of the change of friction factor with Re. Koz et al. [19] calculated the thermal and hydrodynamic characteristics of circular micro pin–fin heat sinks with height over diameter H/D varying from 0.5 to 5 while Reynolds number and heat flux provided from the fluid interacting surfaces of the micro pin–fin are in the range of $20 < Re < 150$ and $100 < q\ (W/cm^2) < 500$, respectively. They showed that the endwall effect decreased with H/D, and local Re. In addition, increasing H/D ratio while keeping S_T/D ratio constant led to a less stable flow, and total force acting in the flow direction and on the micro pin–fin is proportional with H/D and Re. The ratio of viscous to total forces and the friction factor decrease with Re and increases with H/D.

Liu et al. [20] conducted an experimental study on the friction factors associated with forced flow of de-ionized water over staggered and in-line micro/mini cylinder groups with hydraulic diameter of 0.5 mm and height of 1.0 mm, 0.75 mm, 0.5 mm and 0.25 mm, with Re ranging from 25 to 800. Their analysis showed that the value of fRe was approximately a constant in micro/mini cylinder group plates when the flow was purely laminar, whereas the value of fRe increased when $Re > 100$. They believed that some micro-scale effects, such as tip clearance effect, roughness effect, and endwall effect, resulted in obvious discrepancies between their experimental data and predictions of theoretical correlations. Liu et al. [21] experimentally obtained the resistance characteristics of de-ionized water flowing through in-line and staggered arrays of micro-cylinders-group plates with different distances among micro-cylinders at $0 < Re < 300$ with different heating power. They compared their data with existing correlations (*Ref*) and found a large deviation at low Re; they attributed this to the existence of a sluggish zone caused by micro scale and endwall effect. Selvarasu et al. [22] were concerned about the density of micro pin fins for the channel flow at $10 \leqslant Re \leqslant 600$ and through numerical study they found that the friction factor is higher for configurations with higher pin fin density. The losses are dominated by friction drag at low Re but by form drag at high Re as wake recirculation develops. Kosar and Peles [23] performed a parametric study of pressure drop associated with the forced flow of deionized water over five micro pin fin heat sinks of different arrangements and shapes experimentally, with Reynolds numbers ranging from 14 to 720. The pin shapes are circular, hydrofoil, cone-type and rectangular. They found out that the denser arrangement brings the interaction of the wakes of the front bank pin fins with the bank next to it, which increases the flow mixing and causes a greater