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Pressure drop of water flow across a micro-pin–fin array part 1: Isothermal liquid single-phase flow

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ABSTRACT

This is part one of a two-part study that investigates water single-phase and two-phase pressure drop across a staggered array of circular micro-pin–fins. This paper presents results of isothermal liquid single-phase flow, and part two adiabatic liquid–vapor two-phase flow. The micro-pin–fins are 180 μm in diameter, 683 μm in height, and 399 μm in both longitudinal and transverse pitches. Seven temperature levels from 23 to 80 °C, and seventeen maximum mass velocities for each temperature, ranging from 133 to 1538 kg/m^2 s, were tested. The resulting Reynolds number ranged from 26 to 776. Pressure drop across the micro-pin–fin array was measured, and friction factor calculated. The existing friction factor correlations for micro-pin–fin arrays, conventional-size pin–fin arrays, and tube banks were examined and found unable to predict the data. A numerical simulation was performed, and a good agreement was found between the experimental data and numerical results. A new friction factor correlation was developed that is used in part two of the study on calculating liquid–vapor two-phase pressure drop.

1. Introduction

Micro-size pin–fin arrays have recently emerged as a promising alternative to micro-plate-fins as internal heat transfer enhancement structures for liquid-cooled miniature heat sinks intended for high-heat-flux cooling applications [1]. Compared to their plate-fin counterparts, micro-pin–fin arrays offer more design possibilities so as to achieve desired heat sink performance: pin–fins can have different cross-sectional shapes (circular, square, triangle, diamond shape, elliptical, cone shape, airfoil, etc.), and be arranged staggered or aligned in space; characteristic size including diameter, height, and longitudinal and transverse pitches can be varied; and a clearance can be incorporated between fin tips and end wall.

Both single-phase convection and flow boiling can be employed as a means to remove heat from micro-pin–fin arrays. Accordingly, the heat sinks can be classified as single-phase or two-phase. A growing number of studies have been carried out in recent years on thermofluid characteristics of single-phase flow [2–14] and flow boiling [15–21] in micro-pin–fin arrays with the goal of providing fundamental knowledge and accurate predictive tools that are essential to the design and implementation of this novel type of heat sink.

Aiming at further expanding the knowledge in the subject area, the present study concentrates on water flow pressure drop across a staggered circular micro-pin–fin array with height-to-diameter ratio H/D in the intermediate range of 0.5–8, and no clearance over the pin–fin tips. Part 1 of the study, this paper, presents results of isothermal liquid single-phase flow. Part 2, documented in the companion paper [22], reports adiabatic liquid–vapor two-phase flow results.

A number of studies are available in the literature on single-phase pressure drop across micro-pin–fin arrays having similar geometrical features [2–6,10]. Koşar et al. [2] studied water flow pressure drop across two arrays of staggered circular micro-pin–fins having diameter D of 50 and 100 μm, H/D of 2 and 1, respectively, and longitudinal pitch-to-diameter ratio S_L/D and transverse pitch-to-diameter ratio S_T/D of 1.5. Flow Reynolds number ranged from 5 to 128. They found that the existing conventional-size pin–fin array and tube bank correlations were unable to predict their micro-pin–fin data. New friction factor correlations were proposed.

Koşar and Peles [4] investigated water flow pressure drop across a staggered circular micro-pin–fin array with D of 99.5 μm, H/D of 2.43, and S_L/D and S_T/D of 1.5. Flow Reynolds number ranged from 14 to 112. They found that the end wall effect was minor for this particular H/D value, and the previous tube bank correlations predicted the data well. The finding was later confirmed by Peles et al. [3] and Koşar and Peles [5] using water and

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Nomenclature

A_{min}	minimum transverse flow area
A_{p1}, A_{p2}	flow area in plenums
A_{ts}	flow area in test section inlet
C	constant in a power function
d_h	hydraulic diameter of flow passage
D	diameter of a circular pin–fin
f	friction factor
G_{max}	maximum mass velocity
G_{p1},G_{p2}	mass velocity in plenums
G_{ts}	mass velocity in test section inlet and outlet
H	height of a pin–fin
K_{c1}, K_{c2}	contraction loss coefficient
K_{e1}, K_{e2}	expansion recovery coefficient
L	length of test section top platform area
$\dot{m}$	mass flow rate
M	total number of data points
MAE	mean absolute error
n	power index in a power function
N_L	total number of pin–fin rows in longitudinal direction
N_{fd}	number of streamwise pin–fin rows in fully developed region
$N_{T,O}$	number of pin–fins in an odd row
N_{total}	total number of pins in the array
P	pressure
ΔP_{c1}, ΔP_{c2}	contraction pressure loss
ΔP_d	pressure drop across inlet developing rows
ΔP_{exit}	pressure drop across last row
ΔP_{e1}, ΔP_{e2}	expansion pressure recovery
ΔP_{fd}	averaged per-row pressure drop across fully developed rows
ΔP_{sp}	pressure drop across test section
$\Delta P_{sp,fin}$	pressure drop across micro-pin–fin array
Re	Reynolds number
S_L	longitudinal pitch
S_T	transverse pitch
S_w	minimum wall edge to pin center spacing
T	temperature
v	specific volume
W	width of test section top platform area
W_{wall}	thickness of thin side walls along test section edges

Greek

φ	weighting factor in the Gaddis and Gnielinski correlation
μ	dynamic viscosity

Subscripts

exp	experimental
f	liquid
fin	pin–fin array
in	inlet
lam	laminar
num	numerical
out	outlet
p_1	deep plenum
p_2	shallow plenum
pred	predicted
sp	single-phase
ts	test section
turb	turbulent
wall	side wall

refrigerant R-123 as the testing liquid, respectively, in the same array.

Prasher et al. [6] studied water flow pressure drop across three arrays of staggered circular micro-pin–fins having D from 55 to 153 μm, H/D from 1.3 to 2.8, S_L/D from 2.4 to 4, and S_T/D from 2 to 3.6. Flow Reynolds number ranged from 40 to 1000. The friction factor data were plotted against Reynolds number on a log–log scale, and a change in slope in the data was observed to occur at a Re of about 100. They found that the existing micro-pin–fin, conventional-size pin–fin, and tube bank correlations could not predict the data. Two distinct correlations were proposed for the two flow regimes of low ($Re < 100$) and high Reynolds number ($Re > 100$).

Koşar et al. [10] studied water and air flow pressure drop across three arrays of staggered circular micro-pin–fins having D of 100 μm, H/D of 1 and 2.43, S_L/D of 1.5 and 2.5, and S_T/D of 1.5 and 2.5. Flow Reynolds number ranges were 2–310 for water and 2–1800 for air. They found that the existing conventional-size pin–fin and tube bank correlations were unable to predict the data.

Other relevant studies include those on single-phase pressure drop of low Reynolds number flow ($Re < 1000$) across conventional-size (millimeter or larger) pin–fin arrays bearing the same geometrical features [23,24]. Short et al. [23] investigated air flow pressure drop across 44 arrays of staggered circular pin–fins having D from 1.57 to 3.18 mm, H/D from 1.88 to 7.25, S_L/D from 1.83 to 3.21, and S_T/D from 2.0 to 6.41. A new correlation was proposed for $175 < Re < 1000$. Moores and Joshi [24] investigated water flow pressure drop in three arrays of staggered circular pin–fins with and without tip clearance. Pin–fin diameter D ranged from 3.67 to 3.84 mm, H/D from 0.52 to 1.09, S_L/D from 1.13 to 1.18, and S_T/D from 1.3 to 1.36. They also proposed a new correlation for $200 < Re < 1000$.

Single-phase pressure drop across tube banks ($H/D > 8$) has been studied extensively in the past [25–30]. Unlike that in pin–fin arrays, crossflow in tube banks is dominated by tube size and spatial arrangement with negligible endwall effects. The study by Žukauskas and co-workers led to an empirical f–Re relationship presented in graphical format [28,29]. The relationship was based on a large experimental database, and has been adopted in a heat exchanger design handbook [30] as well as a popular heat transfer textbook [31]. Another friction factor correlation developed by Gaddis and Gnielinski [27] was also based on a sizable dataset.

Although the aforementioned studies [2–6,10] provided valuable insight into the characteristics of single-phase pressure drop across staggered circular micro-pin–fin arrays, findings remain inconclusive, especially when comparing experimental data obtained by one party with predictions of the correlations developed by other parties. The objectives of this part 1 of the present study thus are: (1) to provide new data for pressure drop of single-phase flow across a staggered circular micro-pin–fin array over a broad range of Reynolds numbers, (2) to assess the applicability of the existing empirical correlations at predicting the present data, and (3) to perform a three-dimensional numerical analysis, and further assess the effectiveness of numerical methods as a predictive tool.