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Pressure drop of water flow across a micro-pin–fin array part 2: Adiabatic liquid–vapor two-phase flow

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ABSTRACT

This is part two of a two-part study that investigates water pressure drop across a staggered array of circular micro-pin–fins. This paper reports results of adiabatic liquid–vapor two-phase flow, and part one isothermal liquid single-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 maximum mass velocities from 171 to 491 kg/m^2 s, and sixteen vapor qualities for each maximum mass velocity were tested. Two-phase pressure drop across the micro-pin–fin array was measured, and two-phase friction multiplier and Martinelli parameter calculated. It was revealed that a unique functional relationship exists between the two-phase friction multiplier and Martinelli parameter, which proved that the generalized procedure developed by Lockhart and Martinelli could be applied to describe two-phase pressure drop across the micro-pin–fin array. The existing Martinelli–Chisholm type correlations for staggered micro-pin–fin arrays and tube banks were unable to predict the data, and a new correlation was developed.

1. Introduction

Liquid-cooled micro-pin–fin heat sinks utilize micro-size pin–fin arrays as internal heat transfer enhancement structures [1]. Depending on whether boiling of working liquid occurs in the micro-pin–fin arrays, the heat sinks can be classified as single-phase or two-phase (boiling). Effective design and performance assessment of this type of heat sink requires a fundamental knowledge of virtually all aspects of fluid flow and heat transfer in micro-pin–fin arrays. Among others, accurate prediction of pressure drop is of special importance. Due to small flow passages in the micro-scale structures, excessive pressure loss is always a concern. The present study focuses on water pressure drop across a staggered circular micro-pin–fin array. Part 1 of the study, documented in the companion paper [2], reports isothermal liquid single-phase flow results. Part 2, this paper, presents results of adiabatic liquid–vapor two-phase flow.

As the interest in two-phase micro-pin–fin heat sinks is fairly recent, our knowledge on two-phase pressure drop across staggered micro-pin–fin arrays is rather limited [3,4]. Only two studies were found in the literature on pressure drop of adiabatic liquid–gas (vapor) two-phase flow across micro-pin–fin arrays. Krishnamurthy and Peles [3] experimentally studied frictional pressure drop of nitrogen–water two-phase flow across a staggered circular micro-pin–fin array with diameter D of 100 μm, height-to-diameter ratio H/D of 1, and longitudinal pitch-to-diameter ratio S_L/D and transverse pitch-to-diameter ratio S_T/D of 1.5. They found that the existing homogeneous models and Martinelli–Chisholm type correlations were unable to predict the data. Two-phase friction multiplier was found to be a strong function of mass flux. A new Martinelli–Chisholm type correlation was proposed, where the C factor was linearly proportional to liquid Reynolds number.

Konishi et al. [4] investigated frictional pressure drop of water liquid–vapor two-phase flow across a staggered square micro-pin–fin array with side length S of 200 μm, H/S of 3.35, and S_L/S and S_T/S of 2. The existing homogeneous models and Martinelli–Chisholm type correlations were assessed by comparing their predictions with the data. They found that the Martinelli–Chisholm type correlation with a C factor of 5 provided the best agreement.

There are also a few studies on pressure drop of liquid flow boiling in micro-pin–fin arrays, where vapor qualities increased in the stream-wise direction as a result of heat input. Koşar [5] studied pressure drop of refrigerant R-123 flow boiling in a staggered hydrofoil micro-pin–fin array with chord thickness D of 100 μm, fin length of 500 μm, and height H of 243 μm. S_L/D and S_T/D were 5 and 1.5, respectively. They found that the existing homogeneous models and Martinelli–Chisholm type correlations were unable to predict the data. Two-phase friction multiplier was found to be strongly influenced by two-phase flow patterns. Three distinct

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Nomenclature

$A_{\min}$	minimum transverse flow area
$A_{\max}$	maximum transverse flow area
C	C factor in Martinelli–Chisholm type correlations
D	miameter of a circular pin–fin
f	friction factor
$G_{\max}$	maximum mass velocity
$G_{\min}$	minimum mass velocity
G_{p1}, G_{p2}	mass velocity in plenums
G_{ts}	mass velocity in test section inlet and outlet
h	enthalpy
$h_{vg,in}$	enthalpy of the liquid water upstream of the vapor generator
H	height of a pin–fin
K_{c1}, K_{c2}	contraction loss coefficient
K_{e1}, K_{e2}	expansion recovery coefficient
$\dot{m}$	mass flow rate
MAE	mean absolute error
N_L	total number of pin–fin rows in longitudinal direction
P	pressure
P_W	heating power input
ΔP_{c1}, ΔP_{c2}	contraction pressure loss
ΔP_{e1}, ΔP_{e2}	expansion pressure recovery
ΔP_{tp}	pressure drop across test section
$\Delta P_{tp,fin}$	pressure drop across micro-pin–fin array
Q_{loss}	heat loss
Re	Reynolds number
S	side length of a square pin–fin
S_L	longitudinal pitch
S_T	transverse pitch
T	temperature

v	specific volume
W	width of test section top platform area
W_{wall}	thickness of thin side walls along test section edges
x	vapor quality
x_e	thermodynamic equilibrium quality
X	Martinelli parameter
z	stream-wise distance

Greek

α	void fraction
ϕ	two-phase friction multiplier
μ	dynamic viscosity

Subscripts

A	Accelerational
exp	Experimental
f	Liquid
fg	Difference between liquid and vapor
fin	Pin–fin array
F	Frictional
g	Vapor
i	Streamwise segment
$ibd0$	Upstream boundary of segment i
$idb1$	Downstream boundary of segment i
in	Inlet
out	Outlet
$pred$	Predicted
tp	Two-phase
ts	Test section
$wall$	Side wall

Martinelli–Chisholm type correlations were proposed for the flow patterns of bubbly, wavy-intermittent, and spray-annular.

Qu and Siu-Ho [6] studied pressure drop of water flow boiling in a staggered square micro-pin–fin array with side length S of 200 μm, H/S of 3.35, and S_L/S and S_T/S of 2. They found that the frictional pressure drop in the boiling region was the dominant component. Among the existing models and correlations, the Martinelli–Chisholm type correlation with a C factor of 5 yielded the best agreement with the data.

Reeser et al. [7] investigated pressure drop of water and HFE-7200 flow boiling in two micro-pin–fin arrays: an aligned square and a staggered diamond. Both arrays had pin–fin side length S of 153 μm and H/S of 2. S_L/S and S_T/S were 2 for the aligned array, and 2.8 for the staggered one. They found that the existing Martinelli–Chisholm type correlations were unable to predict the data. Separate Martinelli–Chisholm type correlations were proposed for different combinations of working fluid and pin–fin configuration.

Other relevant studies include those on two-phase frictional pressure drop in conventional size tube banks [8–12]. Most of the studies investigated the aligned tube arrangement except the work by Dowlati et al. [10], in which frictional pressure drop of adiabatic air–water two-phase flow across two staggered tube banks was studied. The tube banks had D of 19.05 mm and 12.7 mm, S_L/D of 1.3 and 1.75, and S_T/D of 1.3 and 1.75, respectively [10]. They found that the Martinelli–Chisholm type correlation with a C factor of 20 could adequately predict the data for mass flux $G_{\max} > 200$ kg/m^2 s. For mass flux $G_{\max} < 200$ kg/m^2 s, a strong mass flux effect was observed.

The literature review revealed that the fundamental knowledge on liquid–vapor two-phase pressure drop across micro-pin–fin arrays is rather lacking. The objectives of this part 2 of the study thus are: (1) to provide new data for pressure drop of liquid–vapor two-phase flow across micro-pin–fin arrays, (2) to examine the relationship between two-phase friction multiplier and Martinelli parameter, and assess the feasibility of using Lockhart and Martinelli's generalized procedure [13] to predict two-phase flow pressure drop across the micro-pin–fin array, (3) to assess the accuracy of the existing correlations at predicting the present data, and (4) to develop a new predictive tool.

2. Experimental apparatus and procedure

The same micro-pin–fin test module used in part 1 [2] for the experimental study of single-phase pressure drop was employed here to investigate two-phase pressure drop. Fig. 1 shows a schematic of the test module, which is composed of a test section, a housing, and a transparent cover plate. The test section had a top platform area of 1 cm (width) by 3.38 cm (length). An array of 1845 staggered circular micro-pin–fins was milled out of the platform surface. There were 82 rows in the longitudinal (stream-wise) direction, 23 pin–fins in every odd row, and 22 pin–fins in every even row. The micro-pin–fins were 180 μm in diameter D, 683 μm in height H, and 399 μm in both longitudinal pitch S_L and transverse pitch S_T. The resulting H/D ratio was 3.8, and S_L/D and S_T/D ratios 2.2.

The housing contained inlet and outlet plenums, each consisting of a shallow and a deep section. The inlet and outlet deep plenums had a width of 19 mm and a height of 15.9 mm while the shallow plenums a width of 19 mm and a height of 670 μm. Two type-K thermocouples were installed in the deep plenums to measure the inlet and outlet temperatures T_{in} and T_{out}, respectively. An absolute pressure transducer was connected to the inlet deep plenum to measure the test section inlet pressure P_{in}. A differential