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Toward a generalized correlation for liquid–vapor two-phase frictional pressure drop across staggered micro-pin-fin arrays☆

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ABSTRACT

In a previous study by the corresponding author and co-worker Mita and Qu (2015) (J. Mita, W. Qu, Pressure drop of water flow across a micro-pin-fin array part 2: adiabatic liquid–vapor two-phase flow, International Journal of Heat and Mass Transfer 89 (2015) 1007–1015), a modified Martinelli–Chisholm type correlation was developed to predict adiabatic water liquid–vapor two-phase frictional pressure drop across an array of staggered circular micro-pin-fins. This work expands on the study in ref. Mita and Qu (2015) and examines whether the correlation is geometry specific or it can be extended to describe a different array configuration. A square micro-pin-fin array were prepared, and adiabatic water liquid–vapor two-phase frictional pressure drop across the array was experimentally investigated. The square pin-fins were 200 *microns* in side length, 670 *microns* in height, and 400 *microns* in both longitudinal and transverse pitches. Two-phase friction multiplier and Martinelli parameter were calculated based on the measured pressure drop as well as a single-phase friction factor correlation developed for the same square array. An excellent agreement was found between the experimental data and correlation predictions despite the distinctive geometrical features possessed by the two sets of micro-pin-fin arrays. The result points to the possibility of establishing the correlation as a generalized one applicable to a broad range of staggered micro-pin-fin array configurations.

1. Introduction

Transport phenomena associated with flow boiling in micro-pin-fin structures have received considerable research attention in the past decade [2–7]. The underlying objective of these research activities was to develop a fundamental understanding of the transport process that is vital to the design and implementation of two-phase (boiling) micro-pin-fin heat sinks. The novel type of heat sink utilizes micro-pin-fins as its internal heat transfer enhancement structure, and is considered a promising alternative to micro-channel heat sink for high-heat-flux cooling applications.

A number of these previous studies were dedicated to pressure drop characteristics [5–7]. Koşar [5] experimentally investigated refrigerant R-123 flow boiling pressure drop across a staggered hydrofoil micro-pin-fin array. Existing two-phase pressure drop models and correlations were assessed and deemed unable to predict the data. New Martinelli–Chisholm type correlations were proposed for different flow patterns. Qu and Siu-Ho [6] studied water flow boiling pressure drop across a staggered square micro-pin-fin array. Among 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] studied water and HFE-7200 flow boiling pressure drop across an aligned square and a staggered diamond micro-pin-fin array. Existing correlations were found unable to predict the data. New Martinelli–Chisholm type correlations were proposed for different combinations of working fluid and pin-fin geometry.

With heat induced flow boiling occurring in a micro-pin-fin array, vapor quality would increase appreciably in the stream-wise direction. Reduction in the density of the two-phase mixture leads to an increasing velocity along the flow path. Overall pressure drop across the micro-pin-fin array is thus composed of two components: frictional and accelerational. Accurate determination of the individual components is often a challenge with a variable vapor quality in the stream-wise direction.

To circumvent the difficulty, research efforts have been made to study only the frictional pressure drop by testing adiabatic two-phase flow across micro-pin-fin arrays [1,8,9]. In those studies, liquid–vapor (gas) two-phase mixtures with prescribed vapor quality were produced upstream of the micro-pin-fin arrays, and then forced to flow through the structures under adiabatic condition. With negligible stream-wise variation in vapor quality, the accelerational effect was absent, and the overall pressure drop was caused solely by the frictional effect.

Krishnamurthy and Peles [8] studied frictional pressure drop of adiabatic nitrogen-water two-phase flow across a staggered circular micro-pin-fin array. Existing models and correlations were found unable to predict the data, and a new Martinelli–Chisholm type correlation was

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Nomenclature

A_{min}	Minimum transverse flow area
A_{p1},A_{p2}	Flow area of plenums
C	C factor in Martinelli–Chisholm type correlations
D	Diameter of a circular micro-pin-fin
$f_{sp,fin}$	Single-phase friction factor
$f_{sp,f,fin}$	Liquid single-phase friction factor based on actual liquid flow rate
$f_{sp,g,fin}$	Vapor single-phase friction factor based on actual vapor flow rate
G_{max}	Maximum mass velocity
G_{p1},G_{p2}	Mass velocity in plenums
h	Enthalpy
h_{fg}	Latent heat of vaporization
$h_{vg,in}$	Enthalpy of the liquid water upstream of the vapor generator
H	Height of a micro-pin-fin
H_{p1},H_{p2}	Height of plenums
K_{c1},K_{c2}	Contraction loss coefficient
K_{e1},K_{e2}	Expansion recovery coefficient
$\dot{m}$	Mass flow rate
M	Total number of data points
MAE	Mean absolute error
N_L	Total number of micro-pin-fin rows in stream-wise direction
$N_{T,O}$	Number of micro-pin-fins in an odd row
P	Pressure
$P_{W,vg}$	Heating power input to vapor generator
ΔP	Pressure drop across test section
ΔP_{c1}, ΔP_{c2}	Contraction pressure loss
ΔP_{e1}, ΔP_{e2}	Expansion pressure recovery
ΔP_{fin}	Pressure drop across micro-pin-fin array
$\Delta P_{sp,f,fin}$	Liquid single-phase frictional pressure drop across micro-pin-fin array based on actual liquid flow rate
$\Delta P_{sp,g,fin}$	Vapor single-phase frictional pressure drop across micro-pin-fin array based on actual vapor flow rate
Q_{loss}	Heat loss
Re_{sp}	Single-phase Reynolds number
$Re_{sp,f}$	Liquid single-phase Reynolds number based on actual liquid flow rate
$Re_{sp,g}$	Vapor single-phase Reynolds number based on actual vapor flow rate
S	Side length of a square micro-pin-fin
S_L	Longitudinal pitch
S_T	Transverse pitch
S_w	Minimum wall edge to pin center spacing
T	Temperature
v	Specific volume
W_{p1},W_{p2}	Width of plenums
W_{wall}	Thickness of thin side walls along test section edges
x_e	Thermodynamic equilibrium quality
X	Martinelli parameter
z	Stream-wise distance

Greek

ϕ_f	Two-phase friction multiplier
μ	Dynamic viscosity

Subscripts

avg	Average
exp	Experimental
f	Liquid
fg	Difference between liquid and vapor
fin	Micro-pin-fin array
g	Vapor
i	Stream-wise segment
ibd0	Upstream boundary of segment i
idb1	Downstream boundary of segment i
in	Inlet
out	Outlet
p_1	Deep plenum
p_2	Shallow plenum
pred	Predicted
sp	Single-phase
tp	Two-phase
ts	Test section
vg	Vapor generator
wall	Side wall

proposed. The C factor in the correlation was linearly proportional to liquid Reynolds number. Konishi et al. [9] investigated frictional pressure drop of adiabatic water liquid–vapor two-phase flow across a staggered square micro-pin-fin array. The Martinelli–Chisholm type correlation with a C factor of 5 produced the best agreement among the existing models and correlations.

Mita and Qu [1] recently studied frictional pressure drop of adiabatic water liquid–vapor two-phase flow across a staggered circular micro-pin-fin array with D of 180 μm, H/D of 3.8, and S_L/D and S_T/D of 2.2. Experimental results revealed that a unique functional relationship existed between the two-phase friction multiplier ϕ_f and Martinelli parameter X, indicating that the classic Lockhart–Martinelli generalized procedure, originally developed for calculating two-phase frictional pressure gradient along pipes [10], could be applied to the circular micro-pin-fin array. The following modified Martinelli–Chisholm type correlation was developed to depict the ϕ_f-X relationship:

$$\phi_f^2 = 1 + \frac{2.1675}{X^{0.76}} + \frac{1}{X^2}. \tag{1}$$

The present study expends on the work in ref. [1] by experimentally investigating two-phase frictional pressure drop across a staggered array of micro-pin-fins having a square cross-sectional shape. The goal is to assess whether the correlation, Eq. (1), is only accurate to the circular array for which it was originally developed, thus geometry specific, or whether the correlation can be extended to describe the present square array. Should latter be the case, Eq. (1) may have the potential to become a generalized correlation applicable to a broad range of staggered micro-pin-fin array configurations.

2. Experimental apparatus and procedure

2.1. Test module

Fig. 1(a) shows a schematic of the test module composed of a copper micro-pin-fin test section, a G-7 fiberglass plastic housing, and a polycarbonate plastic (Lexan) cover plate. The test section had a projected top platform area of 3.38 cm (longitudinal) by 1 cm (transverse). An array of staggered square micro-pin-fins were micro-end milled out of the top surface. The array contained 85 pin-fin rows in the longitudinal (stream-wise) direction. There were 24 pin-fins in every odd transverse row, and 23 pin-fins in every even transverse row. The square pin-fins were 200 μm in side length S, 670 μm in height H, and 400 μm in both longitudinal pitch S_L and transverse pitch S_T. The resulting H/S was 3.35, and S_L/S and S_T/S 2. Fig. 1(b) shows a top view and key dimensions of the array.