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Boiling heat transfer characteristics in a microchannel array heat sink with low mass flow rate

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HIGHLIGHTS

► Correlations were developed to predict boiling heat transfer coefficients.
► Nucleate boiling, thin-liquid-film evaporation, and single-phase convection controlled heat transfer in bubbly/slug flow.
► The annular flow was dominated by convective evaporation heat transfer.
► The heat transfer coefficients decreased due to partial dry-out of the wall.

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ABSTRACT

Flow boiling of R134a in a microchannel array heat sink was experimentally studied for mass fluxes ranging from 10 to 35 kg/m^{2}s. The microchannels are 0.5 mm wide and 0.15 mm deep. The cuboid fins are 1.5 mm wide, 0.15 mm deep, and 3.5 mm long. In a bubbly/slug flow, heat transfer was controlled by convective boiling and evaporation. Heat transfer coefficients significantly increased with heat flux. A high degree of subcooling at the inlet increased the heat transfer rates. In semi-annular and annular flows, the heat transfer coefficients were independent of heat flux. The values moderately increased with mass flux, declined with the increase in vapor quality, and approached a constant value at high vapor qualities. This trend was attributed to partial dry-out of the wall. The annular flow was then dominated by convective evaporation heat transfer. Two correlations were developed to predict the heat transfer coefficients, corresponding to the convective boiling and evaporation region as well as the convective evaporation region.

1. Introduction

A microchannel heat sink is known for its ability to produce a high heat transfer coefficient, small overall heat sink mass and size, and small liquid coolant storage and flow rate. Flow boiling heat transfer in microchannels has been studied extensively in the past decade, with the aim of attaining an effective heat sink design [1–9]. Results from these studies indicated that the microscale channel size had a profound effect on the liquid flow boiling behavior; however, the heat transfer correlations developed for conventional size channels were unable to predict microchannel flow boiling data.

Recent advancements in micro-fabrication techniques and synthetic materials have enabled the exploration of other enhancement structures that may be more effective than parallel microchannels. Researchers showed that staggered or aligned microsize pin-fins provided a promising configuration for weakening fluctuations in pressure and wall temperature in the parallel channels [10]. Performance assessments of micro-pin-fin arrays as alternative enhancement structures for two-phase microscale heat sinks have been conducted through experiments to attain a fundamental understanding and accurate prediction of flow boiling heat transfer in the configuration [11–16].

Boiling is defined as the process of phase changing from liquid to gas by heating it past its boiling point. In flow boiling, the fluid has a velocity relative to the heating surface. Heat transfer mechanism in flow boiling is associated with the complicacy of interfacial evolution and phase change. In macro-scale flow boiling, several different boiling heat transfer mechanisms are nucleate boiling, where heat is transferred by means of vapor bubbles nucleating, growing and finally detaching from the surface; convective evaporation, where heat is conducted through the liquid and this one evaporates at the liquid–vapor interface; and film boiling, where the heat is transferred by conduction and radiation through a film

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Nomenclature

A_0	inlet and outlet plenum area (m^2)
A_c	microchannel area (m^2)
Bl	boiling number
c_p	specific heat [J/(kg°C)]
D_{ch}	hydraulic diameter (m)
G	mass flux [kg/(m^2 s)]
H_c	microchannel depth (m)
h_{lv}	latent heat (J/kg)
h, h_{tp}	flow boiling heat transfer coefficient [W/(m^2 K)]
Ja	Jakob number
k	thermal conductivity of liquid [W/(m K)]
L	microchannel length (m)
m	mass velocity (kg/s)
n	number of microchannels in the test section
Nu	Nusselt number
p	pressure (Pa)
Pr	Prandtl number
q	heat flux (W/cm^2)
Q	heat dissipation (W)
Re	Reynolds number
T	temperature (°C)
v	specific volume (m^3/kg)
W	width of heat sink (m)
We	Weber number
W_c	microchannel width (m)
x	vapor quality
X_{vv}	Martinelli parameter

Greek symbols

α	microchannel aspect ratio (H_c/W_c)
η	fin efficiency
μ	viscosity [kg/(ms)]
λ	thermal conductivity [W/(m K)]
ρ	density (kg/m^3)
δ	thickness of the microchannel base (m)
φ_l	two-phase frictional multiplier

Subscripts

f	fluid
l	liquid
ref	refrigeration
sat	saturation
sub	subcooling
sp	single phase
tp	two phase
v	vapor
w	wall

of vapor that covers the heated surface and the liquid vaporizes at the vapor–liquid interface. In addition, if the temperature of the liquid is below the saturation temperature, the process is called subcooled boiling. Where the main heat transfer mechanisms are liquid convection, nucleate boiling and convective evaporation [17]. In microchannel flow boiling, flow pattern map is different from that in macroscale due to confinement of channel dimensions, and heat transfer characteristics are diverse. Previous experiments on boiling heat transfer trends in microchannels and micro-pin-fin heat sinks are listed in Table 1. These studies clearly pointed to a departure in microscale boiling behavior from that of macroscale. For example, several studies demonstrated a decreasing heat transfer coefficient with increasing vapor quality in the saturated flow boiling region, a result contradictory to macrochannel trends. In boiling heat transfer studies of microchannels, heat transfer coefficients have been shown to be closely related to flow patterns. Nucleate boiling and thin-liquid-film evaporation corresponding to the bubbly/slug flow dominated the heat transfer in parallel microchannels [3,8]. Other experiments [1,4] indicated that nucleate boiling and convective boiling were the main heat transfer mechanisms in parallel microchannels. However, studies on micro-pin-fin heat sinks showed that convective boiling dominated the heat transfer regime [10–16]. The unique heat transfer characteristics were attributed to the complex liquid–vapor two-phase transport as a result of the interruptive nature of the flow passages in the micro-pin-fin array. In particular, the liquid droplets entrained in the vapor flow were believed to play an important role [11]. Conversely, the flow instability in the parallel channels was caused by the feedback interaction between parallel microchannels through the common inlet and outlet manifolds, and was intrinsic to the microchannel configuration itself [8]. Experiments on micro-pin-fin heat sinks were shown to provide better flow stability than did their microchannel counterparts because the interconnecting nature of the flow passages in micro-pin-fin arrays promoted a stabler two-phase flow [10].

Studies on microscale flow boiling suggest that heat transfer and fluid flow at a diminishing length scale have some unique characteristics. For example, the heat transfer coefficient is dependent on heat flux, mass flux, and quality; heat flux increases at the onset of nucleate boiling [1,12,13,18,19]. Employing large-scale knowledge and correlation to predict corresponding physical phenomena, such as the heat transfer coefficient, pressure drop, and flow patterns for microchannel flow, is imprudent. A parametric study of the effects of surface tension and flow configurations on cross flow boiling at microscale has yet to be undertaken [12]. In addition, boiling flow and heat transfer are influenced by microchannel configurations. At a low Reynolds number, the liquid-bridge force induced by surface tension is significant in microchannels with complex structures. This visibly influences two-phase transport and flow patterns. The mechanism of the heat transfer and flow regime in microchannels has not been completely understood.

In the current paper, the flow boiling of R134a in a microchannel array heat sink was investigated. The objectives of this study are to: (1) provide heat transfer data for R134a flow boiling in a microchannel array heat sink at low mass flow rates; (2) develop new heat transfer correlations for R134a flow boiling in a microchannel array heat sink; and (3) analyze two-phase cross flow and explore possible heat transfer mechanisms.

2. Experimental setup and procedure

2.1. Experimental system

Fig. 1 shows the test system for microchannel array flow boiling. R134a, supplied by a tank with a steady temperature, flows successively through a valve, a filter, a subcooler, a needle valve (to control the flow rate), and the test section (microchannel heat sink), where R134a exchanges heat with deionized water. The mass flow controller is used for flow rate measurement and controlling. Control valves situated downstream of the test section are used to control the exit pressure. Flowing through the test section, R134a can be condensed and collected in a storage tank. A high-speed camera is used to record the flow boiling patterns in the