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Flow condensation heat transfer enhancement in a mini-channel with hydrophobic and hydrophilic patterns

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ABSTRACT

The study examined the enhancement of flow condensation of steam on hydrophobic and hydrophilic surfaces. Six 1.06 mm mini-gaps were tested at pressures of 350–400 kPa, average qualities of 0.2–0.95 and mass fluxes of 50–200 kg/m^{2}s. The surfaces included hydrophilic copper, hydrophobic Teflon AF™, and four surfaces with combined Teflon and hydrophilic patterns; pattern selection was guided by an analytical model. Condensing heat transfer coefficients on hydrophobic and hydrophobic/hydrophilic patterned surfaces reached a value of up to 425,000 W/m^{2}K, surpassing the hydrophilic surface by an order of magnitude. Enhancement factors of 3.2–13.4 times that of the hydrophilic channel were found in the hydrophobic channel; combined with a lack of dependence on mass flux or quality, the data strongly suggested that dropwise condensation was promoted and sustained throughout the flow condensation process on hydrophobic and patterned surfaces. For the hydrophilic copper mini-gap, heat transfer coefficients were a strong function of quality, as well as a function of mass flux at higher qualities, which demonstrated the development and growth of a liquid film as quality decreased, and were well predicted by Kim et al. (2013) correlation, with a mean average error of 8.9%.

1. Introduction

Condensers are found in numerous industrial applications, such as power plants and water desalination systems, and more compact and effective condensers would reduce the systems' size and weight while increasing power. In order to create improved condensers, fundamental advancements in condensation are needed. Macro-scale condensation has been well documented after over fifty years of study [1,2]. More recently, smaller diameter channels have been shown to offer higher heat transfer coefficients than macro channels, yet mini- and micro-scale condensation has only been explored for the last ten to fifteen years [3,4]. Despite larger heat transfer coefficients achieved by researchers at the mini- and micro-scales, few enhancements other than channel shape have been found at the mini- and micro-scale. Dropwise condensation, on external surfaces and in vapor space, offered an order of magnitude enhancement in heat transfer coefficients [5–13] but has seldom been applied to internal flows. However, promotion of dropwise condensation in internal condensation would reduce condenser size.

Condensation in mini- and micro-channels has garnered great interest over the last decade with an emphasis on refrigerants used for electronics cooling and miniaturized vapor compression cycles. Hydraulic diameter, mass flux, quality, and flow regime have been identified as the governing parameters of filmwise condensation. Heat transfer coefficients have been generally found to increase as diameter decreases at the mini- and micro-scales [14–16]. Condensation heat transfer coefficients increased with increasing mass flux and quality [3,4,17–20], with a few exceptions found at lower mass fluxes [14,21]. Flow regimes affected condensation behavior; the absence of stratified flow, and the presence of annular flow at the mini- and micro-scales suggested that gravity does not play a significant role in small scale condensation [17,20,22–25].

Although mini- and micro-scale condensation heat transfer coefficients are higher than those found at the macro-scale, efforts to further enhance condensation heat transfer have focused on channel shape. In non-circular channels, condensate gathers in corners due to surface tension, thinning the liquid film in areas away from corners and enhancing the heat transfer coefficient. However, depending on channel length and other variables, length-averaged heat transfer coefficients in a circular tube may be higher or lower than a rectangular channel [14,26]. It was expected that shapes with sharp corners would yield heat transfer enhancements [27], yet this has not been observed in all studies [28,29].

Surface modification, though rarely applied to internal flows, has dramatically enhanced external condensation. Fang et al. [16,30] studied micro-scale steam condensation in silicon channels coated with self-assembled monolayers, thus creating hydrophobic,

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Nomenclature

A	area (m^2)
d	gap depth, (m)
D	diameter, (m)
G	mass flux, (kg/m^2 s)
h	heat transfer coefficient, (W/m^2 K)
k	thermal conductivity (W/m K)
L	length, (m)
$\dot{m}$	mass flow rate, (kg/s)
MAE	mean average error
n	number of samples
N	number of hydrophilic areas in patterned surfaces
q''	heat flux, (W/m^2)
$\dot{Q}$	heat transfer rate, (W)
t	time, (s)
T	temperature, (°C)
w	uncertainty
W	width, (m)
x	quality
X	Lockhart Martinelli parameter
y	transverse coordinate, (m)
α	void fraction
β	contact angle
μ	viscosity, (kg/ms)
ρ	density, (kg/m^3)

Subscripts

1, 2, 3	corresponding to first, second, third measuring segment
ch	channel
DWC	dropwise condensation
exp	experimental
f	fluid
FWC	filmwise condensation
g	gradient
i	index
l	liquid
LM	Lockhart Martinelli
$pred$	predicted
seg	segment
tot	total
v	vapor
vv	viscous liquid and vapor
vt	viscous liquid and turbulent vapor
w	wall

hydrophilic, and semi-hydrophobic surfaces. A film wetted the hydrophilic channel walls, while dropwise condensation at the inlet of the hydrophobic channel yielded a slightly (15%) higher heat flux compared to the hydrophilic tube. In contrast, significant enhancement has been found by promoting dropwise condensation of steam on external tubes and plates, which offered heat flux enhancements of 5–20 times that of filmwise condensation under the same conditions [5–13]. Surface modifications promote dropwise condensation by altering contact angles or lowering surface energies, using methods such as coating with polymers [31,32] and self-assembled monolayers [33,34], altering surface roughness [8,11,35], electroplating [36], and ion implantation [10].

There was an apparent tradeoff in two studies which examined the coexistence of dropwise and filmwise condensation on external surfaces; in one study [37], performance was superior when dropwise condensation existed on top of the tube and filmwise on the bottom, as the disruption of the liquid film by falling droplets enhanced heat transfer. In another study [38], the best configuration was when filmwise condensation was on the upper part of the flat plate and dropwise condensation was on the lower part, since film rivulets would clean the dropwise condensation surface. Since the majority of heat transfer occurs through the smallest drops in dropwise condensation [39], droplet sweeping reduces droplet size, thus increasing heat transfer [40–42].

As there have been few studies on internal flow condensation enhancement other than channel shape, the objective of this study is to understand the effects of surface modifications on condensation in a mini-gap. Surface modifications promote dropwise condensation, and the condensation enhancement of hydrophobic surfaces is examined.

2. Experimental method and apparatus

In order to achieve dropwise condensation in an internal flow, patterned hydrophobic/hydrophilic surfaces were fabricated in a 1.06-mm mini-gap. Six patterns were selected to test on the basis of analytical modeling. Condensation heat transfer coefficients were measured and tested in an open loop steam experimental apparatus.

2.1. Analytical modeling for pattern selection

An analytic model guided the selection of hydrophobic/hydrophilic patterns. The geometry was a mini-gap with specified height, d, and cooled length, L_{tot}; the channel was cooled on one side and assumed to be adiabatic on the remaining three (Fig. 1). The cooled length contained both hydrophilic and hydrophobic strips. At a specified quality, it was assumed that all liquid gathered on hydrophilic segments with a specified contact angle β, determined from experiments. The liquid droplet was modeled using a parabola, and the integral of all liquid droplets yielded the total liquid area. Also, the number of hydrophilic strips was specified by the user, and the remaining area was hydrophobic.

The length of the channel occupied by liquid, and thus filmwise condensation, L_{FWC}, was

$$L_{FWC} = NL_{droplet} \tag{1}$$

for droplets on N hydrophilic areas of length $L_{droplet}$, while the length occupied by dropwise condensation L_{DWC} was the difference between the total length and filmwise condensation length.

The area occupied by liquid was then related to the void fraction according to:

$$1 - \alpha = \frac{A_L}{dL_{tot}} \tag{2}$$

Butterworth [43] determined a simple curve fit based on the work of Lockhart and Martinelli [2] to relate void fraction to quality via the Martinelli parameter X,

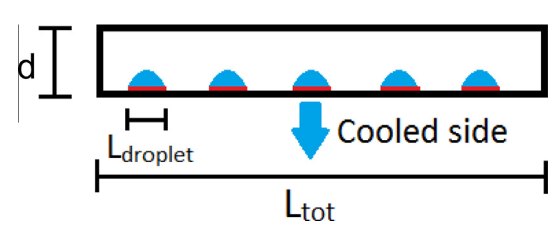

Fig. 1. Basic minigap geometry.