



Contents lists available at ScienceDirect

## International Journal of Heat and Mass Transfer

journal homepage: [www.elsevier.com/locate/ijhmt](http://www.elsevier.com/locate/ijhmt)Flow boiling of dilute emulsions<sup>\*</sup>D. Janssen, F.A. Kulacki<sup>\*</sup>

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## ARTICLE INFO

## Article history:

Received 25 May 2017

Received in revised form 19 July 2017

Accepted 20 July 2017

## Keywords:

Flow boiling

Emulsions

Multi-component flow

Two-phase flow

Heat transfer coefficient

## ABSTRACT

Measurements of heat transfer coefficients are presented for flow boiling of a dilute emulsion in meso-scale channel flow. The emulsions comprises droplets of FC-72 and pentane in water at a droplet concentration of one percent or less by volume. Droplet size is on the order of 5–10  $\mu\text{m}$ . The experimental apparatus comprises a bottom heated flat channel with a gap height of 0.25 mm and constant wall heat flux of 10–50  $\text{W}/\text{cm}^2$ . Mass flux is held constant at  $\sim 100 \text{ kg}/\text{m}^2 \text{ s}$ . Heat transfer coefficients are enhanced on the order of 20–60% when the wall temperature exceeds the saturation temperature of the dilute component but is less than the saturation temperature of the carrier fluid. This increase is attributed to agitation due to the liquid-vapor transition of the suspended component. As the wall temperature approaches the saturation temperature of the carrier fluid, boiling of it commences, and heat transfer coefficients increase dramatically as in single-component flow boiling. Thus, the emulsion exhibits more desirable heat transfer characteristics across the spectrum from single-phase through two-phase flow. At very low heat flux, there is little to no differentiation of heat transfer coefficients of carrier fluid alone and that of the emulsion because the droplets require a degree of superheat before evaporating. The present results provide a useful experiential framework for categorizing flow boiling conditions associated with dilute emulsions and complement existing data on pool boiling.

Published by Elsevier Ltd.

## 1. Introduction

Heat transfer mechanisms in the boiling of dilute emulsions of two components has been a long standing problem in two-phase heat transfer but has received modest attention over the past 35 years. Recent research [14,15] however has identified some surprising and potentially useful characteristics of this mechanism. We consider flow boiling of emulsions comprising two immiscible liquids in which the dispersed component is suspended in a carrier fluid in the form of droplets which have the lower boiling point.

In pool boiling a large degree of superheat is necessary before bubble nucleation can begin. This produces a thermal delay for initiation of boiling of the suspended component because most of the droplets never contact the heated surface. Bubble nucleation must therefore occur separately in each droplet in the emulsion. In the case of flow boiling, however, the nucleation rate is not necessarily limited by a significant thermal delay since droplets are more easily perturbed and are more likely to make direct contact with

the heated surface. This difference makes flow boiling a preferable candidate for phase change cooling methods.

The pioneering work of Mori et al. [1] initiated research on the topic, and Roesle and Kulacki [2,3] have reviewed the early experiments and have provided a theoretical framework for the a description of the boiling process. Early advances in measuring heat transfer coefficients in emulsions have been made by Gasanov, Bulanov and co-workers [4–12]. More recent research [13–17] corroborates early findings and extends them somewhat with respect to the composition of the emulsion. Most of these studies deal with pool boiling on either a heated wire or flat surface in free convection and provide a context and background for the present investigation. The consensus outcome of these experiments is that pool boiling is initiated on nucleation sites on the heat transfer surface and that increased heat transfer coefficients are a result of mixing produced by vapor bubbles in the thermal boundary, and not actually due to the phase change energy which is comparatively small. Visualization of the boiling process [13,15,17] substantiates this conclusion.

An early flow boiling experiment [18] examined boiling heat transfer and flow characteristics of a mixture of FC-72<sup>1</sup> in water

<sup>\*</sup> This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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<sup>1</sup> FC-72<sup>™</sup> is a fluorine electronic liquid manufacture by 3M<sup>™</sup> Inc., St. Paul, Minnesota. It has a boiling point of 56 °C at 1 atm.

**Nomenclature**

A	area (m <sup>2</sup> )
C	specific heat (J/kg K)
h	heat transfer coefficient (W/m <sup>2</sup> K)
k	thermal conductivity (W/mk)
$\dot{m}$	mass flow rate (kg/s)
$Nu$	Nusselt number ( $hD_h/k_f$ )
q	power input (W)
q''	heat flux (W/cm <sup>2</sup> )
t	time (s)
T	temperature (°C, K)
y	distance from wall (m)

**Subscripts**

Cu	copper
e	determined by energy balance
f	fluid
b	base water case
i	inlet
o	outlet
TC	at thermocouple
w	wall

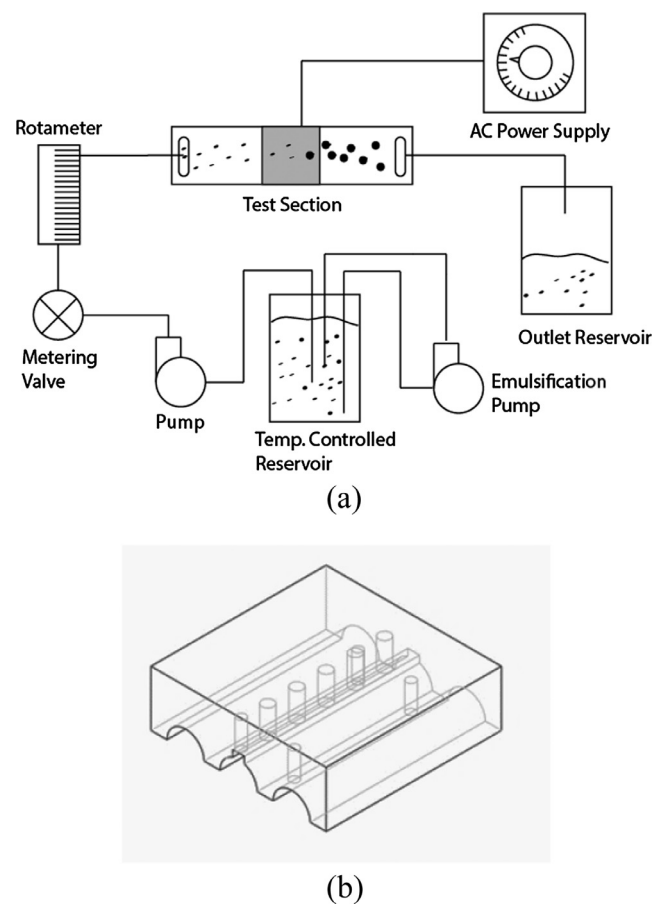
in a 0.1 mm gap microchannel. The channel was 30 mm wide and the heated zone was 30 mm in length on one wall of the channel. Wall heat fluxes from 1 to 22 W/cm<sup>2</sup> were applied to initiate boiling of the FC-72. Mass fractions of FC-72 were significantly higher than in the present investigation, and the total mass flux ranged from 88 to 390 kg/m<sup>2</sup> s, spanning the range of those in the present investigation. The FC-72 was injected into a plenum at the inlet of the channel. The inlet flow was laminar, and inlet subcooling for FC-72 ranged from 24 to 32 °C. Owing to the low flow rate, surface tension forces dominated inertia, which kept the components well separated and prohibited the breakup of the FC-72. The presence of FC-72 decreased heat transfer coefficients as the mass fraction of FC-72 was increased, and the authors speculated that the decrease was due to flow stratification and that increasing FC-72 mass fraction adversely affected the thermophysical properties of the mixture. It was unknown whether pre-mixing of the FC-72 and water streams would have yielded a performance increase or decrease. The present work, however examines the premixing condition, albeit with much smaller FC-72 flow rates.

Gasanov and Bulanov [13] have recently reported experiments in which heat transfer coefficients were measured in flow boiling in tube flow. Their apparatus comprised a 16 mm DIA stainless steel heated tube. The emulsions were water droplets suspended in VO-1C oil, and the water:oil ratio ranged from 0.1% to 1.5%. The inlet bulk temperature was 60 °C, and the mass flux was  $\sim 12.4$  kg/m<sup>2</sup> s ( $2.5 \times 10^{-6}$  m<sup>3</sup>/s). Average heat transfer coefficients were reported for water droplets denoted as “fine” and “coarse”, but no quantitative measure of droplet size was given in their paper. Increases of the heat transfer coefficient of approximately 60% above single phase values were seen for both droplet sizes at a wall temperature of  $\sim 150$  °C, and there was some measurable difference in heat transfer coefficients based on the coarse and fine designations of droplet size. As in pool boiling, a thermal delay of  $\sim 50$  °C in the initiation of nucleate boiling was observed. In the present data, there is no measurable delay in boiling onset. It is theorized that the differences in heating arrangement and flow geometry compromise the stability of superheating droplets, leading to more immediate evaporation.

This paper reports results of an experimental investigation of flow boiling of such emulsions in single wall-heated flat channel flow at low inlet Reynolds numbers of  $\sim 90$ – $180$ . The dispersed components are FC-72 and pentane, which have lower saturation temperatures (76 and 36 °C) than the carrier fluid (water). Inlet flows are sub-cooled with respect to dispersed component. The emulsions are very dilute in all cases, but a range of droplet concentrations is considered. Owing to inlet flow sub-cooling, boiling is initiated downstream of the heated portion of the channel.

**2. Apparatus and procedure**

Experiments are run under steady, fully developed flow in a micro-gap of 0.25 mm. The test section has a 70 mm  $\times$  30 mm  $\times$  0.25 mm entrance channel, a 30 mm  $\times$  30 mm heated section with  $L/D_h = 60$ , and a 70 mm  $\times$  30 mm  $\times$  0.25 mm exit channel. Fig. 1 shows a schematic of the apparatus, the fluid handling system, and a cross section of the copper heating block. The flow channel is built with a G-11 Garolite base that exhibits a high service temperature (165 °C) and is thermally insulating



**Fig. 1.** (a) Apparatus and emulsification system. (b) Detail of copper heating block. The heating block contains three 150 W resistance heaters with wells for thermocouples along the centerline.

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