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Flow Boiling Heat Transfer in Narrow Vertical Channels

FLOW BOILING HEAT TRANSFER IN NARROW VERTICAL CHANNELS

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von

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Chapter 1

Introduction

1.1 Background

Phase change heat transfer finds its applications in almost all engineering disciplines. Boiling is one of the most important phase change processes as it is generally associated with high heat transfer rates.

In 1981, Tuckerman and Pease [1] first introduced the concept of microchannel heat sinks. Thereafter, further advances in flow boiling have been continuously driven by new technological demands, viz., the accommodation of high heat dissipation in confined spaces.

“NARROW” means limited in size. The term “NARROW CHANNEL” is introduced to distinguish such channels from normal-sized channels. In traditional heat exchangers and boilers, the employed channels or tubes usually have hydraulic diameters over one centimeter.

Compact evaporators become widely used in automotive, aerospace, air separation and cryogenic industries. The characteristic length of the evaporation surfaces can be in the millimeter or sub-millimeter range.

The rapid development of the microelectronics industry created entirely new paradigms [2]. The thermal management has been an important concern for the electronics industry for several decades; it is becoming more critical for developing small-sized modern microprocessors. By using two-phase microchannel heat sinks, millimeter-scale hotspots on microprocessors can be handled. Moreover the evolution of ink-jet printing technology showed that boiling is a viable technique for extremely small passages. Controlled growth and collapse of bubbles is used effectively in ink-jet printers, optical multiplexers and switching devices.

For conventional-sized channels, fluid flow and heat transfer have been intensively investigated since the beginning of the twentieth century. For single-phase flow, both the classical theories and widely-accepted empirical correlations have been developed. For flow boiling, some empirical correlations and semi-theoretical models to approach the pressure drop and heat transfer coefficient have also been introduced continuously since the late 40s.

However, the correlations and theories are generally valid only under certain operating and geometric conditions. The reduction of channel size firstly encounters a critical issue: whether or not the theories and correlations that were developed for conventional-sized channels and tubes can be used for narrow channels. Additionally, the decrease in channel size is accompanied by numerous problems during the design and manufacture of heat exchangers, e.g., fouling, flow instabilities, boiling crisis, fabrication, etc..

The irreplaceable advantages in numerous applications of small-sized channels have attracted intensive investigations especially since the late 90s, for both single-phase flow and two-phase flow. However, owing to the difficulties related to the measurement in small-sized channels, the respective flow and heat transfer questions have not yet been answered satisfactorily.

1.2 Classification of Narrow Channels

There are various classifications of channels according to the hydraulic diameter and geometry. For small-diameter channels, the hydraulic diameter was chosen as the criterion to distinguish different channels by Kandlikar [2], as given in Table 1.1.

Table 1.1 Channel classification

Normal-sized channels	$D_h > 3\ \text{mm}$
Minichannels	$3\ \text{mm} \geq D_h > 200\ \mu\text{m}$
Microchannels	$200\ \mu\text{m} \geq D_h > 10\ \mu\text{m}$
Transitional channels	$10\ \mu\text{m} \geq D_h > 0.1\ \mu\text{m}$
Molecular or nanochannels	$D_h \leq 0.1\ \mu\text{m}$

Based on the Bond number Bo*, which relates the characteristic bubble departure size to the channel hydraulic diameter, Kew and Cornwell [3] proposed a Confinement number Co* as another criterion.

$$Co^* = Bo^{*\,-0.5} = D_h^{-1}\left[\frac{\sigma}{g(\rho_L - \rho_G)}\right]^{0.5} > 0.5 \qquad (1.1)$$

For $Co^* > 0.5$, the channel is considered as a narrow channel. According to Eq.(1.1), for water at atmospheric pressure, the definition of narrow channel corresponds to a hydraulic diameter of around 5 mm.

Some experimental results on both single–phase flow and two-phase flow show certain abnormal flow and heat transfer characteristics for channels having hydraulic diameters below 3 mm. Therefore, 3 mm is generally considered as the boundary between conventional-sized and narrow channels. But an exact physical explanation is still not available.

1.3 Size Effect

All description of physical phenomena inside channels is associated with the length-scale. The decrease in channel size influences both flow and heat transfer characteristics. Experience with conventional-sized channels shows a heat transfer augmentation and a rise in pressure drop accompanied with the reduction of the channel diameter. Furthermore, in narrow channels some novel effects can result in a deviation from the conventional theories.

Capillary action is expected to play an important role. Some investigators believed that capillary action should be considered when the hydraulic diameter of the channel is less than 3 mm, e.g., [4]. The electromagnetic force, whose effect is very weak in normal-sized channels, may have to be taken into account in narrow channels.

The relative importance of friction and inertia is reversed in the micro scale. In the macro scale, friction is important but not dominant. In the micro scale, friction is possibly dominant, correspondingly, viscous dissipation effects for liquid flow in the micro scale can not be neglected due to the relatively high velocity gradients.

One of the most apparent features in small-sized channels is the high surface to volume ratio. The surface related characteristics, such as surface roughness and surface geometry, play a more important role with decreasing channel size.

Finally, the so-called rarefaction effect can play a significant role when the channel dimension approaches the mean free path of the molecules in a gaseous flow. In this case, the continuum assumption breaks down. Then the classical Navier-Stokes equations and the Fourier heat conduction law become invalid. Thus the flow and heat transfer behaviors change considerably. The departure from continuum becomes especially pronounced for low pressure gas flows.

The above-mentioned characteristics indicate that the flow and heat transfer phenomena in narrow channels can be greatly different from those in normal-sized channels. The quantitative description of these effects is still an open problem.

1.4 Investigation Objectives

Saturated boiling heat transfer is the key concern of this study. Both boiling and single-phase flow in narrow vertical channels with hydraulic diameters less than 3 mm are investigated. Major objectives are:

- Heat transfer and pressure drop during saturated boiling; development of correlations; comparison with existing results and correlations in the literature;
- Observation of flow patterns and flow pattern transitions; generalization of flow pattern maps; comparison with existing results and maps in the literature;
- For comparison, experiments with single-phase flow are also carried out.

Chapter 2

Experimental System and Error Analysis

2.1 Experimental Set-up

A test rig was constructed to investigate flow boiling in an electrically heated vertical narrow channel. It was designed for operating conditions of maximum 3 bar and 400 K.

A schematic and a photo of the whole experimental set-up are shown in Figs.2.1 and 2.2., respectively. The system consists of 5 main parts: (1) a fluid tank with heating and cooling system; (2) a magnetic gear pump; (3) a preheater; (4) a test section in vertical orientation, and (5) a condenser. The working fluid is circulated from the fluid tank through the flow meter to the preheater, where it is heated to a set temperature. In the test section, the working fluid flows upwards and it is further heated and partly evaporated. Then the vapor-liquid mixture from the test section is condensed in the condenser and flows back to the fluid tank. Between the pump and the preheater there are three flow meters with different measurement ranges to obtain a good measurement accuracy. In addition, a Hewlett Packard high-speed video-camera was employed to observe and record the flow phenomena in the test specimen. A PC–coupled data acquisition system was used to collect and record all measured real time parameters.

There are two main components in the test section (Fig.2.3): heat source and test specimen. The heat source consists of 4 copper heating blocks with two embedded thermal resistance heaters each. The heaters are controlled by a digital electrical power supply. The test specimen (Fig.2.4) is made of copper. It is heated from the back side by the four heating blocks. On the front side of the test specimen, a rectangular channel is machined. Three channel geometries have been employed, as shown in Table 2.1. The channel is covered with a plexiglass plate for visualization. Between the plexiglass plate and the test specimen there is a PTFE layer which ensures that no fluid is leaking out from the channel. Because PTFE can not withstand temperatures over 405 K, the maximum wall temperature has been limited to 400 K.

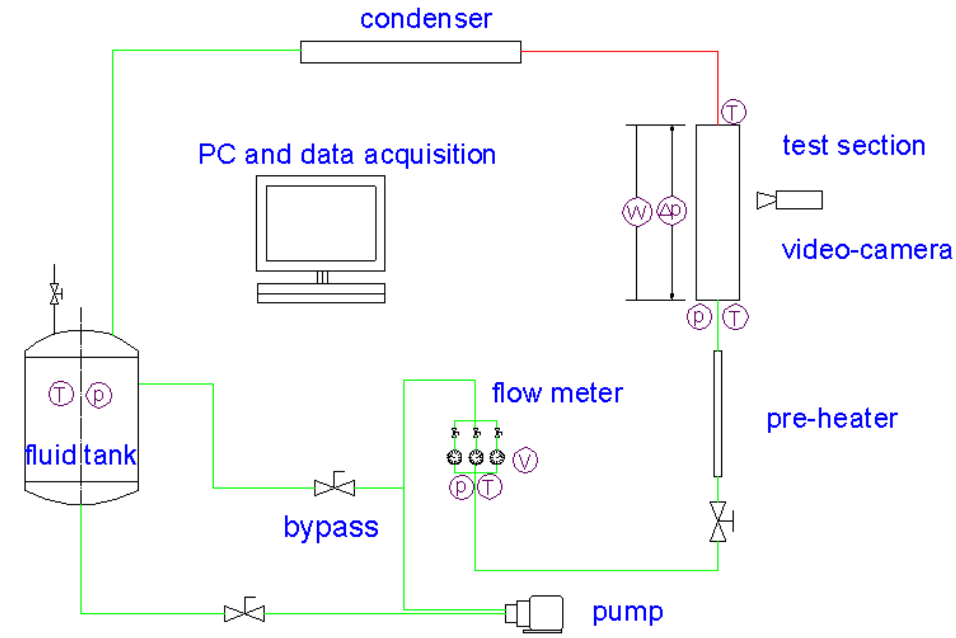

Figure 2.1 Schematic of experimental set-up
((p) (Δp) (T) (V) (W) : pressure, pressure drop, temperature, flow rate and input power measurement)

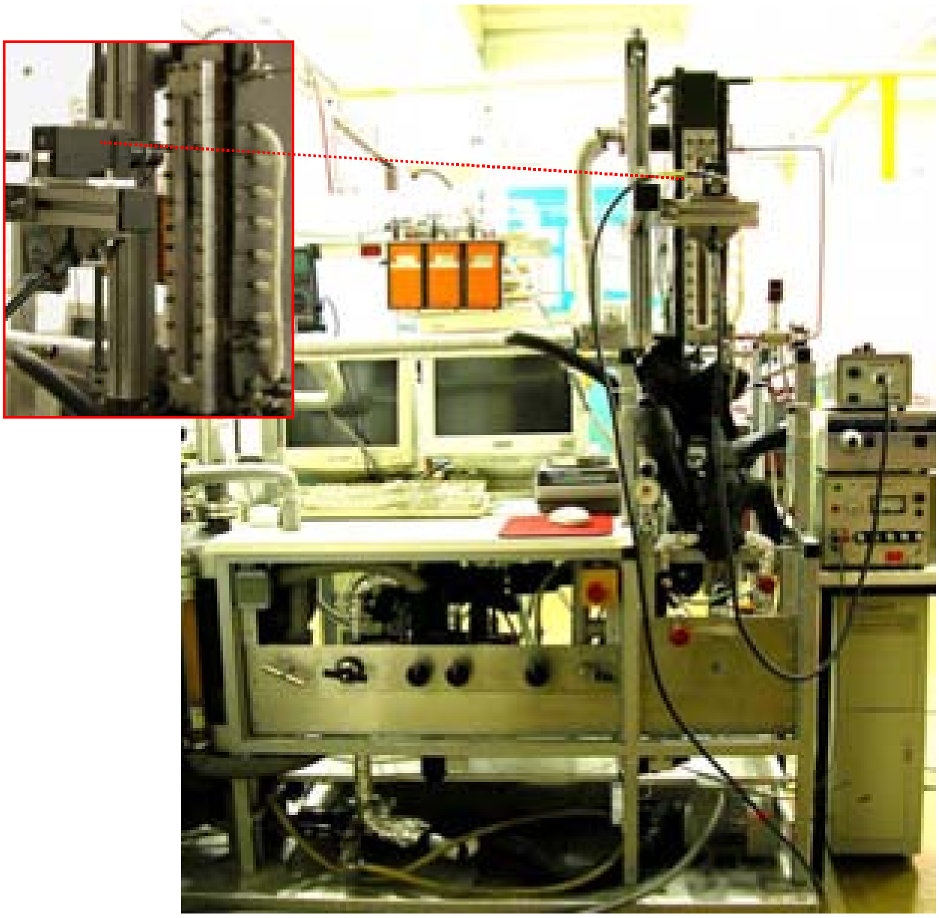

Figure 2.2 Photo of experimental set-up and enlarged view of test section with video-camera.