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Bubble behavior of flow boiling in horizontal rectangular channels with inclined ribs

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ABSTRACT

Visualization experiments were conducted to study flow boiling bubble behavior in ribbed rectangular channels at atmospheric pressure. A transparent conductive oxide film was placed on the inner surface of the channel to act as the heating source. Four rib configurations with different inclinations were examined, and the results are compared to those in a smooth channel. Heat and mass fluxes of 13.3–28.9 kW/m^2 and 152–333 kg/(m^2s) were considered, and the bubble behavior was captured using a high-speed digital camera system. Vapor bubble diameters and velocities were obtained from an analysis of the images, and we found that the bubble diameter decreases with increasing mass flux, which is also associated with an increase in the bubble sliding velocity and an inhibition of sliding bubble coalescence. For the rectangular channel, a rib angle of 45° provides the largest transverse component of the bubble sliding velocity as a result of the axial drag force and guiding force of the ribs. We conclude that a 45°-angle rib offers the best characteristics for flow boiling heat transfer.

1. Introduction

Flow boiling heat transfer is employed for nuclear safety, rocket engine cooling, quenching of metals, and the flow of cryogenic liquids in heated pipes. Thorncroft et al. [1] have indicated that bulk turbulent convection and the growth and detachment of vapor bubbles at the heating surface are the two most important reasons for high heat transfer rates of flow boiling. To clarify the heat transfer mechanism of flow boiling, the bubble dynamics in the near wall region need to be studied.

Understanding the bubble behavior during subcooled flow boiling is an important step in describing the bubble dynamics and boiling heat transfer. Several researchers have focused on studying bubble departure, and several correlations were developed for predicting the bubble departure and lift-off diameter [2–6]. Empirical correlations serve a useful purpose when applied to engineered systems, but the narrow application range means that correlations can rarely be extended to new situations [7]. Moreover, the correlations cannot be directly used for investigating the whole flow boiling heat transfer because they do not consider the effects of the bubble sliding processes.

Experimental studies of the bubble growth and bubble sliding process have also been undertaken [8–11], and the results suggest that sliding bubbles play an important role in flow boiling heat transfer. The results of a visual study undertaken by Thorncroft et al. [1] indicated that there is bubble growth even during the bubble sliding process, which means that there must be microlayer evaporation and transient conduction as the bubbles slide. Yuan et al. [12] examined the effects of system pressure on the vapor bubble behavior in high subcooled flow boiling, and the visualized experimental results showed that the sliding bubble growth rate has a significant effect on the sliding velocity and distance. Xu et al. [13] also indicated that the sliding bubbles play an important role in enhancing the heat transfer in flow boiling, and so the mechanism of bubble sliding requires further investigation. However, the characteristics of the bubble sliding diameter and velocity remain somewhat unclear.

Furthermore, it is important to note that previous studies have concentrated mainly on the bubble behavior of flow boiling in a smooth channel; to the best of the authors' knowledge, no flow boiling vapor bubble dynamic data in ribbed channels have been reported. Ribs are widely used in heat pipes for heat transfer enhancement, and to break the velocity and thermal boundary layers, which prevent heat transfer deterioration [14–17]. The exact mechanism behind this process is still not well understood, prompting the need for an investigation into the vapor bubble behavior of flow boiling in ribbed channels.

The purpose of this work, therefore, is to experimentally investigate the effects of inclined ribs on the vapor bubble behavior of

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Nomenclature

Parameters

D_b	bubble sliding diameter, mm
$\bar{D}_b$	mean bubble sliding diameter, mm
D_h	equivalent hydraulic diameter, mm
G	mass flux, kg/(m^{2}s)
L	length of fully development section, mm
q	heat flux, W/m^2
R	result of a calculation based on several measurements
δR	total relative uncertainty
T	temperature, °C
U	bulk velocity, m/s
V_f	flow direction bubble velocity, m/s
V_t	transverse direction bubble velocity, m/s
x_i	the *i*th variable
δx_i	the accuracy of the *i*th variable
τ	time, s
α	rib angle of attack, degree
ρ	density, kg/m^3

Subscripts

b	bubble
g	gas phase
l	liquid
v	vapor
w	wall (heater surface)

flow boiling in horizontal rectangular channels. We employ the transparent conductive oxide (TCO) technique to examine the characteristics of the flow boiling bubble motion and film production. High-speed digital video images of the flow boiling are analyzed to obtain the vapor bubble diameters and velocities in the ribbed rectangular channel.

2. Experimental description

2.1. Experimental apparatus

The closed flow boiling test loop used in this work is shown in Fig. 1. A diaphragm metering pump is used to pump the working fluid through the facility. Part of the fluid returns to the tank through the bypass line, while the remainder circulates the test section through the preheater and is heated by the TCO film. The power of the film is regulated through the voltage regulator. After flowing through the test section, the working fluid is then cooled in the condenser and returned to the tank. For this study, R113 refrigerant was used as the working fluid, even though water is widely used in industrial applications; the high boiling temperature and latent heat mean that it is difficult to perform the visualization test with water in the flow boiling configuration with sufficient power. R113 has a lower saturation temperature (320.7 K) than water and a moderate latent heat (145.2 kJ/kg).

The test section, shown in detail in Fig. 2, consists of a horizontal rectangular channel with upper and bottom walls of transparent silica-glass plates to facilitate recording the boiling phenomenon with a high-speed digital camera system (Memrecam fx K3). To provide uniform heat, the downward transparent heater is a silica-glass plate with a 5-μm-layer ($SnCl_4$) TCO film. The heater is located at a distance of 475 mm from the inlet of the test section at a point where the fluid flow is estimated to be fully developed turbulent flow (L/D_h = 30, where L is the length of fully developed section and D_h is the equivalent diameter). An alternating current power supply is connected to the plane heater and controlled by silicon-controlled rectifiers. The width of the channel is 40 mm and the length is 910 mm and 10 mm in height.

The ribs in the test section are constructed from copper sheet and are 0.5 mm high and 3.4 mm wide. Four configurations are used, as shown schematically in Fig. 3; the ribs are oriented so that they produce attack angles of 15°, 30°, 45°, or 60° with respect to the flow direction. Here, the regions between the ribs are referred to as grooves. Specific parameters of the rib configurations are listed in Table 1. A smooth channel (channel E) is also investigated for comparison purposes.

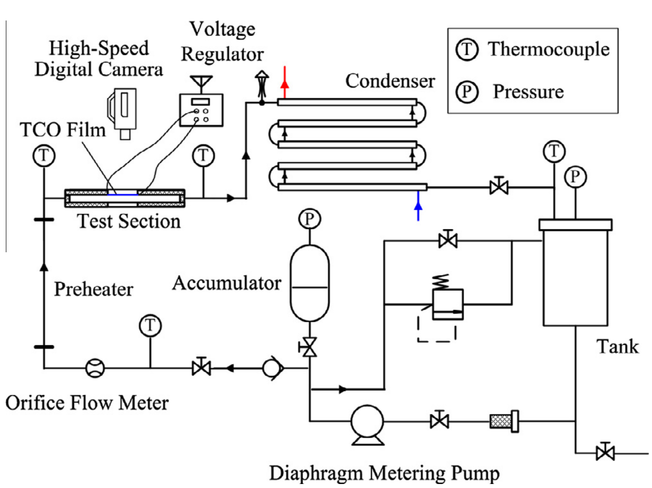

Fig. 1. Flow boiling test loop.

2.2. Experimental procedure

When the working fluid is infused into the test loop, the required flow rate of the working liquid is obtained by adjusting the piston stroke of the pump. The liquid is first heated to 308 K using the strong current generator in the preheater, and a voltage regulator is used to regulate the AC power supply that heats the fluid in the test section. A cooling unit is then run to control the liquid temperature in the channel. The condenser consists of a 1.5-m-long tube-in-tube heat exchanger cooled by water flowing in the direction counter to the refrigerant flow; the cold water is provided by a forced air-cooling water chiller. A short delay is imposed before initiating the data acquisition to make sure that the steady-state condition is attained. The heating power is then increased in small steps during the test, with the heat flux q determined by the voltage and current applied to the heater surface. If the measured wall temperatures increase sharply by more than 10 K in one second, then the data acquisition algorithm assumes that critical heat flux (CHF) conditions are met, and the power supply will be shut down immediately.

A thermal infrared imager is used to obtain the temperature distributions on the outside wall of the heater surface. The imager has an accuracy of ±2 °C. A one-dimensional steady-state heat conduction analysis showed that the temperature difference between the surface of the test section exposed to air and the inside surface of the TCO film was less than 0.5 °C for the highest heat flux considered in this study. Fluid temperatures at the inlet of the test section are measured by T-type sheathed thermocouples to an