PIV measurement of flow field around film boiling in He II

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Abstract

Film boiling phenomena in He II were studied using the PIV (Particle Image Velocimetry). Noisy and silent film boiling states were generated on/around a planar or a cylindrical heater. Tracer particles were neutrally buoyant solid H\textsubscript{2}-D\textsubscript{2} particles. The motions of vapour bubble and of tracer particles were PIV-analyzed. The velocity field was found to be composed of AC and DC velocity components. The AC component is caused by the dynamic behaviour of vapour, and the DC results primarily from the thermal counter flow. The time-averaged PIV velocity field provides with the flow field characteristics of each boiling mode.

Keywords: Super fluid He II; PIV; visualization; noisy film boiling; silent film boiling; He I boiling; thermal counter flow

1. Introduction

Boiling phenomena in superfluid He II have been studied primarily based on the measurements of the temperature and the pressure and through visualization ((Leonard, 1970; Zhang, 2005a; Takada, 2006; Nozawa, 2009)). These days, PIV, with which the flow velocity is computed from the movements of tracer particles in high-speed video images, has come to be generally used also in superfluid thermo-fluid dynamic studies (Zhang, 2005b; Paoletti, 2008; Murakami, 2014). In the application of PIV the velocity of tracer particles that are dragged by the normal fluid component is measured. It has been found that the PIV tracers were considerably decelerated by the particles-quantized vortex lines interaction (Murakami, 2014; Sergeev, 2009). In the present experiment, we attempted to apply PIV to the measurement of flow fields around film boiling in He II, the noisy and the silent film boiling modes, in order to make a detailed study of film boiling modes from a fluid dynamic point of view. High-speed video images of dynamic motions of vapor bubble and tracer particles around a planar and a cylindrical heaters set

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horizontally were taken at the frame rate of 125-1000 fps. From these video images the PIV velocity field were computed.

2. Experiment

The cryostat has three sets of optical windows with an aperture of 60 mm in diameter, in the directions of 0 (entrance for laser light), 90 (for photographing) and 180 degrees. A general-purpose high-speed video camera (FASTCAM-SA3, Photron) was used as a PIV camera. The light source was a CW YAG laser (CW532-5W, Kanomax), and the laser beam was shaped into a light sheet with a thickness of less than 2 mm. Each image covers a flow field of 60 mm (x; horizontal) by 50 mm (y; vertical) mostly with a resolution of 960 pixels in the x-direction by 720 pixels in the y-direction, and is subdivided into narrower interrogation regions of 48 by 48 pixels. The present PIV operation is based on the direct cross-correlation method between two sequential images for a 2-dimensional (x-y) velocity field. It was considered that the velocity of the normal fluid component was measured with the PIV because tracer particles follow the normal fluid component motion due to normal viscosity. Neutrally-buoyant hydrogen-deuterium solid particles with an average diameter of slightly smaller than ten μm were used.

Two kinds of heaters, a planar heater with a size of 10 mm (width) by 39 mm (depth) and a cylindrical heater with a size of 5 mm in the diameter by 50 mm in length, were used, which were set horizontally. Time-averaged velocity field data computed from thousands of instantaneous PIV raw data of the 2-dimensional velocity vectors were used for the present discussion.

3. Visualization result

Direct flow visualization with the video images to be used for PIV analysis is also informative, where dynamic behaviors of vapour bubble or film and of tracer particles are observed. The flow field around a cylindrical heater is highly irregular 3-dimensional one, and thus the instantaneous image of vapor and tracer particles is not axisymmetric. Axisymmetric feature will be recognized, if the image is integrated over the whole axial direction. In the noisy film boiling mode normally caused under a high hydrostatic pressure condition, large size (3~4 cm in diameter) vapour bubble is repeatedly generated and crushed being accompanied by loud noise with a frequency of about 40 Hz as a result of instability of the whole vapour bubble. In response to the large-scale vapour bubble motion, a radially alternating flow velocity field is induced in the whole surrounding He II. In He II boiling, vapour bubbles crush immediately after detachment from a heater and no bubbles rise in He II. Just outside the dynamic vapour region in the case of a planar heater, a vertical plume with positive velocity (in the direction away from the heater) is created. In the silent film boiling, unstable small-scale oscillation of vapour-liquid interphase is caused in thin (~1 mm thick) vapour film. This boiling mode appears under low hydrostatic pressure condition. The direct influence of this boiling on the velocity field is restricted in a narrow region near the heater.

4. PIV Results

4.1. Time-averaged velocity field

After time-averaging the PIV results over 1000 or 2000 instantaneous data, alternating flow composed by total (the superfluid and the normal fluid components all together) He II induced by vapor bubble motion nearly eliminated, and the DC flow composed by the normal fluid component caused by the thermal counter flow and the weak total fluid DC component included in the asymmetric alternating flow induced by dynamic vapour bubble behavior can be extracted. It is important that erroneous velocity data that are assigned zero values should be excepted from the averaging calculation. The DC components compose a rapidly rising plume in the case of the noisy boiling as shown in Fig. 1 (a). It should be noted natural convection of total He II is not caused because of weakly negative thermal expansion coefficient. In the case of the silent boiling shown in Fig. 1 (b), the velocity of the plume is so low that the fluid dynamic instability causes meandering of a plume and the well-defined plume structure disappears in the downstream. It is an interesting finding that He I boiling is sometimes caused in spite of being in He II. A thick vapour film turbulently fluctuates, and strong vertical plume where liquid (He I) rapidly rises by buoyancy convection is formed, just like boiling in water, and preserves a firm structure to the downstream.
It is worth noting that in the cases of weak heating (Fig. 1 (c)) adverse flow into the heater region is sometimes observed. This adverse flow may result from tracer particles trapped on quantized vortex lines that flow with the superfluid component. This flow should be distinguished from the entrainment of surrounding fluid into a plume. It is shown in Fig. 1 (d) for the non-boiling state where nearly axisymmetric flow field is created as a result of the thermal counterflow, where almost no gravity effect is recognized.

4.2. Variation of time-averaged PIV velocity with the heat flux $q$

The time-averaged PIV velocity measured just outside a vapour area, $<U_{PIV}>$, is plotted against $q$ in Fig. 2 (a) for the case of the planar heater and in Fig. 2 (b) for the case of the cylindrical heater. In the non-boiling case for small $q$, $<U_{PIV}>$ is roughly proportional to $q$. If $q$ is larger than a certain level, the noisy film boiling or the silent film boiling occurs depending on the magnitude of the hydrostatic pressure. In extremely calm circumstance with even
rather high hydrostatic pressure the silent boiling mode sometimes appears, but this state readily tends to the noisy boiling after giving a mechanical shock. Even He I boiling may occur in He II at high temperature. The reason why $\langle U_{PIV}\rangle$ is the highest in the case of noisy film boiling is that the flow in the plume is induced by buoyancy-driven vapour bubble motion that causes rapidly rising flow. In any boiling states, $\langle U_{PIV}\rangle$ is lower than the thermal

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**Fig. 2** The time-averaged PIV velocity measured just outside a vapour bubble or vapour film, $\langle U_{PIV}\rangle$, is plotted against the heat flux $q$; (a) in the case of the planar heater at $T=1.8$ K and (b) in the case of the cylindrical heater at $T=1.9$ K.
counterflow theory value $U_{n,\text{theo}} (= q/(\rho ST))$ due to the tracer particles-quantized vortices interaction [7,8]. As $<U_{\text{PIV}}>$ in the case of non-boiling is proportional to $q$ and so is $U_{n,\text{theo}}$, the ratio $<U_{\text{PIV}}>/U_{n,\text{theo}}$ is a function of temperature. The ratio is plotted as a function of temperature in Fig. 3. For reference, the PIV data for the thermal counterflow jet [7] is also shown here. The data for three cases are in fair agreement with each other within the experimental error. It was reported in the reference [7] that the normal fluid velocity in the thermal counterflow jet is, in fact, equal to $U_{n,\text{theo}}$, though the ratio is smaller than unity because of the tracer particles-quantized vortices interaction. It may be thus concluded that the present PIV velocity of the background DC flow in the case of non-boiling is also decelerated by the particles-quantized vortices interaction, and that, in reality, the DC flow of the background flows at the speed the same as $U_{n,\text{theo}}$ as suggested in [7].

5. Conclusion

The effect of the tracer particles-quantized vortex lines interaction appears in PIV He II boiling measurement in the quite similar manner to the case of the thermal counterflow jet.

The flow field around He II boiling is composed of the thermal counterflow as a DC background flow and the alternating flow of the total He II induced by boiling. In the case of the noisy film boiling the alternating flow is generated in the whole He II region by the unstable behavior of the whole vapor bubble. In the silent film boiling it is caused by small-scale instability of the vapour-liquid interphase of thin vapour film and the effect reaches only to local area near heater.

No rising convective flow of the total He II is induced because of weakly negative thermal expansion coefficient. In the case of non-boiling no gravity effect appear and the resultant flow field is nearly axisymmetric. In the cases of the noisy and silent film boiling states, a weak rising flow is indirectly induced by the buoyancy effect on vapor bubble or vapour film. In the He I boiling a local rapidly rising buoyancy convection flow of He I occurs.

Under the condition of small $q$, negative flow towards the heater is sometimes observed. This results from the tracer particles trapped on quantized vortex lines that move with the superfluid component.
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