Study of He II boiling flow field around a heater

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Abstract. We studied boiling phenomena in He II based on the flow velocity measurement data by using a PIV (Particle Image Velocimeter). Noisy and silent film boiling modes together with non-boiling state were generated on/around a horizontal planar or a cylindrical heater. For PIV tracer particles, we used H₂-D₂ solid particles that were neutrally buoyant in He II. Video images showing the development and collapse of vapor bubble or film and the motions of tracer particles were PIV-analysed. We found the PIV velocity field was composed of AC and DC velocity components of the normal fluid. The AC component follows the dynamic behaviour of vapour, and the DC results primarily from the thermal counter flow and secondarily is induced by the asymmetric vapour bubble motion. We also investigated unsteady velocity component. The objective of this series of study is to compare the characteristic features of the flow field of He II film boiling states and peculiar He I boiling state in He II and to make clear the difference in the heat transfer performance of each boiling mode.

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 [1-6]. These days, a PIV, with which the flow velocity is derived from the movements of tracer particles in high-speed video images, has come to be generally used also in superfluid thermo-fluid dynamic studies [7-9]. We have successfully attempted PIV application to He II film boiling phenomenon [10]. In the application of PIV to He II flow measurement, the velocity of tracer particles that are dragged by the normal fluid component owing to its viscous nature is, in fact, measured. It has, however, been found that the PIV tracers were considerably decelerated by the particles-quantized vortex lines interaction [9,11,12]. In the present experiment, we applied a PIV to the measurement of flow field around film boiling in He II, the noisy and the silent film boiling modes, in order to make a detailed study of film boiling states from a fluid dynamic point of view. High-speed video images of dynamic motions of vapor bubble and tracer particles around a planar heater or a cylindrical heater set horizontally were taken at the frame rate of 125-1000 fps. From these video images the PIV velocity field were computed. In the present study, as a progressive extension of the previous one [10], we also paid attention to the unsteady velocity component as a result of the dynamic motion of vapor.
2. Experiment

The cryostat has three sets of optical windows with an aperture of 60 mm in diameter, in the directions of 0 (entrance of laser light), 90 (for photographing) and 180 degree as illustrated in Figure 1. We used a general-purpose high-speed video camera (FASTCAM-SA3, Photron) as a PIV camera. The light source was a 5 W CW YAG laser (CW532-5W, Kanomax), and the laser beam was shaped into a light sheet with a thickness of less than 2 mm. The image covers a flow field of 60 mm (y; horizontal) by 45 mm (x; vertical) mostly with a resolution of 960 pixels in the y-direction by 720 pixels in the x-direction. It is further subdivided into narrower interrogation regions of 48 by 48 pixels as a PIV cell. The present PIV operation is based on the direct cross-correlation method between two sequential images for a two-dimensional (x-y) velocity field. It has been considered that the normal fluid component was measured with a PIV because tracer particles followed the normal fluid component motion due to the normal viscosity. We used neutrally-buoyant hydrogen-deuterium solid particles with an average diameter of slightly smaller than ten µm. Further details of the experimental equipment were presented in the previous reports [9,10]. Two kinds of heaters, a planar heater with a size of 10 mm (width) by 39 mm (depth) and a cylindrical heater with a diameter of 5 mm and a length of 50 mm were used, which were set horizontally (Figure 2).

Figure 1. The cryostat and the PIV system.

Figure 2. Illustration of the heater and the vapor bubble illuminated by a laser light sheet in case of the noisy boiling, (a) for the planar heater, and (b) for the cylindrical heater.
3. Results and discussion

In the high-speed video images to be used for the PIV analysis, we see the movement not only of tracer particles but also of boiling bubbles in the immediate vicinity of the heater. Vapour bubbles in He II boiling, in contrast to those in ordinary liquids, disappear immediately after detachment from a heater without rising. It is not denied that in the narrow region near the heater the motions of vapour bubbles may give a bad effect on the PIV measurement of liquid velocity as a possibility, but it is almost impossible actually. Furthermore the false bubble PIV results, if any, can be easily discriminated from the particle PIV velocity because the former suddenly increase to an extremely large value. The PIV velocity in the present data analysis is measured just outside the vapour bubble region and thus is almost free from the effect of the bubble motion. There is a small influence of the measuring point, a little distance apart from the heater, in the case of the cylindrical heater, where the measured velocity value becomes smaller than the value immediately above the heater by approximately $r_0/(r_0+r)$ ($r_0 = 5\text{mm}$, $r \sim 2\text{mm}$). This effect is rather small in the case of the planar heater.

We summarize below the feature of each boiling mode by focusing on the velocity field around a heater, cited from our previous studies [3-6, 10]. In the noisy film boiling mode appearing in the case of large immersion depth (or large hydrostatic pressure), large scale (a few cm size) vapour bubble is repeatedly formed and collapsed with a frequency of dozens Hz due to large-scale evaporation instability. In the whole He II an oscillating flow field is created, where the direction of the flow velocity is radial centred on the middle of the heater. It is fundamentally a superposition of the bubble-motion-induced zigzag varying flow (the AC component) on the thermal counter flow leaving the heater (DC component) that is theoretically given by $U_{n,\text{theo}} = q/\rho_s T$, where $q$ is the heat flux, and $\rho$, $s$, $T$ are the density, the entropy and the temperature of He II, respectively. The PIV velocity that will be discussed in this present study is the component of the flow velocity perpendicular to the heater surface, which is denoted by $U_{\text{PIV}}$. In more detail, it is the x-component velocity in the case of the planar heater, and the radial component velocity directing upward (for the sake of convenience) in the case of the cylindrical heater.

Figure 3 shows a typical example of the transient velocity record $U_{\text{PIV}}(t)$ measured above the planar heater in the case of the noisy boiling. In this case, the magnitude of the AC component (root mean square (RMS) value), being larger than 100 % of the DC component (mean value), is considerably larger than those of the other cases as discussed later in more detail. In the phase of bubble expansion, the velocity jumps up, and subsequent to it in the phase of bubble collapse it decreases a little slowly down to a negative value (flow velocity towards the heater). In the case of a cylindrical heater, regardless of the noisy or silent boiling, the flow field is, in large, axisymmetric around the heater if a time average is taken, though it is not perfect axisymmetric momentarily due to large-scale
Figure 4. The time averaged PIV velocity measured just outside the vapor area $<U_{PIV}>$ is plotted against $q$ together with the theoretical thermal counterflow velocity drawn by a dotted line. (a) for the case of the planar heater at $T = 1.8$ K, and (b) for the case of the cylindrical heater at $T = 1.9$ K.

Intermittent and turbulent nature of boiling. In the case of silent film boiling caused typically under the condition of small immersion depth (typically smaller than 10 cm), small-scale vapor-liquid interface instability with a frequency of hundreds Hz appears over a thin vapor film with a thickness of the order of 1 mm. The flow field is approximately a DC one basically created by the thermal counterflow accompanied with small instability-induced fluctuating component. We found that in some cases a different kind of boiling mode from the noisy and silent boiling modes was induced, where an obvious rising plume appeared right above the heater. He II seems to change to He I in the vertically long narrow region right above the heater owing to the degradation of heat removal from the heater area to the surroundings, where buoyancy-induced convective plume is created. It should be noted a buoyancy-driven convective flow is only induced in He I not in He II.

3.1. Plot of time averaged PIV velocity $<U_{PIV}>$ against the heat flux $q$

Figure 4 shows the time averaged PIV velocity measured just outside the vapor area, $<U_{PIV}>$, plotted against $q$, which was computed from thousands of instantaneous PIV raw data of the two-dimensional velocity data. Similar results have, in fact, been presented elsewhere [10], but the present data may be regarded as revised ones where the accuracy is much improved by adopting more rigorous averaging operation for the raw PIV outputs where lots of invalid data and lack of data are intermingled. They must be eliminated in the averaging operation. For very small value of $q$ the non-boiling mode appears, where boiling is not caused and heat is transferred in the thermal counterflow mode. Thus, $<U_{PIV}>$ is approximately proportional to $q$ for very small $q$, and some non-linear feature is seen for moderately small value of $q$. These results are consistent with the previous PIV results of the thermal counterflow jet [9] in both qualitative and quantitative senses. For larger $q$, the noisy film boiling or the silent film boiling occurs depending on the magnitude of the hydrostatic pressure at the heater. It is interesting to note that in very calm circumstances even under rather high hydrostatic pressure condition the silent boiling sometimes appears, but this state readily tends to the noisy boiling after knocking the cryostat. It is seen from the figure, though the temperature is slightly different between Figures (a) and (b), that the onset heat flux of film boiling is larger for the planar heater than for the cylindrical heater. This is the result of the edge effect that the heat removal is enhanced along the
Figure 5. The time averaged PIV velocity measured just outside the vapour area \(<U_{PIV}>\) is plotted against \(T\) for several values of \(q\) together with the theoretical thermal counterflow curve drawn by a dotted line. The data are shown in the form of \(<U_{PIV}>/q\).

planar heater with a finite width. The noisy boiling branch is positioned approximately on the extension of the theoretical thermal counterflow branch. This feature is exactly true for the temperatures very close to \(T_\lambda\). The reason why \(<U_{PIV}>\) is the highest and is positioned on the extension of the thermal counterflow branch is that the violent total He II flow is induced by the boiling bubble motion where an average velocity is not zero but has a positive value, and that due to the co-flow structure of the super and the normal components the effect of high-density quantized vortices by which the tracer particles are decelerated is suppressed. And, in addition, the measuring point is outside a large-scale vapour bubble being apart from the heater area where the quantized vortex density is high. The silent boiling branch, which is considerably lower than the noisy boiling branch, seems to range smoothly from the upper end of the non-boiling branch. Sometimes peculiar He I boiling is caused, in particular at higher temperatures, where a strong buoyancy-driven rising plume of He I is formed.

3.2. Temperature dependence of \(<U_{PIV}>\)

Figure 5 is the plot of \(<U_{PIV}>/q\) against the temperature for a number of \(q\) values for each boiling mode together with the theoretical line of the thermal counter flow \(U_{n,\text{theo}}/q (=1/\rho sT)\). It is seen from Figure 4 (a) and (b) that the noisy boiling first appears for a moderate value of \(q\), where the first data point is approximately on the extension of the theoretical \(U_{n,\text{theo}}\) line. This suggests that under this heating condition the influence of high-density quantized vortices to decelerate the tracer particles is weak at the measuring point as compared with the non-boiling and the silent boiling modes. However, as \(q\) increases, the \(<U_{PIV}>\) vs. \(q\) data curve for the noisy branch becomes non-linear and even a stagnant tendency appears to the curve. This may be the reason why the data points of the planar heater (for large \(q = 6.0\times10^4\) W/m²) in Figure 5 are below the theoretical curve \(U_{n,\text{theo}}/q\). This non-linear tendency does not appear and thus the data points are rather close to the theoretical curve in higher temperature cases. The reason that the data for the cylindrical heater seem larger than those of planar heater in the case of noisy boiling is because the data for the cylindrical heater in Figure 5 are those in the case where \(q\) is small \((2.0\times10^4\) W/m²) and accordingly the non-linearity does not appear. Among the data of cylindrical heater those for the silent boiling are the smallest at the same \(q\) value. These PIV data are
strongly affected by the deceleration effect of quantized vortices to the tracer particles and thus they are on the extension of the non-linear part of the non-boiling branch that is lower than the theoretical curve. The result of the He I boiling seems nearly temperature-independent. The He I flow forming a rising plume is presumably nothing to do with superfluidity. Accordingly, He I boiling data are larger than the theoretical thermal counterflow curve for higher temperatures than 2.0 K and are smaller than that for lower temperatures. In this mode, the major portion of the thermal energy generated by the whole heater surface is convectively carried upward along with the He I flow forming a vertical plume. The total heat generation rate per unit heater length for the cylindrical heater, \( \pi dq \) (\( d \): 5 mm, = heater diameter), is larger by a factor of \( \pi/2 \) than for the planer heater, \( wq \) (\( w \): 10 mm, = heater width), for the same \( q \). This is the reason why the data for the case of the cylindrical heater are larger than those of the planar heater.

3.3. Fluctuating component of the velocity, \( \Delta U_{PIV}/<U_{PIV}> \)

In heat transfer, not only the DC flow component but also the fluctuating (AC) component \( \Delta U_{PIV} \) is important. In general, the fluctuating component is significant in boiling heat transfer. The AC component in this study is the RMS value of the velocity fluctuation, and the averaging calculation is performed as an ensemble average. The result is presented in the form of \( \Delta U_{PIV}/<U_{PIV}> \) in the Table 1. The AC component in the case of the noisy film boiling is generated primarily in response to the large-scale growth and collapse of a boiling bubble. In the case of the silent film boiling the fluctuating component is induced by fluctuating behaviour of the thin vapour film, and thus it is small in the magnitude, and the effect does not extend to far downstream region. On the other hand, in the case of He I boiling it results from a turbulent flow of buoyancy-driven rising plume. As naturally expected, \( \Delta U_{PIV}/<U_{PIV}> \) is largest in the case of noisy boiling, as large as more than 100%. Those of the silent film boiling and the He I boiling are considerably smaller than that of the noisy film boiling. It is a general tendency except for a case of non-boiling mode that if \(<U_{PIV}> \) is the larger, \( \Delta U_{PIV} \) the larger. The ratio \( \Delta U_{PIV}/<U_{PIV}> \) is, in general, the smallest in the case of non-boiling mode. However, it should be noted that \( \Delta U_{PIV} \) might become large due to the meandering of the thermal counterflow as the result of flow instability, even if \( q \) is small and accordingly \(<U_{PIV}> \) is small.

4. Conclusion

It is seen from the measurement result with the PIV applied to He II boiling that high density quantized vortices influence the PIV measurement result in the quite similar manner to the thermal counterflow jet. The He II flow field induced by boiling is composed of the thermal counterflow as a DC background flow and the alternating (AC) flow of total He II induced by vapor bubble or film motion. In the noisy film boiling state the AC flow is generated over the whole He II region by the unstable behavior of a vapor bubble. The velocity jumps up responding to the expansion of a bubble and drops a little more slowly to a negative value during bubble collapse. In the silent film boiling state the AC component caused by small-scale instability of vapor-liquid interphase of thin vapor film is rather small in magnitude and appears only in a narrow area near the heater. No rising convective flow of the total He II (super + normal components) is induced because of weakly negative thermal expansion coefficient of He II. However, a weak rising total flow is indirectly caused by the buoyancy-driven rising of vapor bubble or vapor film in the cases of the noisy and silent film boiling states. In the case of non-boiling, no gravity effect appear, and the resultant flow field is approximately axisymmetric if the time average is taken. In the He I boiling in He II, a local rapidly rising buoyancy-driven flow of He I was formed. The magnitude of the AC component becomes to

Table 1. Fluctuating component of the velocity, \( \Delta U_{PIV}/<U_{PIV}> \).

| Boiling Mod    | Noisy | Silent | He I  | Non–Boiling |
|----------------|-------|--------|-------|-------------|
| \( \Delta U_{PIV}/<U_{PIV}> \) (%) | 130~100 | \( \leq 40 \) | \( \leq 30 \) | \( \leq 25 \) |
more than 100% of the average value in the case of the noisy boiling, and is far larger than those in other boiling modes.

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