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The effective use of focused shadowgraphy for single bubble nucleate pool boiling investigations

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Abstract. Nucleate pool boiling is known for its high heat transfer coefficients. Despite being widely implemented, the prediction of nucleate pool boiling mechanisms remains complex and single bubble heat transfer analysis is helpful to simplify the problem. Owing to the interesting bubble behaviour during nucleate pool boiling, publications tend to focus on the bubble dynamics while the experimental setup is only briefly discussed. Small but critical information on the experimental setup is often omitted, which makes it challenging or even impossible to reproduce or compare experimental data. Therefore, the purpose of this study is to provide a systematic approach to using focused shadowgraphy for the investigation of single bubble dynamics using R245fa. A pool boiling experimental setup has been built and equipped with temperature, pressure and heat flux sensors, as well as a high-speed camera and light source. The nucleate pool boiling takes place at a single cavity on a copper block. The influences of the heat transfer surface area, light source, and diffuser films were investigated to provide a systematic approach to the use of focused shadowgraphy for the investigation of single bubble dynamics.

1. Introduction

Nucleate pool boiling is known for its high heat transfer coefficients and is widely implemented from macroscales (e.g. boilers in power plants) to microscale (e.g. thermal management of electronic equipment). However, the prediction of nucleate pool boiling mechanisms remains complex due to the fast bubble growth as well as the interaction of the bubbles with the surface, liquid and neighbouring bubbles. As the vapour bubbles are responsible for heat transfer, a thorough understanding of the mechanisms behind the formation, growth and detachment of the bubbles from the heated surface is required. Mohanty and Das [1] pointed out that the accuracy of boiling heat transfer correlations depends on the accuracy of the correlations to predict the bubble dynamics parameters. Single bubble analysis is helpful to simplify the problem and improve our understanding of the bubble dynamics.

Vafaei and Kim [2] gave an extensive overview of experimental research on single bubble boiling from artificial cavities. While different methods have been used, the majority of the studies made use of a vessel in which the test section is placed, a light source and a high-speed camera. In most cases, a cavity is fabricated in a polished surface heated by a cartridge heater [3] or an electrical heater connected to a small-diameter copper rod [4], while others used very small surfaces, e.g. a heated needle [5]. The drawback of decreasing the heat transfer area to a point source is that it does not closely resemble bubble dynamics on a flat surface, typically found in practice.

To visualise the bubble growth during nucleate pool boiling, different methods are used, such as shadowgraphy, high-speed videography and infrared-based thermography. Despite significant advancements in optical methods and instrumentation, older methods such as shadowgraphy are still commonly used. Focused shadowgraphy involves parallel-light shadowgraphy with additional optical elements between the test surface and shadowgram to obtain a focused shadowgraph [6]. The variable magnification of the shadowgram and the flexibility to adjust the sensitivity and resolution by focusing a lens makes it particularly suitable to study single bubble dynamics. Due to its perceived simplicity, publications tend to provide more detail on the image acquisition, such as the frames per second and image resolution, than the focused shadowgraphy setup, such as the light source, lenses and filters used. This becomes especially important when investigating fluorinated refrigerants, such as R245fa, as the bubbles are typically much smaller compared to water. Furthermore, increasing the heat flux or pressure not only decreases the bubble growth time and bubble diameter, but also intensifies Schlieren effects due to higher temperature gradients and higher gradients in the refractive index. This makes it increasingly challenging to obtain images of sharp bubbles that can be used for single bubble analysis.

Therefore, the purpose of this study was to follow a systematic approach to investigate single bubble dynamics of R245fa using focused shadowgraphy. Special attention was given to the experimental heat transfer and optical setup to ensure nucleation from a single cavity only and to optimise the quality and accuracy of the images obtained.

2. Experimental setup

Figure 1 contains the schematic of the experimental setup, which consisted of a stainless-steel vessel with a height of 130 mm and an inside diameter of 150 mm. The fluid inlet, vacuum port, pressure sensor, and condenser were fixed to the top of the vessel, while the bottom of the vessel housed the test section, heating element and fluid outlet. Four auxiliary heaters were mounted inside the vessel walls and connected to a temperature regulator. The vessel was insulated using 32 mm-thick HT Armaflex insulation (thermal conductivity of 0.042 W/mK). Two Pt100 probes were used to measure the saturation temperatures of the liquid and vapour.

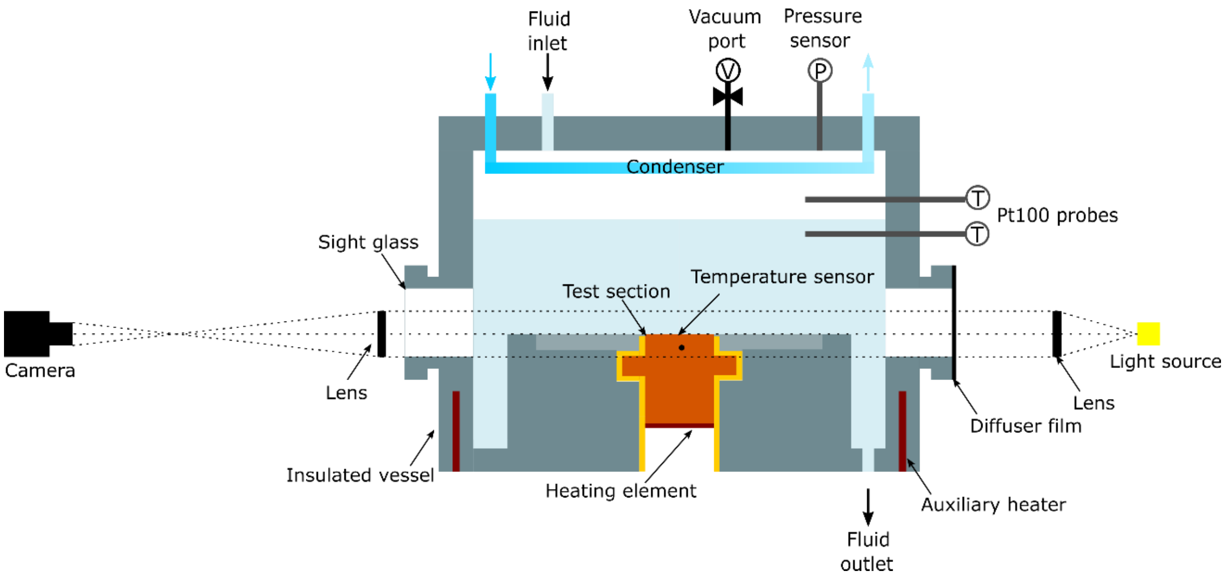


Figure 1. Schematic of the experimental setup used to conduct pool boiling experiments.

Different copper test sections were investigated and the details are provided in Section 3.2. The reference test section had a surface area of 20 mm × 20 mm that was exposed to the boiling fluid as well as an overall height and width of 32 mm and 35 mm, respectively. A temperature sensor was mounted 8 mm below the upper surface of the test section. To ensure single bubble nucleation, a single conical cavity was made in the centre of the test section using a Rockwell hardness tester with a 120° cone indenter. The cavity diameter was measured to be 363 µm using an optical microscope (Zeiss Axioplan 2) and the cavity depth was calculated to be 105 µm from the known angle of the indenter. The surface was polished to remove any scratches or burrs from the manufacturing process.

Care was taken to insulate the test section to minimise heat losses and ensure bubble formation from the cavity only. A 2.5 mm-thick Teflon seal was tightly fitted around the test section. The height of the Teflon seal was 1 mm less than that of the test section to allow the application of a thin layer of high-temperature silicone (WEICON Silicon HT 300) on top of the Teflon seal. A meniscus layer effect was created to prevent any silicone protruding above the test section surface as that would obstruct the view of the bubble formation.

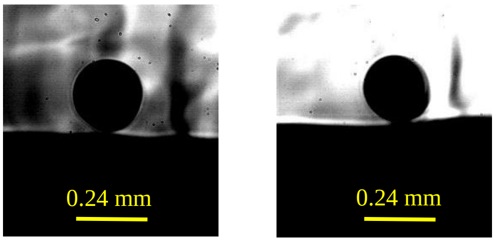
The optical setup consisted of a light source and a planoconvex lens to ensure fully parallelised light passing through the sight glasses. A planoconvex achromatic lens with a focal length of 100 mm was used for focussing and magnification. A Photron Fastcam SA-X2 high-speed camera with a full resolution of 1 024 × 1 024 at 12 500 fps was used and the image resolution was approximately 2.97 µm per pixel. As the bubble growth rate was influenced by heat flux, 12 500 fps were found to be sufficient to capture the bubble growth at higher heat fluxes. Furthermore, a white polycarbonate film was used to reduce reflections. The shutter time was set to 1/800 000 when no film was used, but adapted 1/12 661 when using the film.

The images were cropped using ImageJ and post-processed using MATLAB. The Image Segmenter application was used for binarisation. The binarised image was compared to the original image and the segmentation threshold was adjusted until the mask corresponded to the actual bubble. The image sequence of the specific bubble was batch-processed using a function to ensure consistency in the analysis of the bubble growth. The bubble area was obtained from the Image Region Analyzer application and the equivalent bubble diameter was considered to be the diameter of a spherical bubble with the same area ($D_{eq} = (4A/\pi)^{1/2}$). Finally, the equivalent diameter in pixels was converted to mm using the conversion obtained from the reference image.

3. Results

3.1. Light source

The temperature difference between the surface and fluid leads to the nucleation of bubbles, as well as convection currents and Schlieren effects, which are undesirable when using focused shadowgraphy. One method of reducing the Schlieren effects is to use a higher intensity light source. Figure 2(a) and (b) compare the images obtained using a Halogen- and a Laser-Driven Light Source.



(a) (b)

Figure 2. Comparison of images obtained using a (a) Halogen- and (b) Laser-Driven Light Source at a heat flux of 10 kW/m^2.

An increase in intensity reduced the Schlieren effects and increased the sharpness. From close inspection in Figure 2(b), the surface on which the bubble grew appeared to be inclined. It was initially thought to be an uneven application of the silicone during the sealing process. However, further image processing in Figure 3 revealed that the surface was hidden below the interface on which the bubbles appeared to form. Figure 3(a) compares the reference image (before heating) to the raw (Figure 3(b)) and processed (Figure 3(c)) images during heating. During post-processing, it became evident that the cavity was hidden below the perceived interface. During the experiments, significant convection currents were observed on the heat transfer surface. These currents led to Schlieren effects and multiple reflections of the light along the surface, which created the effect of a boundary layer which appeared dark in the camera image.

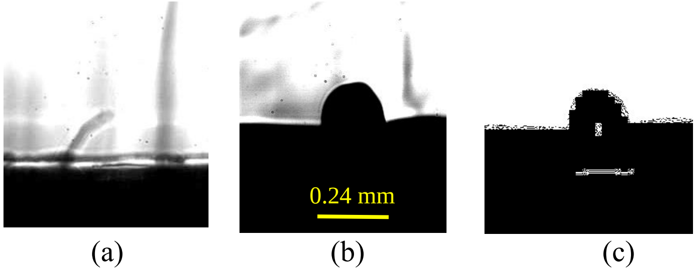


Figure 3. Comparison of (a) the reference image without heating, (b) a raw and (c) processed image containing a growing bubble when the surface was heated.

3.2. Heat transfer surface area

Three test sections were used to investigate the influence of the heat transfer surface area on the boundary layer observed in Figure 3. The reference test section (Figure 4(a)) ensured a uniform heat flux distribution and temperature gradient throughout the test section. In Figure 4(b), the heat transfer surface area was reduced in the line of sight of the camera to reduce Schlieren effects, while in Figure 4(c), the heat flux was focused in the centre to mimic point-source heating on a flat surface.

Furthermore, the images obtained during unheated (no bubbles) and heated (bubble growth) conditions using the reference (Figure 4(a)), reduced surface (Figure 4(b)), and focussed heating (Figure 4(c)) test sections are compared. When reducing the heat transfer surface in the line of sight of the camera, the boundary layer problem in Figure 3 was eliminated. The effect of the heat transfer surface area on the bubble dynamics was also investigated by comparing the bubble growth rates. It was found that there was a loss of information for the reference and the focused heating surface with respect to the bubble size, as the bubble nucleated below the visible interface, while there was also a loss of information with respect to the bubble growth time, as the onset of bubble nucleation could not be observed inside the boundary layer.

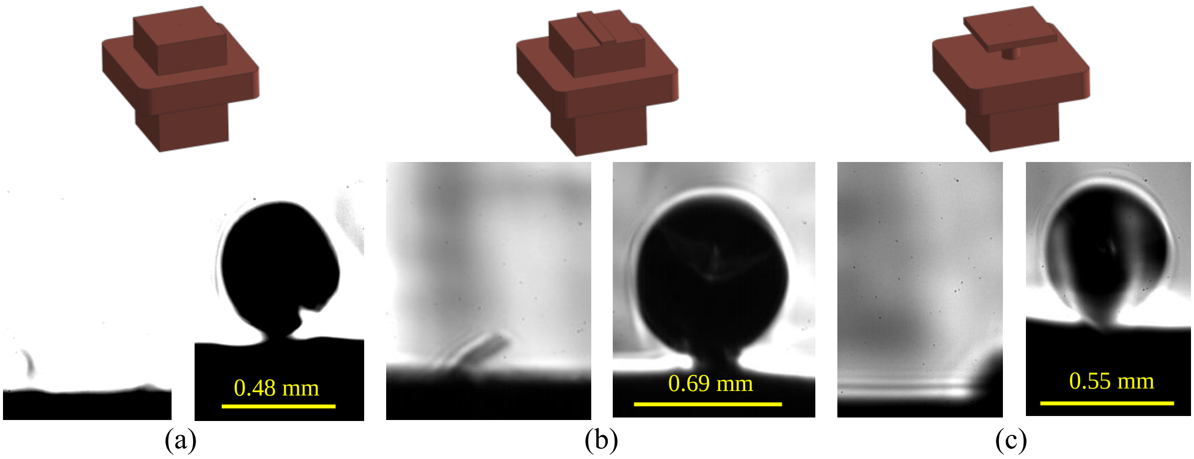


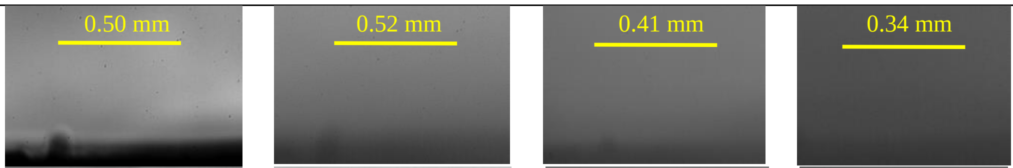
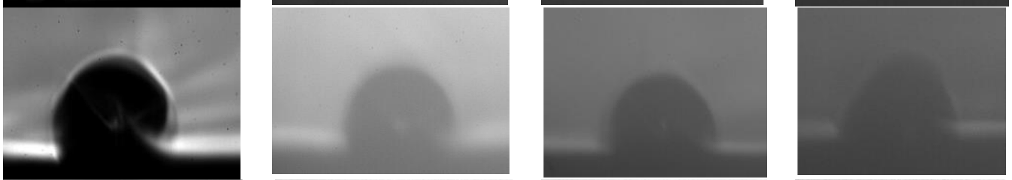
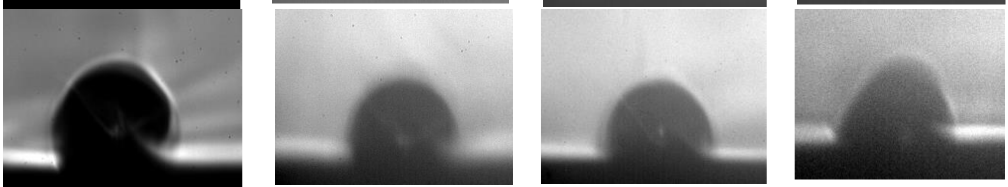
Figure 4. Comparison of the images obtained for unheated and heated surfaces using the (a) reference, (b) reduced surface, and (c) focussed heating with reduced surface area test sections. Due to the varying heat transfer surface at the top the test section, the heat input and heat flux to the bottom of the test section was fixed to 7 kW/m^2.

3.3. Diffuser film

Diffuser films assist in removing minor reflections and background noise in the images. The distance between the white polycarbonate film and the nucleation site was varied while comparing the images to a reference case obtained without the film in Table 1. In general, the brightness and sharpness of the images decreased as the distance between the nucleation site and film increased.

When comparing the images obtained with the film at 12 cm to those obtained without a film, the reflections near the surface and in the background were reduced. A further increase in distance led to a slight increase in reflections, background noise and minor deformations in the shape of the bubble. The contrast was maximised during the image post-processing, however, when comparing the processed and raw images, it follows that post-processing could not compensate for the lack of information when the film was positioned too far from the nucleation site. Due to the diameter of the insulated vessel, it was not possible to position the film closer to the nucleation site.

Table 1. Comparison of bubble images obtained at a heat flux of 10 kW/m^2 using a diffuser film at different positions from the nucleation site.

	No film	12 cm	20 cm	40 cm
Reference				
Raw				
Adjusted				
Binary				

The binary images in Table 1 illustrate the compromise between sharpness and noise. In the absence of any film, a sharp bubble with clear edges and almost negligible boundary layer effects was observed. However, the reflection on the right side of the bubble caused deformation when processing the images. The images obtained with the film resulted in smoother bubbles, which is beneficial for post-processing. However, a boundary layer effect, not due to convection effects (eliminated through the reduction of the heat transfer surface) but due to the lack of sharpness of the reference pictures, became visible. Furthermore, when comparing the interface between the bubble and surface, it follows from Table 1 that as the distance between the nucleation site and film was increased, the sharpness of the interface increased, while the sharpness of the bubble decreased. This was due to the slight increase in reflection combined with a decrease in brightness.

To further investigate the effectiveness of the film for the study of single bubble dynamics in nucleate pool boiling, the bubble growth rates of the four cases in Table 1 were compared in Figure 5. This figure indicates that similar bubble growth rates were obtained when using a film, while the bubbles appeared to grow at a faster rate when no film was used. This was due to the images being sharper without the film, and therefore, small variations in diameter with time could be captured more accurately. At first glance, it might also appear as if the bubble departed earlier when no film was used, however, this was not the case. As no film was used, a reflection existed near the surface which led to a loss of information during the final bubble growth stages, just before departure. Once a film was added, the reflection was reduced (as shown in Table 1) and it was possible to track the bubble for its entire growth cycle. The brightness and sharpness of the bubble in the images decreased when the distance between the film and nucleation site was increased. This explains why the bubbles seemed to depart earlier and with a smaller diameter at film positions of 20 cm and 40 cm. Although it was evident from the comparison in Table 1 that the film not only reduces the reflection but also the brightness and sharpness, it can be concluded from Figure 5 that this slight loss of information can be considered acceptable for single bubble dynamics analyses. When comparing the departure diameter and time of the blue (no film) and orange (film at 12 cm) data, the film led to a 10% reduction in the departure diameter, while the reflection that existed when no film was used led to a 40% reduction in bubble growth time.

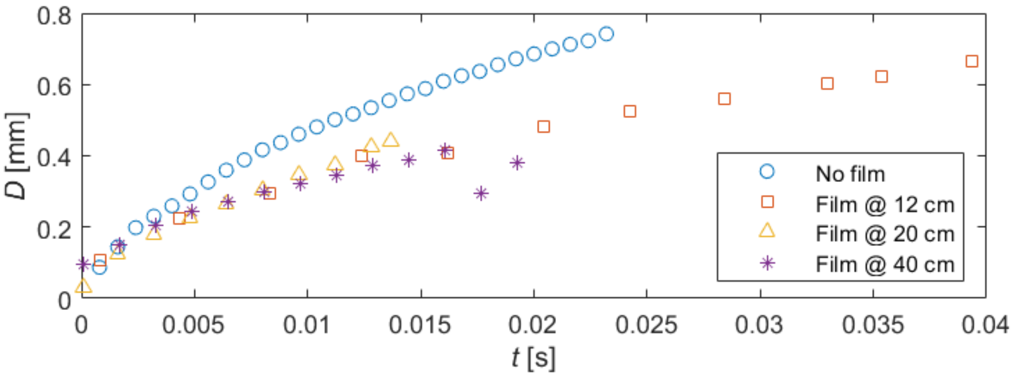


Figure 5. Comparison of bubble growth rates at a heat flux of 10 kW/m^2 obtained without and with using a diffuser film at different positions from the nucleation site.

4. Conclusions

In this study, a systematic approach was followed to investigate single bubble dynamics of R245fa using focused shadowgraphy. Special attention was given to the experimental setup to minimise heat losses and prevent bubbles from forming elsewhere than the nucleation site, as well as to the optical setup to optimise the quality and accuracy of the images obtained. It was found that Schlieren effects can be reduced using a stronger light source, but that it is even more important to reduce the heat transfer surface area in the line of sight of the camera. Furthermore, to improve the quality of the images and facilitate the post-processing process, a polycarbonate diffusing film assisted in minimising reflections.

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