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High-speed visualisation of nucleate boiling in vertical annular flow

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Abstract

High-speed video recording was carried out of annular flow of steam–water mixtures in an internally heated annulus test section. The heated section was 0.32 m long and made of stainless steel. The equivalent diameter of the channel was 12.9 mm. The results demonstrated the interaction between disturbance waves in the liquid film and the activity of nucleation sites.

1. Introduction

Little is known about the role of nucleate boiling in high quality phase change systems. Many authors support the idea that a suppression of this phenomenon exists at high qualities [1,2]. Others claim that this may be the dominant mechanism of heat transfer in such situations [3,4].

A fact beyond doubt is that the hydrodynamics of the annular regime gives rise to complex interactions between waves, droplets and bubbles. Amongst these, one may cite phenomena such as bubble sliding and bursting, liquid entrainment, nucleation suppression and enhancement etc.

Early visualisation experiments carried out at the UK Atomic Energy Research Establishment, Harwell, shed some light on the interaction between the activity of bubble nucleation sites and disturbance waves in annular flow [5]. The high-speed cinematography sequences from that work showed that as the thickness of the liquid film varied with the presence of the disturbance waves, so did the intensity of the nucleation of the sites. In those experiments, the waves seemed to locally trigger off rather than suppress nucleation activity.

The amount of experimental evidence (number of ciné sequences) from the Harwell experiments is very small and, at the time, the authors did not attempt to provide an explanation for the observed phenomenon. Therefore, one of the goals of the present study is to extend these experiments by carrying out high-speed video recording of such flows.

Although the onset and suppression of nucleate boiling in convective systems is a topic extensively dealt with in the literature [6–8], considerably less work has been conducted for wavy films. Marsh and Mudawar [9] carried out detailed experiments on nucleate boiling in turbulent falling films (using water and FC-72) and also developed a theoretical model for predicting the onset of nucleate boiling for this case. Their approach adapted earlier boiling incipience models [7,8] so as to cope with the presence of waves and with the turbulence in the falling film. Instead of assuming a linear liquid temperature profile [8], they employed a turbulent film temperature profile.

Based on visual observation of the flow, Marsh and Mudawar [9] postulated a heat transfer mechanism by which the waves in the film actually trigger bubble nucleation. In their words, '...during nucleate boiling, a larger wall superheat is created upon the passage of large waves, providing more favourable conditions for nucleation compared to the thin film between the large

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Nomenclature

p	pressure bar
$\dot{m}_\mathrm{T}$	total mass flux (kg/m^{2}s)
$\dot{q}_\mathrm{w}$	wall heat flux (W/m^2)
Re	Reynolds number (–)
X	mass quality (–)

Subscripts

in	Inlet
LF	liquid film
LFC	critical liquid film

waves. At the point of incipience, wall regions which are instantaneously favourable for bubble growth due to the passage of large waves are quickly covered with thin film flow, which, together with the turbulent eddies, tend to deprive wall cavities of the superheat required for nucleation...' However, their final conclusion was that nucleation was generally reduced for increasing film Reynolds number.

In the present work, a visualisation study of the onset of nucleate boiling in upwards co-current annular flow is presented. A specially constructed annulus test section enabled a direct observation of the flow. The temperature of the heated wall was measured using a sliding radiation equilibrium thermocouple.

This paper is organised as follows. In Section 2, the experimental apparatus and procedure are outlined. Section 3 presents the visualisation results on the interactions between disturbance waves and the activity of nucleation sites. Conclusions are finally drawn in Section 4.

2. Experiments

2.1. Experimental facility

The experimental apparatus was described in detail in previous publications [10,11]. Here, for completeness, the apparatus and the test section are illustrated in Figs. 1 and 2, respectively and described briefly.

Water is injected at the bottom end of the test section and passed through a porous sinter on to the outer surface of the heated inner tube. It then flows as a film coating the inner tube surface dragged upwards by the steam entering at the bottom header and flowing in the annular gap between the inner tube and a concentric glass tube. The glass tube allows a direct observation of the flow; condensation at the inner wall of this tube is prevented by surrounding the glass tube with a further glass tube and passing hot air through the gap between the glass tubes. The basic dimensions of the test section are summarised in Table 1.

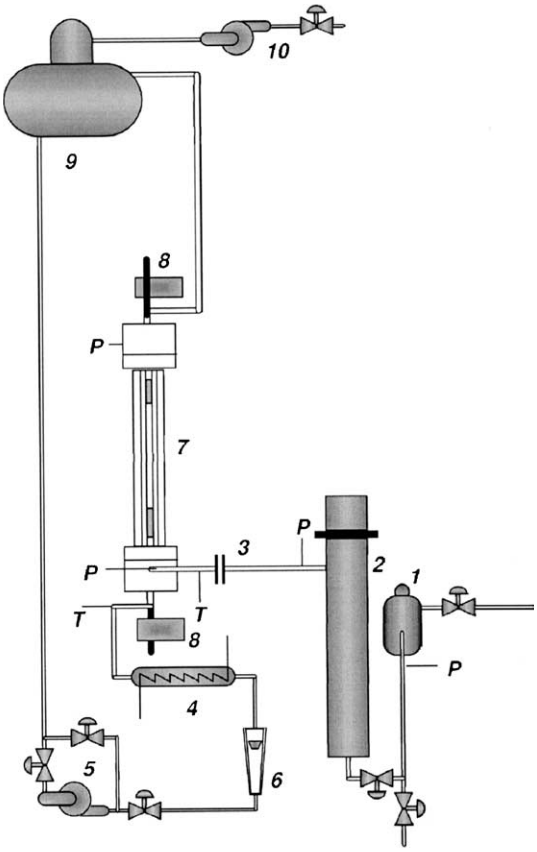

Fig. 1. The experimental apparatus. (1) Pressure reducing valve; (2) steam drier/superheater; (3) orifice plate; (4) water preheater; (5) mono pump; (6) water flowmeter; (7) test section; (8) heater terminals; (9) reflux condenser; (10) vacuum pump.

Power is delivered to the heated inner surface by passing a low voltage, high amperage electrical current through the inner rod. The 50 Hz AC current is set by means of a Variac-controlled transformer. The maximum current is of the order of 1000 A giving a voltage drop of approximately 20 V and a maximum power of the order of 20 kVA.

2.2. Visualisation equipment

Direct observation of the flow is carried out using a high-speed video recording system. The Kodak Ektapro

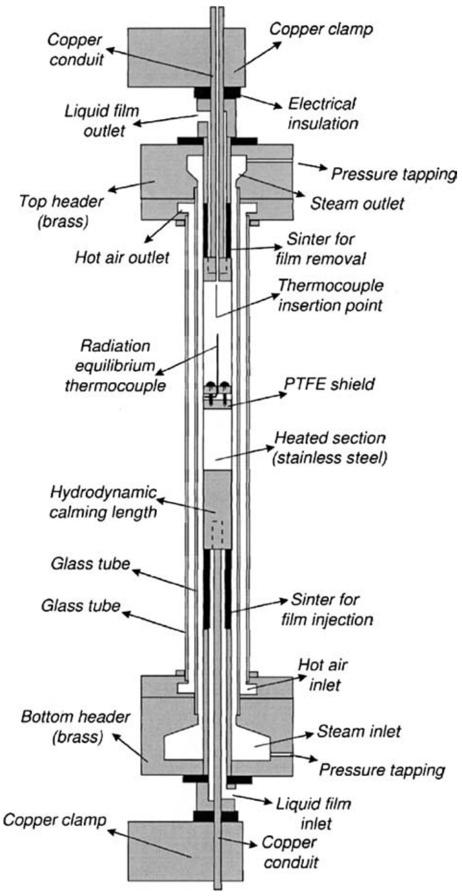

Fig. 2. The test section.

2000 camera is equipped with a Canon Macro 50 mm lens and is capable of producing video footage at up to 2000 frames per second. The system is linked to a computer for data acquisition. Illumination was carried out using two 500 W halogen lamps. Video shots were taken at various distances from the bottom end of the stainless steel heater.

2.3. Experimental procedure

Firstly, the liquid film and steam flow rates and inlet temperatures are adjusted. The electrical power to the heater is then gradually increased. For each value of heat flux, when steady-state is attained, the wall temperature is measured at various distances along the heater using a traversing radiation equilibrium thermocouple [10,12]. It is believed that steady-state conditions are reached when the thermocouple reading at the initial traversing position is constant (This generally takes place 5–10 min after the wall heat flux is set).

3. Results from visualisation

In this section, results from the visualisation studies are presented as still frames extracted from the video footage. In all pictures, the section of the inner rod under investigation appears as a dark horizontal cylinder in the middle of the frames. The dark line at the very bottom of the pictures is the wall of the inner glass tube. The direction of flow is from right to left. It should be emphasised that there are difficulties in presenting evidence from video sequences in terms of prints of frames from the video. Phenomena which are obvious in the video are often difficult to show clearly in still pictures. We have tried to enhance the still pictures by the use of arrows which indicate where events seen clearly in the video sequences are occurring.

3.1. Disturbance wave initiation and entrainment

Fig. 3a and b show respectively the region of smooth film between consecutive disturbance waves (a) and a disturbance wave on the liquid film (b) in an experimental run in which $\dot{q}_w = 0$. The highly disturbed nature of the wave region can be distinguished due to the reflection of light at the film interface.

In annular flow, the droplet entrainment process is intimately related to the existence of waves in the liquid

Table 1
Dimensions of the test section for the boiling visualisation experiments

Parameter	Dimension (mm)
Outer diameter of the inner rod	19.05 (3/4″)
Outer diameter of sinters	19.05
Inner diameter of the inner glass tube	32
Inner diameter of the outer glass tube	48
Wall thickness of glass tubes	2
Length of calming section	90
Length of inlet sinter	77
Length of heater (stainless steel)	320
Thickness of heater wall	0.56
Total length of test section (between outer edges of headers)	790
Length of visualisation section (between inner edges of headers)	565

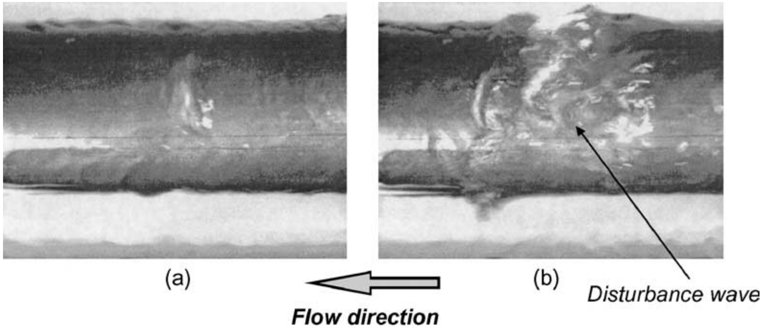

Fig. 3. (a) Region of smooth film between disturbance waves and (b) a disturbance wave. Experimental conditions: $p_{\mathrm{in}} = 1.9$ bar, $\dot{m}_{\mathrm{T}} = 30.2\ \mathrm{kg\,m^{-2}\,s^{-1}}$, $X = 0.63$, $\dot{q}_{\mathrm{w}} = 0\ \mathrm{W\,m^{-2}}$.

film [13], and several criteria for the inception of disturbance waves and entrainment have been proposed in the literature [14–17].

Fig. 4 presents a sequence in which liquid entrainment from the crest of a disturbance wave takes place ($Re_{\mathrm{LF}} \approx 350$). In this sequence of frames, the entrainment process begins at frame 4c and, in the subsequent frames, the droplets are all situated left of the wave in a faster-moving vapour flow. As will be seen from frame 4e, the droplets appear as streaks being ejected from the wave. Nucleating bubbles are present in all frames (some were marked with black arrows in frames a, b and c). In frame 4d, the visible active nucleation sites are marked by arrows. The greater number of arrows immediately upstream of the wave provide an indication of the increased bubble nucleation induced locally by the passage of the wave. This issue will be dealt with in detail later. In frame 4f, some of the droplets entrained from the wave deposit on the glass tube. The time interval between consecutive frames is 1 ms.

Fig. 5 illustrates a sequence of 12 frames in which $Re_{\mathrm{LF}} = 166$; the motion and break-up of a disturbance wave are clearly seen. The process of wave break-up is seen as the formation of a filament which eventually breaks away from the body of the wave giving rise to suspended entrained drops. For the conditions of this case, approximate Re_{LFC} values given by various published inception criteria are, Ishii and Grolmes [14], 340;

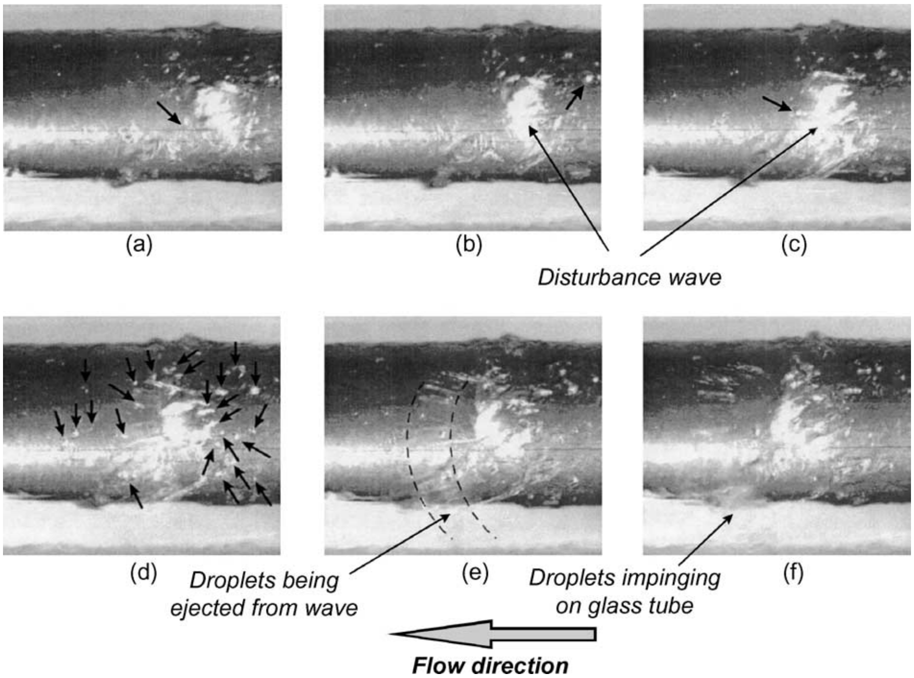

Fig. 4. Droplet entrainment from the crest of a disturbance wave. Experimental conditions: $p_{\mathrm{in}} = 2.0$ bar, $\dot{m}_{\mathrm{T}} = 27.3\ \mathrm{kg\,m^{-2}\,s^{-1}}$, $X_{\mathrm{in}} = 0.77$, $\dot{q}_{\mathrm{w}} = 146.2\ \mathrm{kW\,m^{-2}}$.

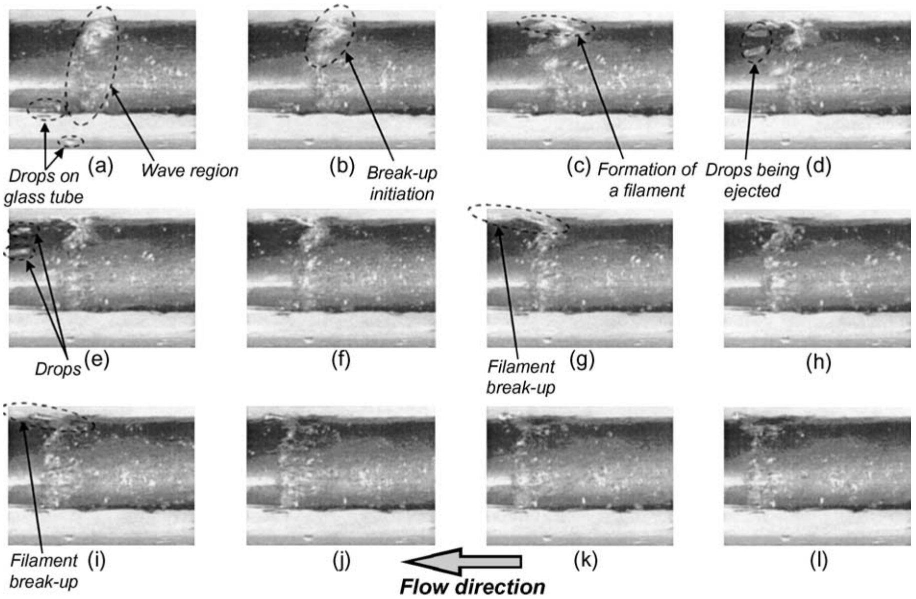

Fig. 5. Nucleation and droplet entrainment at a low film flow rate. Experimental conditions: $p_{\mathrm{in}} = 1.9$ bar, $\dot{m}_{\mathrm{T}} = 24.0\ \mathrm{kg\,m^{-2}\,s^{-1}}$, $X_{\mathrm{in}} = 0.87$, $\dot{q}_{\mathrm{w}} = 195.8\ \mathrm{kW\,m^{-2}}$.

Asali et al. [15], 610; Owen [16], 710; Azzopardi [17], 170. No disturbance waves were observed at Re_{LF} lower than that of the case illustrated in Fig. 5; it would seem that the correlation of Azzopardi [18] is the most consistent with the present results.

3.2. Nucleate boiling in liquid film

An increase in the wall heat flux leads to fully developed nucleate boiling in the liquid film. This is shown in Fig. 6. In this figure, one cannot identify the process of droplet entrainment from the disturbance wave. This is due to the creation (by drop deposition) of a thicker film of water on the glass tube. However, the presence of this film may, in itself, be an indication of enhancement of droplet entrainment at higher heat fluxes. There is also a significant increase in the number of active nucleation sites. From these frames, it is not possible to distinguish the wave-induced nucleation phenomenon. The time interval between consecutive frames is 3 ms.

An event which was observed in the moving video sequences (specially the 2000 frames per second runs) was that related to the enhancement of nucleation activity. At measured wall superheats characteristic of the onset of nucleate boiling (typically 10–12 K), it was observed that the bubbling frequency was increased under the wave region. Moreover, from the sets of pictures presented in Figs. 7 and 8, it can be seen that there are more active nucleation sites upstream of the disturbance wave than ahead of it. This is an indication that, locally, nucleation is being triggered off by the wave.

In Fig. 7, events such as the appearance of entrained droplets (frame 7a) and the reflection of light on the liquid film on the glass tube (seen in all frames, but pointed out in frame 7b) are depicted. The time interval between consecutive frames is 5 ms. In Fig. 8, the wave break-up phenomenon shown in Fig. 5 is again illustrated. The time interval is 3 ms.

There are several hypotheses which may explain the observed nucleation enhancement in the wave region:

1. *Reduction of heat transfer coefficient in the wave region.* Since the liquid film may be typically 5–6 times thicker in the wave region [18], if the flow were laminar in the waves, then this would imply a considerable decrease in heat transfer coefficient, a consequent increase in the wall temperature and an increased propensity to nucleation. However, modelling of disturbance waves using computation fluid dynamics (CFD) [19] indicates that, under the disturbance wave, the convective heat transfer coefficient was higher than in the is the substrate film between the waves. Thus, it was suggested that the disturbance waves were ‘packets’ of turbulence travelling over a laminar film substrate. This conclusion is supported by direct measurements of wall shear stress under the waves reported by Martin and Whalley [20] who found that peaks in wall shear stress occurred underneath disturbance waves which will be consistent with the hypothesis of a highly turbulent flow in the waves. In view of this computational and experimental evidence, it seems likely that the heat

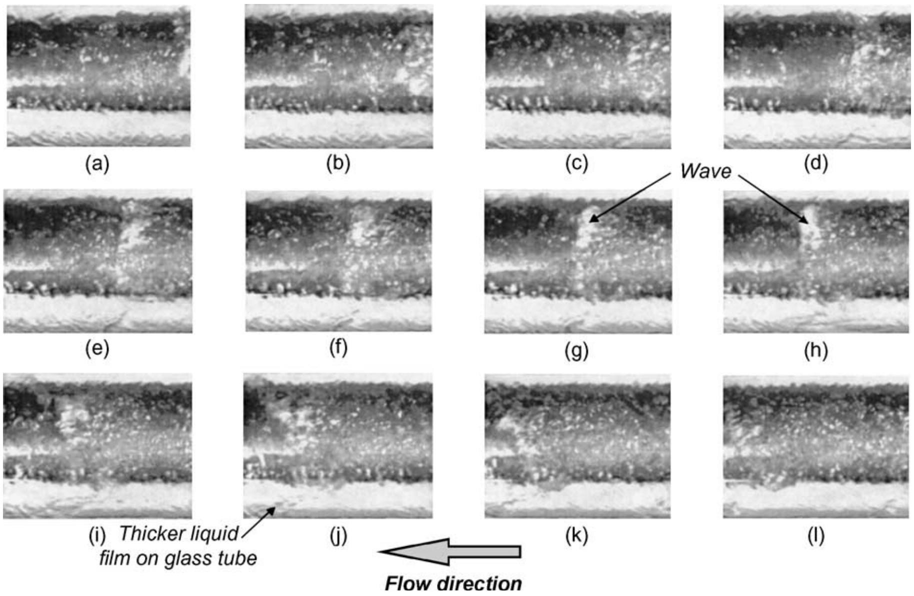

Fig. 6. Fully developed nucleate boiling in the liquid film. Experimental conditions: $p_{\text{in}} = 2.0$ bar, $\dot{m}_{\text{T}} = 30.2\ \text{kg}\,\text{m}^{-2}\,\text{s}^{-1}$, $X_{\text{in}} = 0.63$, $\dot{q}_{\text{w}} = 485.6\ \text{kW}\,\text{m}^{-2}$.

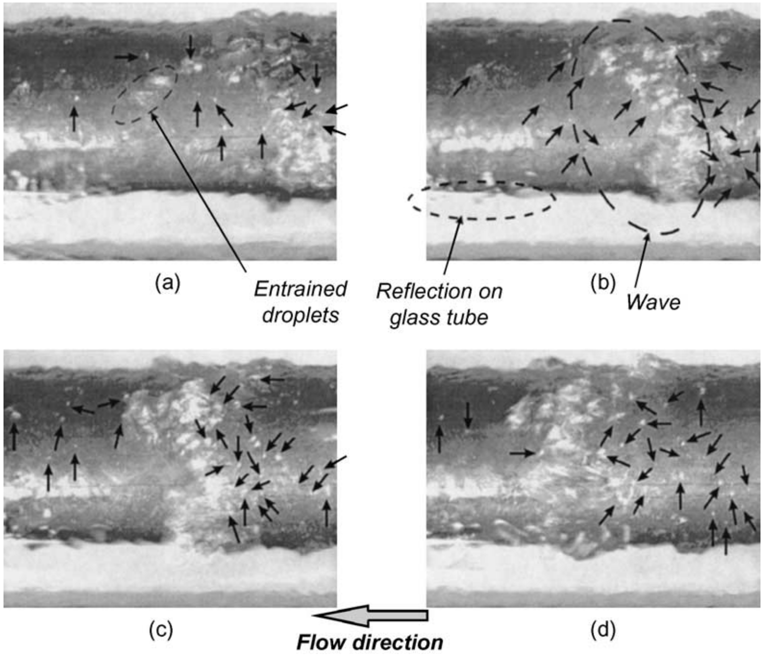

Fig. 7. Identification of active nucleation sites in the wave region. Experimental conditions: $p_{\text{in}} = 1.9$ bar, $\dot{m}_{\text{T}} = 30.2\ \text{kg}\,\text{m}^{-2}\,\text{s}^{-1}$, $X_{\text{in}} = 0.63$, $\dot{q}_{\text{w}} = 158.7\ \text{kW}\,\text{m}^{-2}$.

transfer coefficient will increase in the wave region, though there are no direct measurements to confirm this conclusion.

2. *Reduction of pressure in the wave region.* Because the gas contracts in order to flow over the wave, this implies a reduction in pressure in the wave region. One may associate this to a reduction in saturation temperature and an increased propensity to nucleation. Approximate calculations on the pressure change in passing from the substrate region to the wave peak

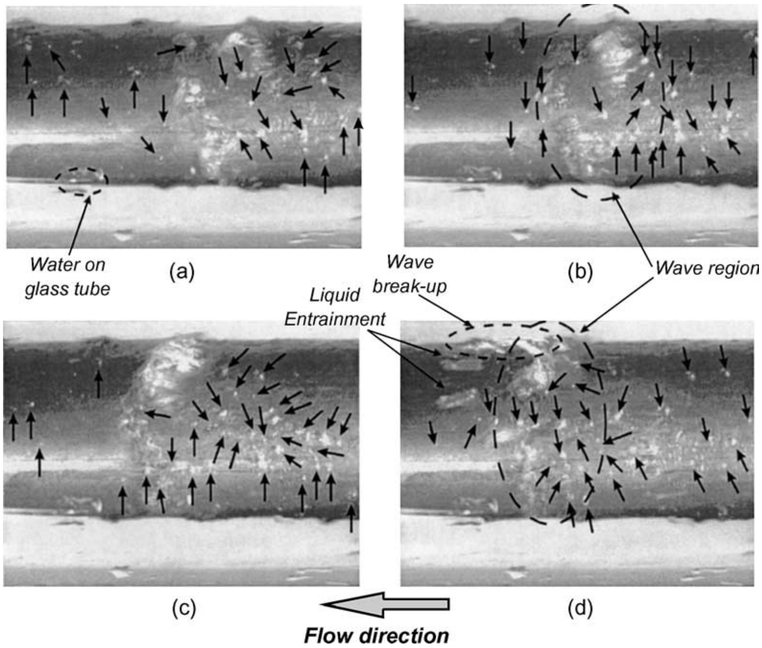

Fig. 8. Identification of active nucleation sites in the wave region. Experimental conditions: $p_{in} = 1.9$ bar, $\dot{m}_T = 24.0$ kg m^{-2} s^{-1}, $X_{in} = 0.87$, $\dot{q}_w = 195.8$ kW m^{-2}.

indicate a value of the order of 500 Pa for the present results. This corresponds to a small fraction of a degree in saturation temperature and so this explanation is unlikely to account for the transient increase in intensity of nucleation which is observed.

3. *Bubble entrainment in waves.* The highly disturbed motion of the interface in the wave region can give rise to the entrainment of small bubbles which may penetrate to the more highly superheated zone near the wall and trigger nucleation at existing centres there. The role of bubble entrainment in boiling in thin films has been discussed by, for instance, Mesler and co-workers [3,21]. One could hypothesise that bubbles attaching themselves to nucleation centres would grow and detach, leaving small super-critical bubbles remaining at the site. This process would continue but eventually die out.

The most likely explanation for the effect observed is that of bubble entrainment but it should be stated that no entrained bubbles were observed in the present experiments (though they may have been too small to have been seen). Clearly, more quantitative measurements are required to further elucidate this interesting phenomenon.

3.3. Wave characteristics

The video sequences were analysed to obtain information on the characteristics of the waves. However, the video sequences were generally too short to obtain accurate statistical data on the waves and the quantitative data is not reported here. Further details of these data are given by Barbosa [10]. The main qualitative observations were as follows:

1. *Frequency.* At a given point in the channel, the disturbance wave frequency decreased with increased heat flux. This reflects the decrease in film flow rate due to evaporation and is consistent, for instance, with the findings of Sawai et al. [22] who observed that the mean separation time (i.e., the time elapsed between the passing of two successive disturbance waves observed at a fixed distance) gradually increases as the the dryout region is approached, reflecting the reduction in film flow rate towards zero for dryout.
2. *Axial development of disturbance waves.* The wave frequency is seen to decrease with distance partly due to the film evaporation effect referred to above but also, near the entrance region, due to coalescence of waves as reported by Hall-Taylor and Neddermann [23]. No attempt has been made to separate out the two effects, though the wave coalescence phenomenon was observed in the absence of heat flux also.
3. *Wave velocity.* The measured waves velocities were in the range of 0.5–1.7 m/s, i.e. several times the mean film velocities but several times less than the gas velocities. These results are consistent with earlier findings on disturbance waves.

4. Conclusions

Boiling in annular flow has been successfully visualised using an annular test section, heated on the inside with a heated gas wall on the outside to allow detailed observation using high-speed video. The most important finding from the work has been to confirm earlier observations [5] that disturbance waves on the annular film tend to trigger nucleation. The most likely explanation for this effect is that micro bubbles are entrained in the disturbance waves and initiate (temporarily) nucleation from existing centres on the heated surface. However, further quantitative work on this interesting phenomenon needs to be done before the mechanism can be confirmed. Other observations regarding the disturbance waves on the film surface are briefly summarised (details are given in [10]) and are generally consistent with earlier observations in adiabatic air–water systems.

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