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Experimental Observations of Boiling and Flow Evolution in a Coiled Tube

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Abstract

A sequence of visually experimental observations was conducted to investigate the flow boiling and two-phase flow in a coiled tube. Different boiling modes and bubble dynamical evolutions were identified for better recognizing the phenomena and understanding the two-phase flow evolution and heat transfer mechanisms. The dissolved gases and remained vapor would serve as foreign nucleation sites, and together with the effect of buoyancy, centrifugal force and liquid flow, these also induce very different flow boiling nucleation, boiling modes, bubble dynamical behavior, and further the boiling heat transfer performance.

Bubbly flow, plug flow, slug flow, stratified/wavy flow and annular flow were observed during the boiling process in the coiled tube. Particularly the effects of flow reconstructing and thermal non-equilibrium release in the bends were noted and discussed with the physical understanding. Coupled with the effects of the buoyancy, centrifugal force and inertia or momentum ratio of the two fluids, the flow reconstructing and thermal non-equilibrium release effects have critical importance for flow pattern in the bends and flow evolution in next straight sections.

Key words: Coiled tube; Tube bend; Flow boiling, Visual observation; Bubble dynamics; Interface

1. Introduction

Tube and channel evaporators are widely employed in modern energy conversion and utilization systems of power systems, HVACR (Heating, Ventilation, Air Conditioning & Refrigeration) heat exchangers etc. In last 20 years for some high-tech applications, such as electronic cooling, there are increasingly urgent demands in high compactness and high .performance heat transfer enhancement technologies. In these heat transfer devices, evaporators and condensers are commonly involved and particularly considered as most important parts.

Generally, boiling heat transfer has excellent advantages of heat transfer rate, temperature uniformity and small temperature difference due to liquid-vapor phase-change. The convective boiling and two-phase flow in tubes/channels were comprehensively investigated as a classical topic of boiling heat transfer in open literature. Collier and Thome [1] depicted the typical flow patterns of flow boiling in a horizontal tube as bubbly flow, plug flow, slug flow, wavy flow and annular flow. In 1998, Kattan and Thome [2] developed an accurate flow pattern map for refrigerants under flow boiling condition. Lately, some modifications or new diabatic flow pattern maps were presented, which including the work of Wojtan [3] and Cheng [4].

There were also many efforts focusing on the prediction of the heat transfer of flow boiling. Kandlikar [5] presented a modified correlation for flow boiling in circular tubes with 5246 experimental data, covering working fluids of water, R11, R12, R13B1, N_2, NH_3, etc. Kew [6] presented the heat transfer coefficient correlation for R141b flowing through tubes 500mm long with diameters of 1.39-3.69mm. And a general correlation for flow boiling in tubes and annuli, for both horizontal and vertical ones, was developed by Gungor [7]. Particularly, many researchers paid their great attention to the investigations on flow boiling

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and heat transfer of different refrigerants and presented many new achievements [8-10]. Recently, many experimental and theoretical investigations were also conducted for flow boiling and associated two-phase flow under some special conditions, like in micro-channels [11], under microgravity [12], and in U-shape tube [13].

Besides the experimental and theoretical investigations, there were also many efforts focusing on numerical simulation models. Concerning the complexity of two-phase flow, none of the simulation models was suitable for all two-phase flow applications. However, two-fluid model was considered to be a promising method to acquire deeper understanding of two-phase flow. Some recent investigations were conducted by different researchers, including Lee [14], Luo [15], Hibiki [16], and Richard [17], etc.

As the physical nature is so complicated, basic phenomena and mechanisms of two-phase flow boiling and heat transfer are still far from full understanding. And meanwhile very limited work was done to investigate the flow boiling and liquid-vapor two-phase flow in coiled tubes or evaporators which are widely employed in current refrigerators and other compact phase change devices/systems.

Due to the shortage of appropriate guidance, present evaporators were usually designed with a larger profuse degree for safely operation, resulting in a long length and a high superheat. Understanding flow boiling in a coiled tube/channel could potentially decrease the cost of manufacture and energy consumption, and increase the efficiency of associated evaporators. For coiled tube evaporators, coiled geometry, especially tube bends are highly expected to have great influences on flow boiling, heat transfer performance, and two-phase flow pattern. In this paper, an experimental facility was built and experimental investigation was conducted to visually observe the flow boiling and liquid-vapor two-phase flow in a coiled circular tube.

2. Experimental description

The test facility built for flow boiling visualization is shown in Fig. 1, mainly consisting of a liquid tank, pump, flow meter, pre-heater, test section, filter, condenser, and two mixing chambers at the inlet and outlet of the test section, respectively. The whole dimension of the test facility was about 1.2m × 0.8m × 0.40m, established on a moveable base for the convenience of connection flexibility. The mixing chambers at the inlet and outlet were designed to suppress the cross-sectional non-uniformity of the flow due to the compactness of the test rig. The working fluid was circulated in a close loop. It was pumped from the tank, flowed through a flow meter with an estimated error of ±2.5 %, the pre-heater, the inlet mix chamber, and then entered the test section, where the working liquid was heated to the boiling point, and accordingly flow boiling nucleation and liquid-vapor two-phase flow were induced. Then it flowed out the test section to the outlet mixing chamber, passing through the filter, and was cooled and condensed in the condenser, and finally returned to the tank. The temperatures and pressures of the working fluid were measured at the inlet and outlet of the test section, and the uncertainties in measurements were estimated as ± 0.37 % and ±2.5 %, respectively. The pressure in the tank was monitored and maintained at a specified value. Flow patterns in the transparent test section were recorded by a high-speed CCD video system (at a speed of 50fps or much higher speeds dependent upon the experimental conditions) and transferred to a computer (PC) for further analysis.

The coiled tube as a test section with a horizontal layout was made of quartz glass, which has the characteristic of high temperature duration, low thermal expansion, highly transparence, as illustrated in Fig. 2. It consisted of 4 straight sections and 3 bends. The straight section had a length of 200 mm, and the 180° bend had a curvature radius of 50 mm, with the tube size of Φ10×1mm. The surfaces of the straight sections are coated with electric conducting metal oxide film. Copper connectors were used to well connect the straight sections with the bends, and at the same time, to provide electrodes for the electric conducting film connecting with an electric power supplier. The applied power of the coating film was adjusted with a

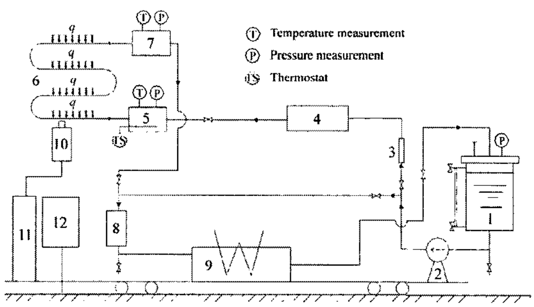


Fig. 1.Test facility.
1. Tank; 2. pump; 3. flow meter; 4. pre-heater; 5. pre-mixing chamber; 6. test section; 7. post-mixing chamber; 8. filter; 9. condenser; 10. CCD; 11. computer; 12. circuit controller

voltage regulator, and the uncertainty in heat flux reduction was estimated as ± 3 %.

Liquid R141b was employed as the working liquid, which has a relatively high boiling point of 34.5 °C. This refrigerant is corrosive to most rubber and would react with light metals. Considering compatibility, all the tubes in the loop were made of copper ($\Phi 10\times 1$). The tanks, pre-heater and mixing chambers were made of stainless steel, the pump (PA074 – V, made in Italy) made of cooper, and all joints were sealed with corrosion resistant materials, such as teflon, viton resin etc. Main operating parameters in the experiments are listed in Table 1.

The experiments were conducted under different conditions or at different applied heat fluxes and mass flow rates in the coiled tube shown in Fig. 2. The vapor quality at the outlet of the test tube was only 0.12, however, the experiments explored the fundamental phenomena and characteristics of the flow boiling and the liquid-vapor two-phase flow in this coiled tube evaporator very well. In the experiments, liquid temperatures, pressures and applied power were all measured. However, these measurements were not very accurate since the heat loss would be great and the inner wall temperature was very difficult to estimate for visually observation experiments. The attention is only paid to present the experimental observations and discussions of the boiling and associated two-phase flow phenomena.

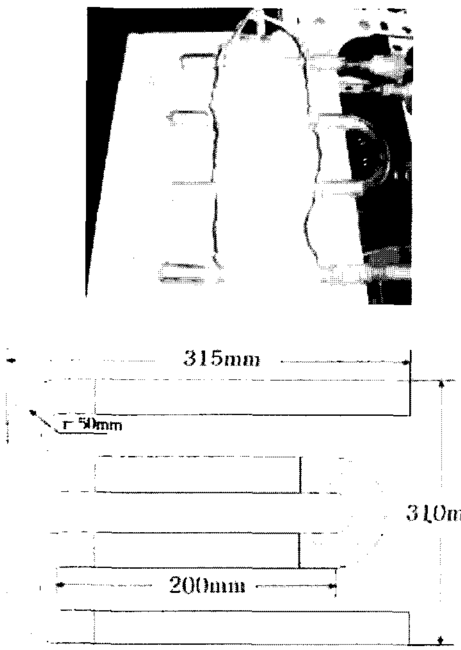


Fig. 2. Test section.

Table 1. Operating parameters.

Flow flux	Q=18, 15, 10 l/h
Voltage	U=5~85V
Heat flux	q''=0-15kW/m^2
Inlet temperature	T_{in}= 32°C
Outlet quality	x ~ 0.12

3. Boiling behavior

3.1 Nucleation

For a mass flow rate of 10 l/h, the nucleation of the flow boiling was initiated on the top inner surface near to the inlet of the first heating straight section at a heat flux of 2.03kW/m^2, and normal bubbles generated from the nucleation sites on the top centerline of the inner tube wall, as illustrated in Fig. 3. Here the nucleation exactly means that the first bubble generation occurred in whole coiled tube. Usually this site located on the top inner wall near to the inlet in the first heated straight tube, which was greatly dependent upon the test conditions, including inlet temperature or quality, mass flow-rate, and applied heat flux. After this first nucleation, the bubble moved to downstream with liquid flow along the top centerline and more nucleation followed in the top centerline zone downstream. Meanwhile bubbles emerged to form larger ones along the flow direction. In the outlet zone of the second heating section and the third heating

Fig. 3. Nucleation at 2.03 kW/m^2.

section some nucleation was observed on the inner tube surface not only at the top centerline. This might be the consequence that the liquid was heated to the saturation temperature along the tube, particularly flowed through one or two tube bends with very well mixing, which made the nucleation downstream more uniform occurring on the whole tube surface.

All experimental observations demonstrate that the nucleation would be easy to happen and firstly extend on the top center surface. Absolutely, there would be some foreign disturbances or nucleation catalysts existing in the top centerline zone. Highly expectedly, some non-condensable gas or remained vapor would be accumulated to the top centerline to serve as nucleation sites or catalysts. Normally liquid would have some dissolved gases. After the liquid flowed through the pre-heater and/or was heated in the inlet zone of the first heating straight section, part of the dissolved gases was degassed. Also probably, the air was not clearly exhausted as the system was filled with the working liquid. And some vapor might remain in the liquid after the test run. These gases and vapor were accumulated to the top centerline owing to the buoyancy and would induce the nucleation as observed.

As applied heat flux increased, boiling became more violent and nucleate boiling area extended to whole upper wall of the tube near to the inlet. Fig. 4 illustrates the image of the flow boiling near to the inlet of the first straight section at the applied heat flux of 3.83kW/m^2. Apparently, more nucleation sites on the upper wall surface were actuated to form bubbles. Bubbles obliquely moved towards to the top centerline along the inner surface and coalesced to large bubbles moving longitudinally forward with the working liquid flow.

Fig. 4. Nucleation at 3.83kW/m^2.

3.2 Boiling modes

The above-mentioned experimental phenomena were basically the nucleation, though different boiling regimes emerged to a certain extent. As applied heat flux increased further, the boiling would experience different modes. For the experiments at an applied heat flux greater than 5.63kW/m^2, the nucleation occurred and bubbles generated on almost whole inner surface. On the top wall bubbles grew very quickly, and meanwhile, these large bubbles further coalesced to form slugs with the bubbles from upstream zone and the lower wall of the tube. On lower wall surface of the tube, small bubbles were observed to form and string upward to the top to join larger bubbles or slugs. The bubbles generated on upper wall surface have large size than those generated on lower wall surface and usually smaller bubbles from lower surface formed larger ones. The typical CCD images are presented in Fig. 5.

When applied heat flux was increased greater than 8.82kW/m^2, bubbles formed from everywhere on the inner wall surface of the tube, and the nucleation was quite uniform and tempestuous. Fig. 6 illustrates several photos of typical boiling modes for these cases. Due to the existence of the buoyancy, many large

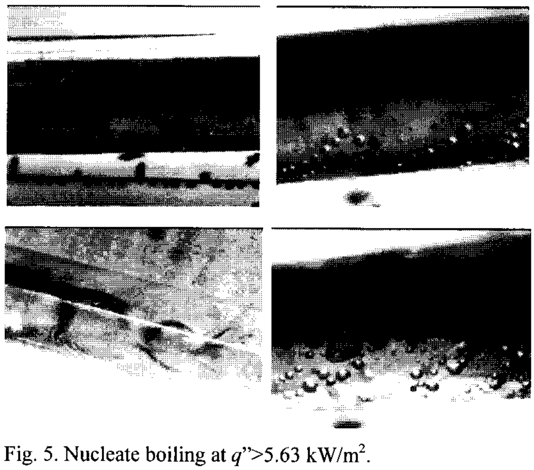


Fig. 5. Nucleate boiling at q''>5.63 kW/m^2.

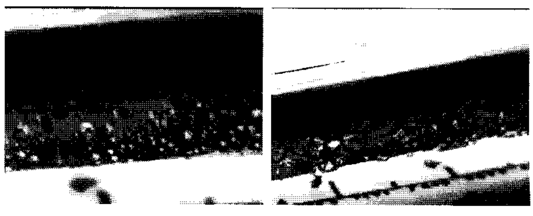


Fig. 6. Nucleate boiling at q''>8.82 kW/m^2.

bubbles or vapor slugs generally occupied the upper tube close and very few bubbles were observed to generate from the upper surface. As the void fraction became larger, the nucleate boiling downstream the tube converted to liquid film evaporation corresponding to slug, stratified and annual flow pattern.

From the experimental observations, flow boiling in a horizontal straight tube could be classified to different modes as applied heat flux increased, namely boiling nucleation (the case in Fig. 3), upper part boiling (Fig. 4), full nucleate boiling on the tube wall (upper large bubble boiling and lower small bubble boiling, corresponding to Fig. 5), upper film evaporation and lower part full nucleate boiling (some cases in Fig. 5), uniformly tempestuous nucleate boiling (Fig. 6). Identifying these different nucleate boiling modes and boiling phenomena is very helpful to recognize the heat transfer processes occurring locally and evolution along the tube, and to understand and flow boiling mechanisms in a coiled tube.

Along the flow direction, the mode evolution of the nucleate boiling was mainly dependent of the boiling intensity upstream. Usually, the boiling was very easy to evolve to the upper large bubble and lower small bubble boiling mode for lower applied heat fluxes, and upper film evaporation and lower nucleate boiling for higher applied heat fluxes. For the latter the lower nucleate boiling would be very violent or tempestuous for a very high applied heat flux and is corresponding to stratified or upper slug flow pattern.

3.3 Bubble dynamical behavior

During flow boiling in the coiled tube, bubble dynamical evolution displayed some difference from each other for each boiling mode and along the tube. At the top centerline, bubble generated and grew up coalescing with the bubbles generating downstream while it moved forward. This kind of bubble dynamical behavior can be clearly observed from Figs. 3 and 4, and greatly altered the nucleation at the top centerline downstream.

For both upper and lower part nucleate boiling, bubbles generated on the surface and spirally moved with the liquid flow along the surface to the top centerline. Quite a few of bubble were observed to depart from the surface and coalesced with other bubbles at the top centerline, see Figs. 4 and 5. Only for the cases of very low liquid flow rates, bubble departure was observed and bubbles vertically departed from the bottom surface, as illustrated in Fig. 7. During their moving, the bubbles grew up by absorbing many nucleation sites and embryo bubbles, and also coalesced with other bubbles along the surface. This bubble dynamical evolution significantly made the change of the nucleation and dominated the boiling heat transfer of these surface areas. Normally the bubble movement would destroy the nucleation sites absorbing and coalescing with them or actuated the nucleation sites remaining or filling with the vapor as the bubbles passed. As a result, the boiling heat transfer was dominantly dependent upon the nucleation and bubble dynamical behavior.

For the modes of the upper film evaporation and lower nucleate boiling (Fig. 5) and tempestuous nucleate boiling (Fig. 6), bubbles on the surface were very violent and similar to usual cases. However, some attention should be paid to the bubble dynamical behavior close to or at the stratified liquid-vapor interface. These large bubbles grew up or evolved fast, including very complicated and strong interactions, such as bubble coalescing, bubble interaction, and the interaction of bubbles with the stratified interface, which induced very significant consequence on the stratified interface, and even violently influenced the whole flow pattern, as shown in Fig. 8. Furthermore, this violent nucleate boiling stratified flow pattern is not similar to the usual stratified two-phase flow and wavy interface. The flow exhibited highly violent transient behavior and the heat transfer would be greatly enhanced. More experimental information is necessary to understand and describe this nucleate boiling and associated flow.

Fig. 7. Bubble departure at low liquid flow rate.

(a) 0s (b) 0.002s (c) 0.004s

Fig. 8. Bubble evolution at the stratified interface. (q">8.82 kW/m^2)

4. Flow characteristics

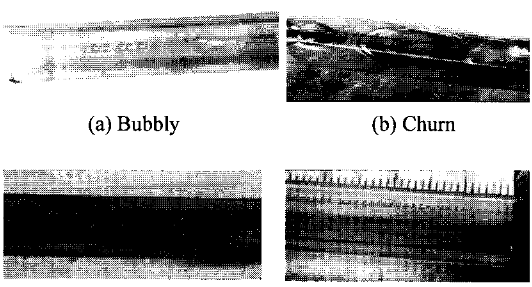
4.1 Flow pattern in straight tube

The flow regimes underwent bubbly flow, churn flow, slug flow, stratified or wavy flow while the flow advanced along the heated coiled tube, as shown in Figure 9(a)-(d). The bubbly flow was characterized by discrete bubbles forming and distributing in the flow. At the beginning of the boiling, bubbles usually generated at the top sites of the tube as discussed above. As the bubbles went downstream, it seemed that they chased one by one. As being heated, the bubbles grew very quickly and combined to form slugs as shown in Figs. 3 and 10, a snatch of a video recording the initial flow boiling process, including the bubble formation, combination and aggregation.

The slug flow was named because the vapor phase was shaped as long slugs, and was separated by liquid phase, which also shaped as slugs, as in Fig. 9(c). They alternatively appeared in the specified view field. Between the bubbly flow and the slug flow, there was a stage that the distribution of liquid and vapor phases was instable, with the tiny bubbles and large slugs coexisting but varying instantaneously. Here it is termed as "churn flow", see Fig. 9(b).

After the 2nd or 3rd bend, the flow exhibited a typical stratified pattern. Vapor occupied the upper part of the tube, and liquid the lower, see Fig. 9(d). An interface appeared between the two phases. This is termed as the stratified flow. Sometimes the interface showed very fluctuating and hence is termed as the wave flow here. As noted in previous section, the stratified liquid-vapor interface was very violently fluctuated at high applied heat fluxes and the boiling in the liquid zone was very intense and entirely full violent bubbly flow. Apparently, a careful attention should be paid to discuss this kind stratified two-phase flow.

The annular flow was reported in literature for flow boiling both in horizontal or vertical tubes. Therefore though it was not observed in the present experiments, it would probably present at a higher quality in coiled tubes.



(a) Bubbly (b) Churn

(c) Slug (d) Stratified (wavy)

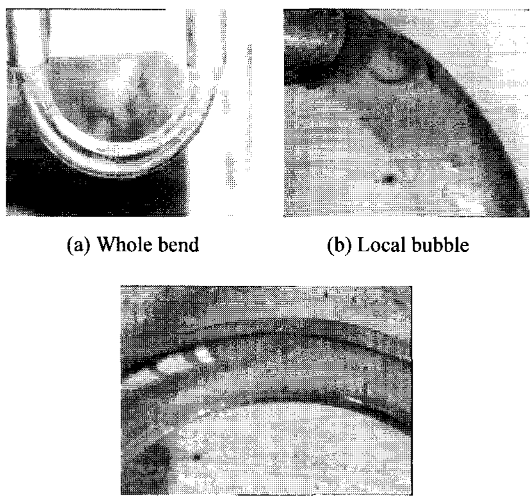
Fig. 9. Typical liquid-vapor flow regimes in the coiled tube.

Fig. 10. Initial flow boiling and flow pattern.

4.2 Flow in Bends

The unheated bend regions were of special interest in this investigation. In these regions secondary flow and particular flow patterns might be expected if the buoyancy, centrifugal force and inertial effect are considered, and may have important influence on the downstream flow and heat transfer characteristics. Fig. 11 presents some video images of bubble/slug transport in the bends.

For such a horizontal layout of the test section, vapor consequentially gathered upward due to the density difference of liquid and vapor, and hence the body force. Besides, there was another important bend causing the vapor to gather toward the inner



(a) Whole bend (b) Local bubble

(c) Bubble slug

Fig. 11. Flow reconstructing in the unheated bend region.

factor, the centrifugal force due to the curvature of the upper part of the bend. The higher the mean velocity was, the more obvious this phenomenon was. However, when the vapor fraction was higher and had flow momentum, the vapor flow was also observed along the outside of the tube bends, and vapor flow was like a jet flow from the straight section, as shown in Fig. 11(c). For this case, another, probably the most important parameter would be the ratio of the liquid momentum and vapor momentum. These flow phenomena in the bends were the coupled effect of buoyancy, centrifugal force and momentum ratio of the two phases.

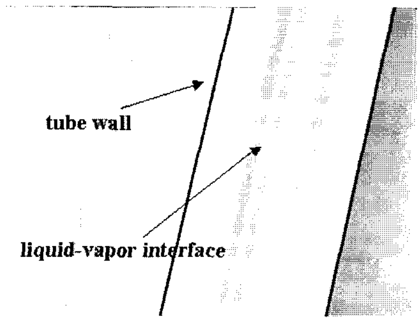
At the connect location between the straight section and the bend, accumulation of vapor was commonly observed. The accumulated vapor usually released at intervals ranging about 0.3~2s. The interval was highly dependent upon the local quality and the void fraction. This means that the two-phase flow through the bends without heating might have the variation of flow behavior. Actually, because of the vapor gathering upward and inward in the bend, and the vapor accumulation and released at the connectors, the flow pattern in the bend was changed more or less from the upstream pattern. This phenomenon is herein referred to the "flow reconstructing" effect of the unheated bend. In the experiments, this flow reconstructing effect was frequently observed and significantly altered the flow pattern downstream or next straight section.

In the present experiments, some bubbles and slugs were also observed shrunk or changed with their size and even collapsed as the two-phase flow passed through the bends. This is, in fact, another important effect, or thermal non-equilibrium release (or accumulation) for the boiling two-phase flow in the bends. When the flow passed the straight sections of the coiled tube with heating, the liquid or vapor was partially or locally superheated, which is a usual situation for flow boiling. As the flow entered into the bends without heating, the liquid and vapor were very well mixed with each other, at least partially due to the flow reconstructing effect, and cooling and heating would take place for them, which caused the release (or accumulation) of the thermal non-equilibrium existing in both the liquid and vapor. The release effect of thermal non-equilibrium actually contributed a lot to the flow reconstructing in the bends. However, for this non-equilibrium issue it is very difficult to determine its real or exact contribution.

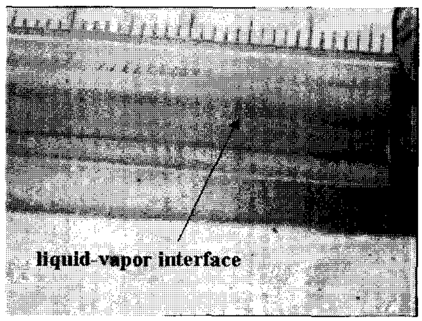
4.3 Effect of parameters on the flow

In the experiments, some primary operating parameters, such as heat power input and mass flow-rate, were changed to investigate their influences on the flow boiling and two-phase flow pattern in the coiled tube. Increasing the heat power input made the formation of bubbles taking place earlier. Similar phenomena were also observed when decreasing the flow rate. Higher heat power input also resulted in a faster growing rate and transporting velocity of bubbles. Consequently, the transitions of flow regime are relatively earlier, or the locations of transition were closer to the inlet of the test section.

Furthermore, the higher heat power input and lower mass flow-rate also caused a more violent turbulence. Fig. 12 compares the two video images of the liquid-vapor interfacial turbulence with the heat power input at an electric voltage of 24V and 50V, respectively. From the video images, the interfacial turbulence was obviously increases with the heat power input increasing. Fig. 8 shows the same influence on the wavy interface.



(b) 24V



(b) 50V

Fig. 12. Interfacial turbulence increasing with the heat power input.

6. Conclusions

An experimental observation was conducted to investigate the flow boiling and two-phase flow in a coiled tube. The boiling regimes and flow patterns were observed under different test conditions, different heat fluxes ranging from 0-9.0kW/m^2, different flow rates and appropriate inlet and outlet qualities.

The characteristics of the boiling nucleation, boiling modes and bubble dynamics were all described with discussions for the flow boiling in the coiled tube. Different boiling modes and bubble dynamical evolutions were identified for better recognizing the phenomena and understanding the two-phase flow evolution and the heat transfer mechanisms. The dissolved gases and remained vapor would serve as foreign nucleation sites and induced very different flow boiling nucleation, boiling modes and bubble dynamical behavior, and boiling heat transfer performance.

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