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Transient oscillatory saturated flow boiling heat transfer and associated bubble characteristics of FC-72 over a small heated plate due to heat flux oscillation

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ABSTRACT

An experiment is carried out here to investigate the transient oscillatory boiling heat transfer and associated bubble characteristics of FC-72 flow over a small circular plate subject to a time varying heat flux with the plate flush mounted on the bottom of a horizontal rectangular channel. At the inlet the flow is maintained at saturated liquid state with zero vapor quality. The imposed heat flux oscillates periodically with time in the form of rectangular waves. In the experiment the FC-72 mass flux G varies from 300 to 400 kg/m^2 s, mean imposed heat flux $\bar{q}$ ranges from 0 to 10 W/cm^2 and the amplitude of the heat flux oscillation Δq is fixed at 10–50% of $\bar{q}$ with the period of the heat flux oscillation varied from 10 to 30 s. The experimental results show that the time-averaging FC-72 oscillatory boiling heat transfer characteristics resemble that for stable flow boiling. However, the imposed heat flux oscillation causes significant temporal oscillations in the heated plate temperature, boiling heat transfer coefficient, bubble departure diameter and frequency, and active nucleation site density. These physical quantities oscillate at the same frequency as the heat flux oscillation and at a higher $\bar{q}$, a larger $\Delta q/\bar{q}$, and a longer t_p they exhibit stronger oscillations. Besides, a slight time lag in T_w oscillation is seen. Moreover, the size of departing bubbles, active nucleation site density and bubble departure frequency decrease as the heat flux is reduced to the low level of $\bar{q} - \Delta q$. The opposite processes take place for the heat flux raised to the high level of $\bar{q} + \Delta q$. Furthermore, at the mean imposed heat flux close to that for the ONB in the stable boiling we observe intermittent boiling in the flow. A regime map is provided to delineate the boundaries among single-phase liquid flow, intermittent boiling and persistent boiling.

1. Introduction

With continuing significant progress in IC (integrated circuit) technology, the IC chips are currently designed to be relatively light, thin, short, and small to enhance their performance. As the electronic equipments become rather small, the power dissipation density in them increases substantially. It is also well known that the IC junction temperature must be kept under 85 °C to maintain normal operation [1]. Recently, the direct liquid cooled method accompanying with boiling of forced flowing liquid is known to be capable of rapidly removing high power dissipation in advanced CPU because of the latent heat exchange involved. Moreover, the power dissipation in IC chips is often time dependent in practical operation. Therefore the heat removal rate must be varied in time to meet the required time varying cooling load. However, the transient flow boiling heat transfer subject to a time varying heating remains largely unexplored. Therefore, the transient oscillatory flow boiling of dielectric liquids, which is normally used in electronics cooling, resulting from a temporally varying heat load needs to be explored.

Over the past transient single-phase channel-flow forced convection heat transfer has received some attention. Girault and Petit [2] investigated heat transfer in a horizontal plane channel with different time varying imposed heat fluxes on the channel walls. During the power-on both the top and bottom plate temperatures were found to vary smoothly. But there is a noticeable wall temperature oscillation for the power-off situation, which is considered to result from the time variation of the internal energy stored in the channel walls. Bhowmik and Tou [3] experimentally studied transient FC-72 forced convection heat transfer from a four-in-line chip module in a vertical rectangular channel. The Reynolds number based on the heat source length ranges from 800 to 2,625 for the heat flux varying from 1 to 7 W/cm^2. Their data suggest that the transient characteristics of the overall heat transfer coefficient are important during the power-on and power-off periods. In a similar experiment [4] for an array of 4×1 chips using water as the working fluid, the Nusselt numbers associated with the four chips at the beginning of the power-off period were noted to be close but then they diverged with time. However, the Nusselt

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Nomenclature

A_{cp}	surface area of copper plate (m^2)
Bo	boiling number $Bo = \bar{q}/G \cdot i_{fg}$
d_p	mean bubble departure diameter (μm)
D_h	hydraulic diameter of rectangular-channel (m)
D_p	diameter of copper plate (m)
f	mean bubble departure frequency (1/s)
g	acceleration due to gravity (m/s^2)
G	mass flux (kg/m^2 s)
$h_{1\varphi}$	single-phase liquid convection heat transfer coefficient (W/m^2 K)
$h_{2\varphi}$	boiling heat transfer coefficient (W/m^2 K)
H	a dimensionless function $Re_L^{0.5} \cdot (\Delta q/\bar{q})^{0.5} \cdot (t_p/t_c)$
i_{fg}	enthalpy of vaporization (J/kg K)
I	measured current from DC power supply (A)
k_L	liquid thermal conductivity (W/m K)
L	characteristic length(diameter of copper plate) (mm)
N_{ac}	active nucleation site density (n/m^2)
$\overline{Nu}_L$	average Nusselt number based on copper plate diameter $h_{1\varphi} \cdot D_p/k_L$
q	instantaneous imposed heat flux (W/cm^2)
$\bar{q}$	time-average imposed heat flux (W/cm^2)
$\bar{q}_{\mathrm{ONB}}$	time-average heat flux at ONB (W/cm^2)
Q_n	net power input (W)
Q_t	total power input (W)
Re_L	liquid Reynolds number based on copper plate diameter, $G \cdot D_p/\mu_L$
t	time (s)
t_c	time constant (s)
t_l	time lag (s)
t_p	heating period (s)
t_0	time instant at beginning of a periodic cycle (s)
t_1, t_2, t_3	time scales (s)
T_{in}	temperature of FC-72 at test section inlet (°C)
T_{sat}	saturated temperature (°C)
T_w	temperature of heated wall for copper plate (°C)
V	measured voltage from DC power supply (V)
Greek symbols	
α_w	thermal diffusivity of copper (m^2/s)
Δq	amplitude of heat flux oscillation (W/cm^2)
ΔT_w	amplitude of heated plate temperature oscillation (°C)
μ_L	liquid dynamic viscosity of FC-72 (Ns/m^2)
ρ_l	liquid density of FC-72 (kg/m^3)
ρ_v	gas density of FC-72 (kg/m^3)
σ	surface tension (N/m)

numbers increase with time, due to the chip wall temperatures decrease with time.

It is also noted that several studies have been conducted for the transient flow boiling. Kataoka et al. [5] examined transient flow boiling of water over a platinum wire subject to an exponentially increasing heat input. The wire diameter and length vary respectively from 0.8 to 1.5 mm and from 3.93 to 10.4 cm. Two types of transient boiling were observed. In A-type (heating period of 20 ms, 50 ms, or 10 s), the transient critical heat flux increases at decreasing period for constant flow velocity. While in B-type (heating period of 5 ms, 10 ms, or 14 ms), the transient maximum heat flux decreases first with the period and then increases. Two-phase flow and heat transfer of R-141b in a small tube of 1 mm in internal diameter were studied by Lin et al. [6]. At a high heat flux input, significant fluctuation in the wall temperature can occur. This was attributed to a combination of time varying heat transfer coefficient and time varying local pressure and fluid saturation temperature. Two-phase flow instability in the flow boiling of various liquids in a long heated channel has been recognized for several decades [7,8]. Under certain operating condition significant temporal oscillations in pressure, temperature, mass flux and boiling onset were noted. Recently, some detailed characteristics associated with these instabilities were explored. Specifically in flow boiling of refrigerant R-11 in a vertical channel, the pressure-drop and thermal oscillations were observed by Kakac et al. [9]. Two-phase homogeneous model was used to predict the condition leading to the thermal oscillation. And their predicted periods and amplitudes of the oscillations well agree with their measured data. Kakac and his colleagues [10] further noted the presence of the density wave oscillation superimposed on the pressure-drop oscillation. In a continuing study for R-11 flow in a horizontal tube of 106 cm long, Ding et al. [11] examined the dependence of the oscillation amplitude and period on the system parameters and located the boundary of various types of oscillations. A similar experimental study was carried out by Comakli et al. [12] for a longer tube. They showed that the channel length had an important effect on the two-phase flow dynamic instabilities.

The dynamic behavior associated with a horizontal boiling channel connected with a surge tank for liquid supply has also received some attention. Mawasha and Gross [13] used a constitutive model containing a cubic nonlinearity combined with a homogeneous two-phase flow model to simulate the pressure-drop oscillation. Their prediction matched with measured data. Later, the channel wall capacity effect was included [14] in their analysis to allow the wall temperature and heat transfer coefficient to vary with time. Brutin et al. [15] reported the pressure-drop oscillations of n-pentane liquid in a vertical small rectangular channel (D_h = 0.889 mm, L = 50 & 200 mm). A non-stationary state of two-phase flow was observed. The effects of the inlet flow conditions on the boiling instabilities were found to be relatively significant [16].

The above literature review clearly indicates that the detailed characteristics of the transient oscillatory flow boiling of dielectric liquids resulting from time varying heat input are still poorly understood. In an initial attempt, an experimental study is carried out here to investigate how a controlled imposed heat flux oscillation in the form of rectangular waves affects the time oscillatory boiling heat transfer and associated bubble characteristics of a saturated FC-72 liquid flow over a small heated circular plate.

2. Experimental apparatus and procedures

The experimental system used in this study to explore the transient oscillatory flow boiling heat transfer and associated bubble characteristics of FC-72 over a small heated copper plate is schematically shown in Fig. 1, which is modified slightly from that employed in the previous study [17]. This system includes four major parts, namely, a degassing unit, a coolant loop, a hot-water loop, and a cold water loop. The liquid coolant FC-72 is driven by a gear pump and the inlet temperature of the coolant is regulated by a pre-heater with a hot water circulation in it. The coolant vapor generated from FC-72 boiling in the test section is then condensed in a condenser which is cooled by another water thermostat and then returns to a receiver. The test section mainly consists of a cir-

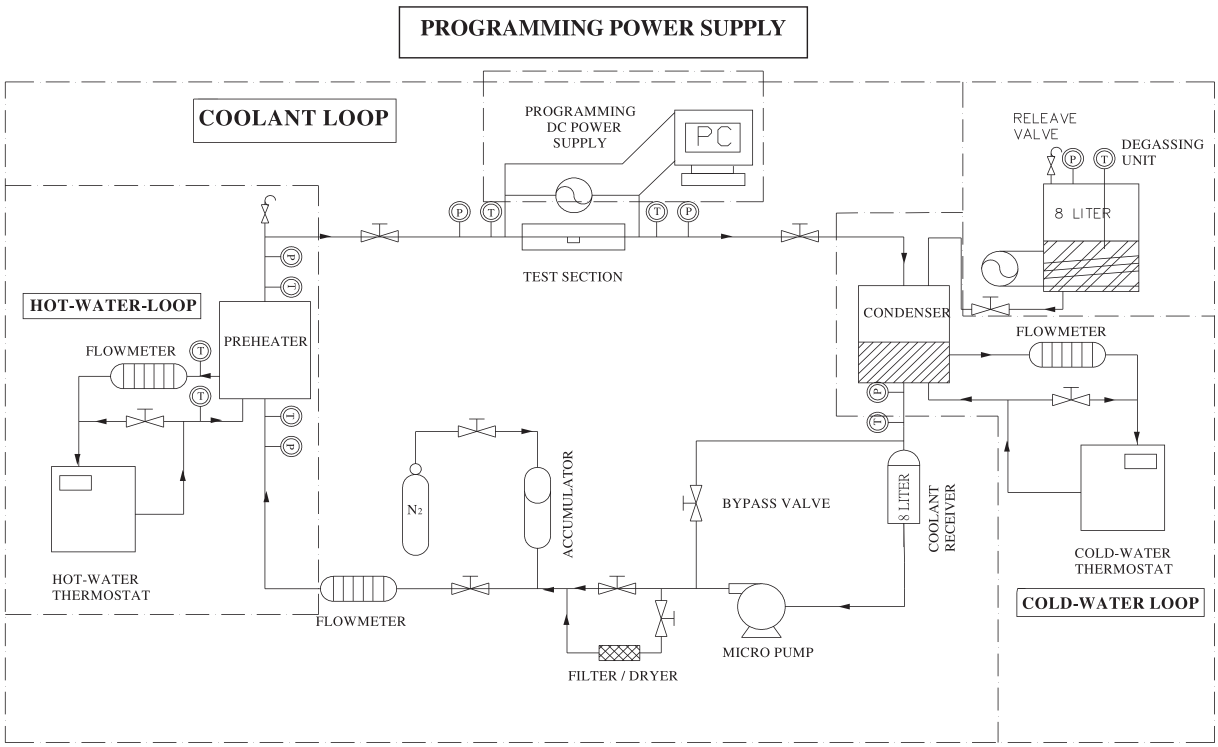

Fig. 1. Schematic diagram of experimental apparatus.

cular copper plate flush mounted on the bottom of a horizontal rectangular channel. The rectangular flow-channel includes a gradually diverging inlet section, the main test section, and a gradually converging exit section. They are all made of stainless steel plate. The installation of the inlet and exit sections intends to avoid sudden change in the cross section of the channel. The test section is 20 mm in width, 5 mm in height, and 150 mm in length. The heated plate is placed around the geometric center of the bottom plate of the test section. A ladder-shaped acrylic window is installed on the upper lid of the test section right above the heated plate. The temperature and pressure of the FC-72 flow at the inlet and exit of the test section are measured by calibrated thermocouples and pressure transducers. The copper plate module (Fig. 2) consists of a hollow cylindrical Teflon block, a cylindrical Teflon bolt, a copper plate, two mica plates, a Teflon plate, and an electric-heater. The diameter of the copper plate is 10 mm and the plate is 2 mm thick and is heated by passing DC current through the electric-heater. Besides, three thermocouples are fixed at the back surface of the copper plate to estimate the temperature of the upper surface of the copper plate and another two thermocouples are fixed at the top and bottom surface of the electric-heater to measure their surface temperatures. The mica plates are placed between the heater and copper plate and between the heater and Teflon plate, intending to prevent the leaking of the DC current to the copper plate.

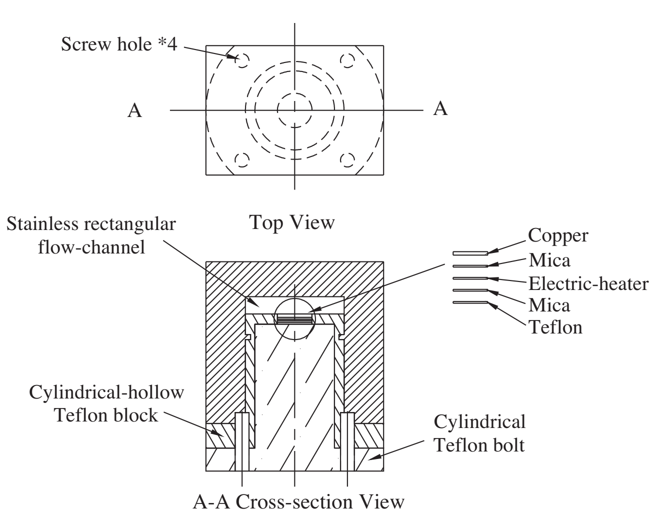

Fig. 2. Schematics of the copper plate module.

In each transient oscillatory flow boiling experiment, the liquid FC-72 in the coolant container is degassed first. Besides, the non-condensable gases in the coolant loop are evacuated and the liquid FC-72 is filled into the loop. Then, we turn on the controller for setting the required rotation rate of the AC motor to regulate the FC-72 flow rate. Next, the temperature and flow rate in the hot-water loop are adjusted so that the liquid FC-72 temperature at the test section inlet can be maintained at a preset level. The heat flux imposed to the coolant in the test section is provided by a programmable DC power supply. The programmable power supply allows us to impose the required temporal heat flux oscillation in the form of rectangular waves. In addition, we can calculate the heat transfer rate to the coolant by measuring the voltage across the electric-heater and the current delivered to the electric-heater. Temperature and flow rate of the cold water in the cold-water loop can be adjusted to condense and subcool the liquid-vapor mixture of FC-72 from the test section. Meanwhile, we regulate the FC-72 pressure at the test section inlet by adjusting the gate valve locating right after the outlet of the test section. All measurements proceed when the experimental system has reached statistical state. Finally, the scanning rate for each data channel is chosen to be 2 Hz and all the data channels are scanned for a period of 180 s.

3. Data reduction

First, the net power input Q_n to FC-72 flowing over the copper plate is evaluated from the difference between the total power input Q_t from the electric heater and the total heat loss from the heater assembly Q_{loss}. Here the total power input can be calculated from the measured voltage drop across and electric current passing through the electric-heater, $Q_t = I \times V$. Then, the total heat loss from the heater assembly can be approximately estimated by accounting for the radial conduction heat transfer from the copper plate to the cylindrical Teflon block and downward heat conduction from the electric heater to bottom Teflon plate or by convection from the test section to the ambient. Here we adopt the former measure to evaluate the heat loss. The net imposed heat flux at the copper plate surface is defined as

$$q = Q_n/A_{cp} \tag{1}$$

where A_{cp} is the surface area of the copper plate. The average single-phase liquid convection heat transfer coefficient over the copper plate is defined as

$$h_{1\phi} = \frac{Q_n}{A_{cp} \cdot (T_w - T_{in})} \tag{2}$$

where T_{in} is the coolant temperature at the inlet of the test section and T_w is the space-average temperature of the upper surface of the copper plate. Besides, the average boiling heat transfer coefficient for the coolant flow over the copper plate is defined as

$$h_{2\phi} = \frac{Q_n}{A_{cp} \cdot (T_w - T_{sat})} \tag{3}$$

Note that the above definitions for single-phase convection and boiling heat transfer coefficients are usually adopted in steady heat transfer research. They are also employed here for the transient oscillatory boiling heat transfer investigation with Q_t and Q_n evaluated from the measured instantaneous values for V and I and the measured instantaneous temperature data at selected locations. Uncertainties of the single-phase liquid convection and flow boiling heat transfer coefficients and other parameters are estimated by the procedures proposed by Kline and McClintock [18]. The detailed results from this estimation show that uncertainties of the dimension, temperature, pressure, mass flux, mean imposed heat flux, period of q oscillation, amplitude of q oscillation, and boiling heat transfer coefficient measurements are less than ±0.5%, ±0.2 °C, ±2 kPa, ±3%, ±2.1%, ±0.25 s, ±0.3% and ±12.3%, respectively.

4. Results and discussion

The present experiments are conducted for the FC-72 mass flux G fixed at 300 and 400 kg/m^2 s for the time-average imposed heat flux $\bar{q}$ varied from 0.1 to 10 W/cm^2. Besides, the amplitude of the heat flux oscillation Δq is set at 10, 30 and 50% of the average heat flux. In addition, the period of the heat flux oscillation t_p is fixed at 10, 20 and 30 s. The coolant FC-72 in the test section is at a slightly subatmospheric pressure of 99 kPa with T_{sat} = 55 °C. Moreover, at the test section inlet the FC-72 flow is kept at completely saturated liquid state with no vapor present. In the following the heat transfer performance is presented mainly in terms of the time variations of the space-average surface temperature of the copper plate and the space-average boiling heat transfer coefficient. The effects of the experimental parameters including $G, \bar{q}, \Delta q/\bar{q}$, and t_p on the transient oscillatory FC-72 flow boiling heat transfer performance will be examined in detail.

In this study of transient oscillatory flow boiling of FC-72 resulting from the heat flux oscillation, several relevant time scales need to be understood at first. The conduction time scale t_1 is estimated by considering a slab of the characteristic length L_c (thickness) subject to a constant heat input at one of its surface at certain time instant and t_1 is the duration for the other surface to begin to feel the heat input [19]. According to the thermal diffusion speed, $t_1 \approx L_c^2/\alpha_w$. For the present copper plate $t_1 \approx 0.034$ s. Next, the convection time scale t_2 can be estimated by the equation $t_2 = D_h/(G/\rho_l)$[20]. In the present test, t_2 varies from 0.04 to 0.055 s. Then, the time scale for bubble growth or departure t_3 can be approximated by $d_p/\left[\frac{\sigma g(\rho l - \rho v)}{\rho_l^2}\right]^{\frac{1}{4}}$ [21]. Here t_3 varies from 0.0013 to 0.0028 s. Finally, the time constant of the present flow boiling over the copper plate t_c is obtained directly by measuring the time response of T_w subject to a step change in the imposed heat flux for various G and $\bar{q}$. The measured data indicate that the time constant associated with flow boiling investigated here ranges from 13 to 20 s which is known to mainly results from thermal inertia of the copper plate. The precise value of t_c was found to mainly depend on the imposed coolant mas flux. Thus t_c is much larger than the other time scales and hence dominates the time response of the copper plate subject to the time dependent imposed heat flux. Note that the oscillation period of q chosen above is at the same order as t_c.

Before beginning the unsteady boiling tests, the corresponding steady single-phase convective heat transfer coefficients for liquid FC-72 flow are measured for constant G and q, intending to check the suitability of the experimental system for the present boiling experiments. The measured data are compared with the correlation proposed by Gersey and Mudawar [22]. Their correlation is based on the experimental data procured from the same liquid and same flow configuration as the present study and the comparison is shown in Fig. 3 for the dimensional and dimensionless heat transfer coefficients. The results show that our data are in good agreement with their correlation. Because of lack of unsteady turbulent forced convection heat transfer data in the open literature, direct validation of the present time periodic liquid heat transfer data is not possible.

4.1. Stable and time-average flow boiling heat transfer

The time-average data deduced from the present transient oscillatory flow boiling heat transfer experiments for various amplitudes and periods of the heat flux oscillation are compared with that from the stable flow boiling in which the imposed heat flux does not vary with time. The results from the comparison show that the time-average boiling curves and boiling heat transfer coefficients are not noticeably affected by the amplitude and period of the heat flux oscillation. In fact, they are nearly the same as that for the stable boiling.

4.2. Transient oscillatory flow boiling heat transfer characteristics

The transient oscillatory boiling heat transfer characteristics for the FC-72 flow over the heated copper plate resulting from the imposed temporal heat flux oscillation are illustrated by presenting the effects of the experimental parameters on the time variations of the space-average heated surface temperature T_w and boiling heat transfer coefficient $h_{2\phi}$ at the statistical state. The results given in Fig. 4 for $G = 300\text{kg/m}^2\text{s}, \Delta q/\bar{q} = \pm 10\%$ and t_p = 10 s indicate that significant temporal oscillations in the space-average heated surface temperature occur even at a small amplitude of the heat flux oscillation with $\Delta q/\bar{q} = \pm 10\%$ for various $\bar{q}$ at t_p = 10 s. For clear presentation the imposed heat flux oscillation is also shown in the figure. Due to the thermal inertia of the heated plate a small but finite amount of time is needed for the heat flux to change from the two different levels and we have slightly imperfect rectangular waves. Note that the resulting temporal oscillation of T_w is more or

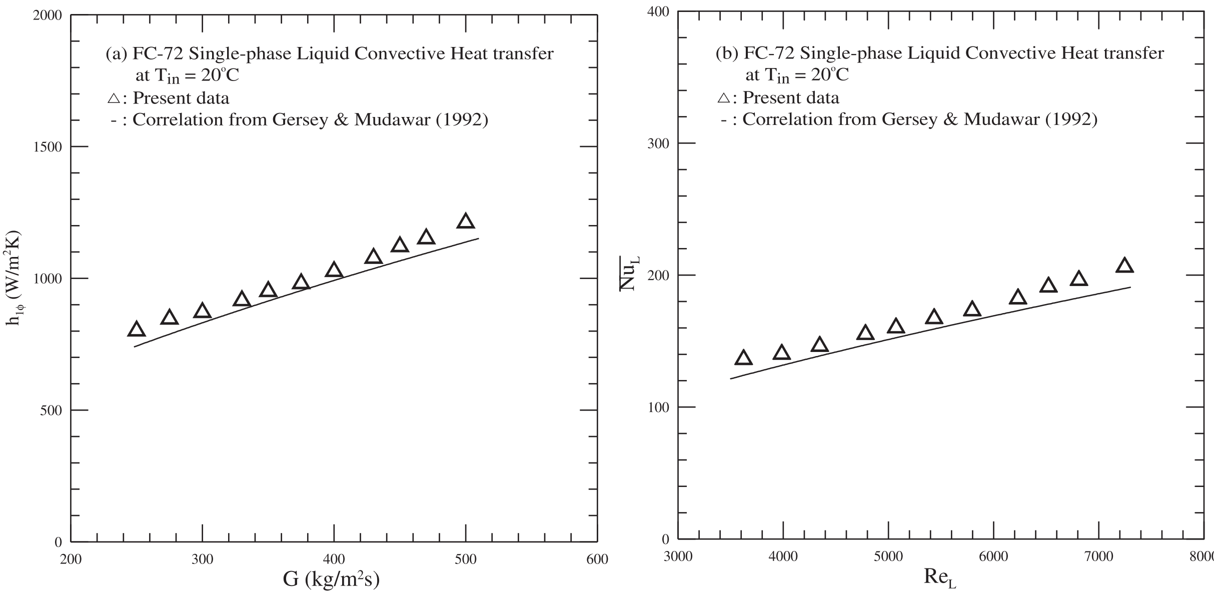

Fig. 3. Comparison of the present steady single-phase liquid convection heat transfer data with the correlation of Gersey and Mudawar (1992) for (a) $h_{1\varphi}$ vs. G and (b) $\overline{Nu_L}$ vs Re_L.

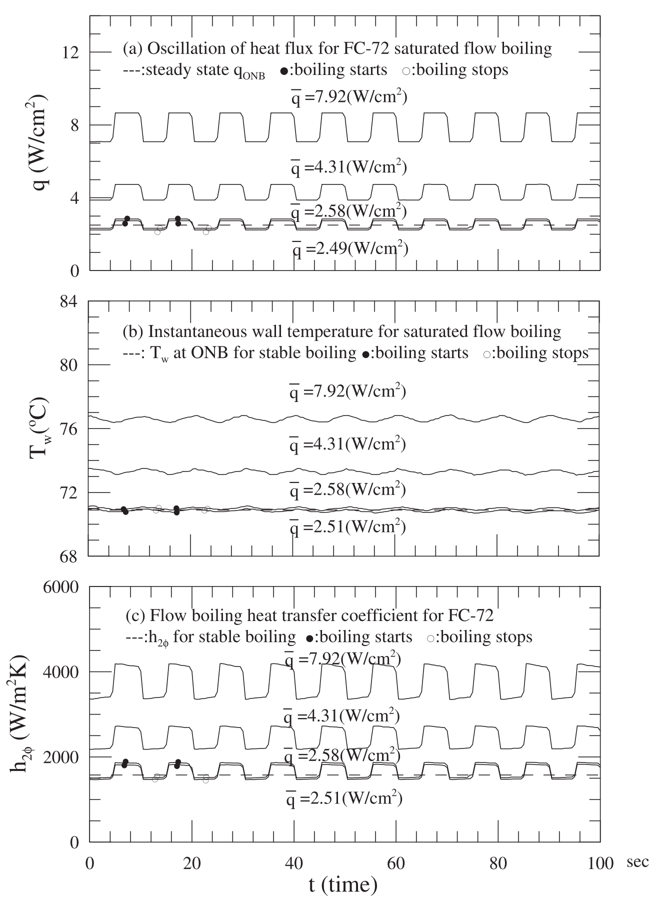

Fig. 4. Time variations of (a) imposed heat flux at $\Delta q/\bar{q} = \pm 10\%$, (b) copper plate temperature and (c) heat transfer coefficient in transient oscillatory saturated flow boiling for various mean imposed heat fluxes for $G = 300$ kg/m^2 s with $t_p = 10$ s. (transient flow boiling$\bar{q}_{ONB} = 2.51$W/cm^2).

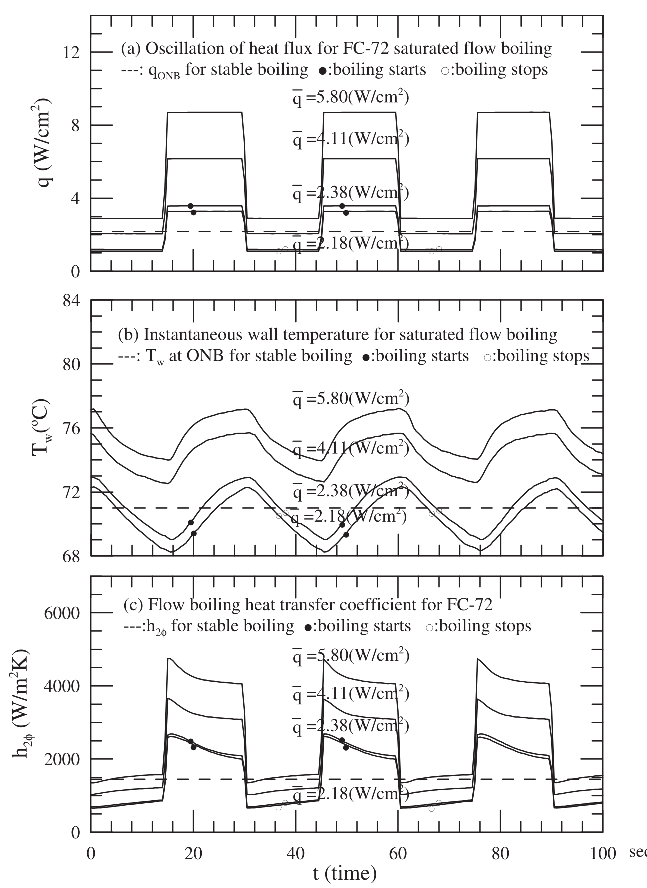

Fig. 5. Time variations of (a) imposed heat flux at $\Delta q/\bar{q} = \pm 50\%$, (b) copper plate temperature and (c) heat transfer coefficient in transient oscillatory saturated flow boiling for various mean imposed heat fluxes for $G = 300$ kg/m^2 s with $t_p = 30$ s. (transient flow boiling $\bar{q}_{ONB} = 2.18$W/cm^2).

less like a sinusoidal wave and it is also periodic in time and is at the same frequency as the imposed heat flux oscillation. Besides, at a higher mean imposed heat flux, the heated surface temperature oscillation is stronger for the same $\Delta q/\bar{q}$ for a short t_p. However, at a longer t_p of 30 s the amplitude of the T_w oscillation varies nonmonotonically with the mean imposed heat flux

(Fig. 5). Moreover, the heated surface temperature oscillates in a larger amplitude for a higher $\Delta q/\bar{q}$ and/or a longer t_p. It should be mentioned here that even for the single-phase liquid forced convection with $\bar{q} < \bar{q}_{\mathrm{ONB}}$ the heated surface temperature exhibits some temporal oscillation. A close inspection of the data shown in Figs. 4 and 5 further reveals that the temporal increase of T_w following the step rise in the imposed heat flux experiences some delay. And the time delay of the T_w oscillation relative to the period of the q oscillation is slightly longer for a lower mean imposed heat flux, suggesting the response of the heated plate temperature to a step change in q is faster at a higher $\bar{q}$. Similar time delay in the T_w oscillation is also found for a step fall in q. This time delay in T_w results mainly from the thermal inertia of the heated copper plate. Besides, the relative time lag in the T_w oscillation t_l/t_p is shorter for a longer t_p. Similar trend is noted from the data for a higher G of 400 kg/m^2 s. Finally, the quantitative data evaluated from the present experiments are summarized in Table 1 for the oscillation amplitudes of the space-average heated surface temperature and the relative time lag of T_w for various cases tested here for G = 300 kg/m^2 s. The corresponding time variations of the space-average flow boiling heat transfer coefficient affected by the imposed heat flux oscillation are also shown in Fig. 4(c) and Fig. 5(c). The results manifest that the flow boiling heat transfer coefficients also oscillate periodically in time and are at the same frequency as the q oscillation. At a higher mean imposed heat flux and for a larger amplitude and a longer period of the imposed heat flux oscillation, the boiling heat transfer coefficient oscillates stronger.

Table 1
Amplitudes of heated surface temperature oscillation ΔT_w and relative time lag t_l/t_p in transient oscillatory saturated flow boiling for various mean imposed heat fluxes and amplitudes and periods of the heat flux oscillation at G = 300 kg/m^2 s.

$\Delta q/\bar{q}$	G = 300 kg/m^2 s			
	Period t_p(s)	$\bar{q}$(W/cm^2)	ΔT_w (°C)	t_l/t_p
±10%	10	0.80	0.18	0.15
		2.51	0.31	0.13
		4.31	0.43	0.09
		6.14	0.52	0.072
	20	0.82	0.32	0.0385
		2.48	0.51	0.0345
		4.32	0.52	0.0235
		6.14	0.55	0.018
	30	0.80	0.51	0.0173
		2.49	0.88	0.0156
		4.25	0.69	0.0106
		6.04	0.68	0.0083
±30%	10	0.80	0.42	0.149
		2.49	0.79	0.131
		4.30	0.88	0.09
		6.16	0.95	0.07
	20	0.82	0.65	0.0365
		2.50	1.45	0.0325
		4.37	1.57	0.0225
		6.20	1.64	0.0175
	30	0.79	0.83	0.016
		2.44	2.44	0.0146
		4.18	1.69	0.0103
		5.90	1.74	0.008
±50%	10	0.81	0.52	0.148
		2.50	1.04	0.128
		4.34	1.43	0.088
		6.10	1.73	0.068
	20	0.83	0.86	0.0365
		2.51	2.44	0.032
		4.41	2.51	0.0225
		6.19	2.88	0.017
	30	0.77	1.21	0.016
		2.38	3.91	0.0133
		4.11	3.18	0.01
		5.81	3.29	0.0076

4.3. Intermittent boiling

It is of interest to note in the visualization of the boiling flow over the heated copper plate that for the mean imposed heat flux only slightly above the heat flux corresponding to ONB (Onset of Nucleate Boiling) for the stable boiling, intermittent boiling appears. The heat flux, heated plate temperature and boiling heat transfer coefficient at ONB in the stable boiling are also indicated in Figs. 4 and 5 for references. More specifically, in a typical periodic cycle for given refrigerant mass flux and amplitude and period of the heat flux oscillation bubble nucleation on the heated plate is first seen at a certain time instant after the imposed heat flux is raised to the high level. We have a start of boiling in the flow. Since then the boiling process continues. But after some period following the sudden reduction of the imposed heat flux to the low level, bubble nucleation disappears and the boiling stops. The above processes of intermittent boiling are repeatedly seen in the flow. To be more clear, we indicate the time instants at which boiling starts and stops in Figs. 4 and 5 for the cases with the presence of the intermittent boiling. Note that at a higher mean imposed heat flux the onset of boiling is earlier and the termination of boiling is later. A close inspection of the data presented in Figs. 4 and 5 further reveals that the heat flux for the onset of nucleate boiling for the present transient oscillatory heating conditions can be significantly higher than that for the stable boiling. This can be attributed to the heat capacity effect of the copper plate subject to the time varying heating. Besides, the heat flux for the disappearance of boiling can be much lower than that for the ONB in the stable boiling. It is worth noting that for a higher $\Delta q/\bar{q}$ and/or a longer t_p boiling persists at a heat flux well below q_{ONB} for the stable boiling (Fig. 5(a)). Besides, the heated surface temperature at ONB can be noticeably above or below that for the ONB in stable boiling. A flow regime map to delineate the boundaries separating three different flow regimes, namely, the persistent boiling, intermittent boiling and single-phase flow, in terms of the Boiling number versus the relative period of the imposed heat flux oscillation is given in Fig. 6. The results show that the intermittent boiling prevails over a significantly wider range of the Boiling number for a higher amplitude and a longer period of the imposed heat flux oscillation. Besides, at the higher coolant mass flux the intermittent boiling appears at a higher Boiling number. Based on the present data, the conditions leading to the appearance of the intermittent boiling can be empirically correlated as

$$1.26 \times 10^{-5} \cdot Re_L^{0.5} - 1.82 \times 10^{-6} \cdot H < Bo < 1.31 \times 10^{-5} \cdot Re_L^{0.5} + 1.3 \times 10^{-6} \cdot H \quad (4)$$

where H is defined as $Re_L^{0.5} \cdot (\Delta q/\bar{q})^{0.5} \cdot (t_p/t_c)$. The standard deviation of the above correlation when compared with the present data is 1.2% and more than 95% of the present data falls within the above correlation.

4.4. Effects of heat flux oscillation at very short and long periods

Due to the thermal inertia of the copper plate, it takes a finite amount of time for the plate to respond to the imposed heat flux oscillation. This in turn causes a time lag in the temporal variations of the space-average temperature of the heated plate, as illustrated above. This time lag becomes longer relative to t_p at a shorter period of the heat flux oscillation (Table 1). Is it possible that the plate is not able to respond to a fast heat flux oscillation at a very small t_p and we have a stable flow boiling on the plate? This possibility is tested here by reducing t_p to 4 s, which is the shortest t_p we can attain in the present experimental facility. The data from this test are shown in Fig 7(a). These results do indicate that even at a very high mean imposed heat flux with $\bar{q} = 6.08$W/cm^2 and a large $\Delta q/\bar{q}$ of

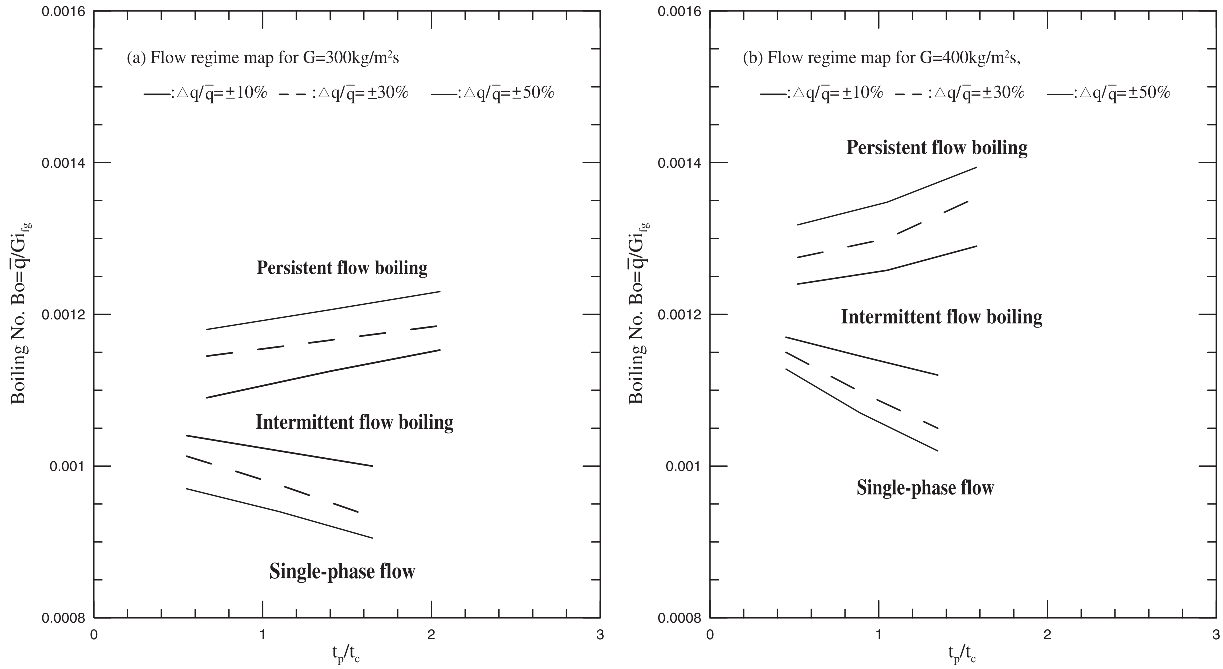

Fig. 6. Two-phase flow regime maps for transient oscillatory FC-72 saturated flow boiling at (a) $G = 300\ \mathrm{kg/m^2\ s}$ ($t_c = 14.6$ s) and (b) $G = 400\ \mathrm{kg/m^2\ s}$ ($t_c = 19.0$ s).

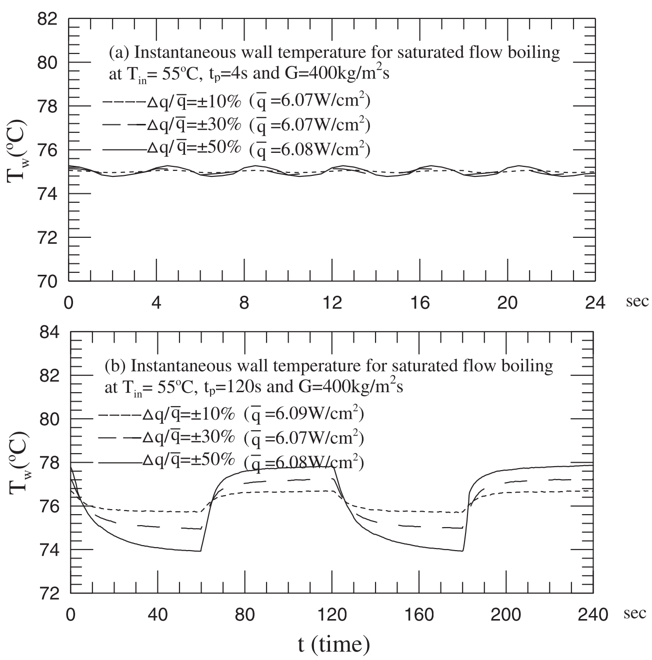

Fig. 7. Effects of short and long heating periods of imposed heat flux oscillation on copper plate temperature in transient oscillatory saturated flow boiling for various $\Delta q/\bar{q}$ at $G = 400\ \mathrm{kg/m^2\ s}$ and $\bar{q} = 6.09 m/\mathrm{cm}^2$ with (a) $t_p = 4$ s and (b) $t_p = 120$ s.

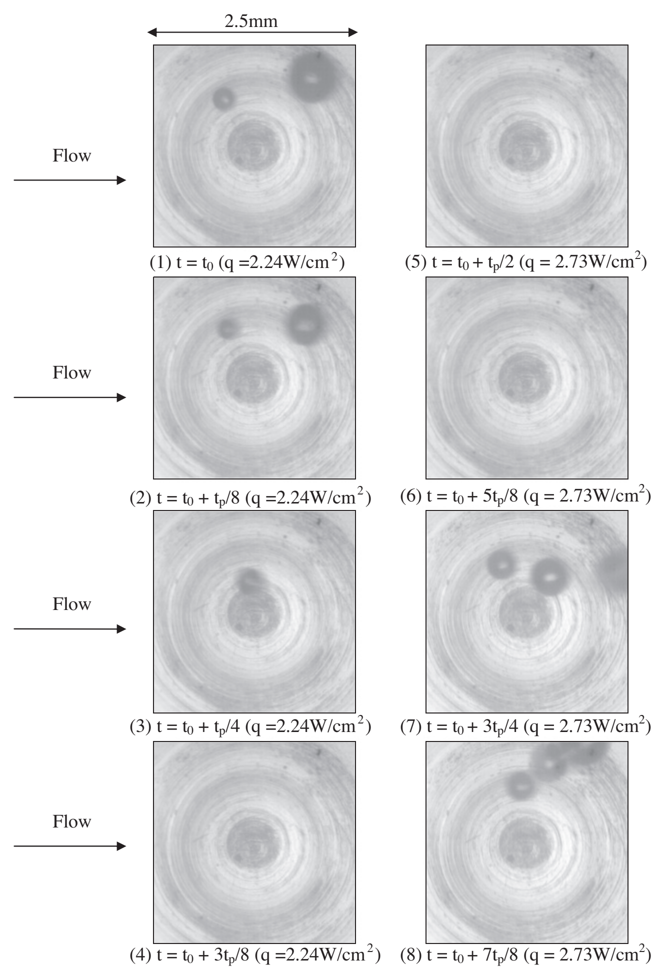

Fig. 8. Photos of intermittent saturated flow boiling at certain time instants in a typical time periodic cycle due to imposed heat flux oscillation at $\Delta q/\bar{q} = \pm 10\%$, $\bar{q} = 2.51\mathrm{W/cm^2}$, $G = 300\ \mathrm{kg/m^2\ s}$, and $t_p = 10$ s.

50% the oscillation amplitude of T_w is only about 0.26 °C at $t_p = 4$ s. This small amplitude of the T_w oscillation is very close to the background thermal disturbances and the boiling in the flow approaches that at steady state. For the lower $\Delta q/\bar{q}$ of 10% and 30% the boiling is essentially at steady state for $t_p = 4$ s.

Then, the time response of the copper plate subject to a very slow heat flux oscillation is explored. The measured data for the temporal variations of the space-average heated surface temperature for selected cases with $t_p = 120$ s are shown in Fig 7(b). The results for $t_p = 120$ s indicate that for the cases with high $\bar{q}$ and low

$\Delta q/\bar{q}$ the heated plate temperature at either half cycle of the high heat flux level at $\bar{q} + \Delta q$ or the low heat flux level at $\bar{q} - \Delta q$ gradually levels off and nearly approaches a steady state value corresponding to the heat flux at that half cycle. Besides, the nearly stable T_w is also very close to that in stable boiling. Obviously, at a higher $\Delta q/\bar{q}$ an even longer t_p is needed for T_w to level off.

4.5. Bubble characteristics

To elucidate the above transient oscillatory flow boiling heat transfer characteristics, the data for the associated bubble characteristics obtained from the present flow visualization are examined in the following. The bubble characteristics in the temporal flow boiling are first illustrated by presenting the top-view photos of the boiling flow at eight selected time instants in a typical periodic cycle in Fig. 8 for a case with the presence of the intermittent boiling for the mean imposed heat flux slightly above that for ONB in the stable boiling. In these figures the symbol "$t = t_o$" signifies the time instant at the beginning of a periodic cycle in the statistical state. The results clearly indicate that in the first half of the cycle with the copper plate subject to the low heat flux level of $\bar{q} - \Delta q$, the number and size of the bubbles at first diminish noticeably with time. Note that the bubbles cease to nucleate from the heated surface at a certain time instant near $t_0 + 3t_p/8$ and boiling stops completely. Then in the second half of the periodic cycle after the imposed heat flux is raised to the high level of $\bar{q} + \Delta q$ at $t_0 + t_p/2$ the plate temperature increases gradually (Fig. 4(b) and Fig. 5(b)). As the superheat of the plate exceeds certain critical limit at certain later time instant between $t_0 + 5t_p/8$ and $t_0 + 3t_p/4$ bubbles start to nucleate from the heated surface. The precise instant of time at which onset of nucleate boiling occurs depends on G, $\bar{q}, t_p$ and $\Delta q/\bar{q}$. Beyond ONB the number and size of the bubbles increase drastically. Next, the photos of the boiling flow for the case with the mean imposed heat flux well above the heat flux for the ONB in the stable boiling are shown in Fig. 9. At this higher $\bar{q}$ we have persistent boiling in the flow. The results indicate that in the first half of the periodic cycle with the imposed heat flux at the low level of $q - \Delta q$, the bubble population decreases with time and the bubbles get smaller. The opposite is the case in the second half of the cycle with the imposed heat flux at the high level of $q + \Delta q$. A number of big bubbles are seen in these photos. They are formed from the merging of small bubbles. These changes in the bubble characteristics are more significant at a higher amplitude of the heat flux oscillation and at a higher mean imposed heat flux.

To quantify the bubble characteristics, the measured data for the time variations of the space-average bubble departure diameter and frequency and active nucleation site density in a typical periodic cycle are given in Figs. 10–12 for various coolant mass fluxes, periods of the imposed heat flux oscillation, and mean imposed heat fluxes at $\Delta q/\bar{q} = \pm 50\%$. The results in Fig. 10(a) indicate that the bubbles departing from the copper plate are somewhat smaller for the mass flux raised from 300 to 400 kg/m^2 s in the

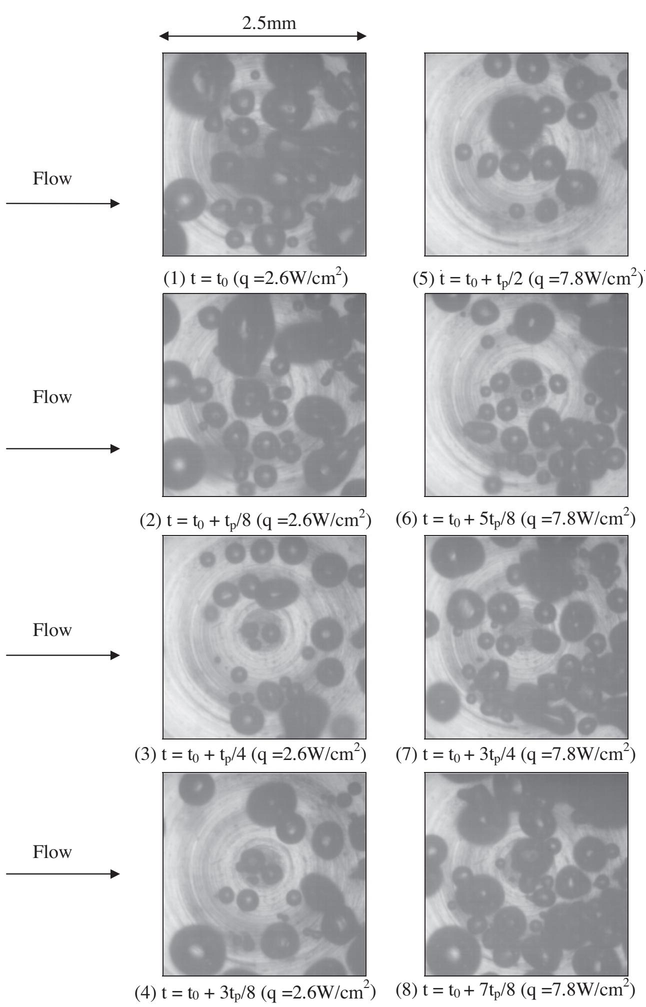

Fig. 9. Photos of persistent saturated flow boiling at certain time instants in a typical periodic cycle subject to an imposed heat flux oscillation at $\Delta q/\bar{q} = \pm 50\%, barq = 5.2\text{W/cm}^2$, $G = 300$ kg/m^2 s, and $t_p = 30$ s.

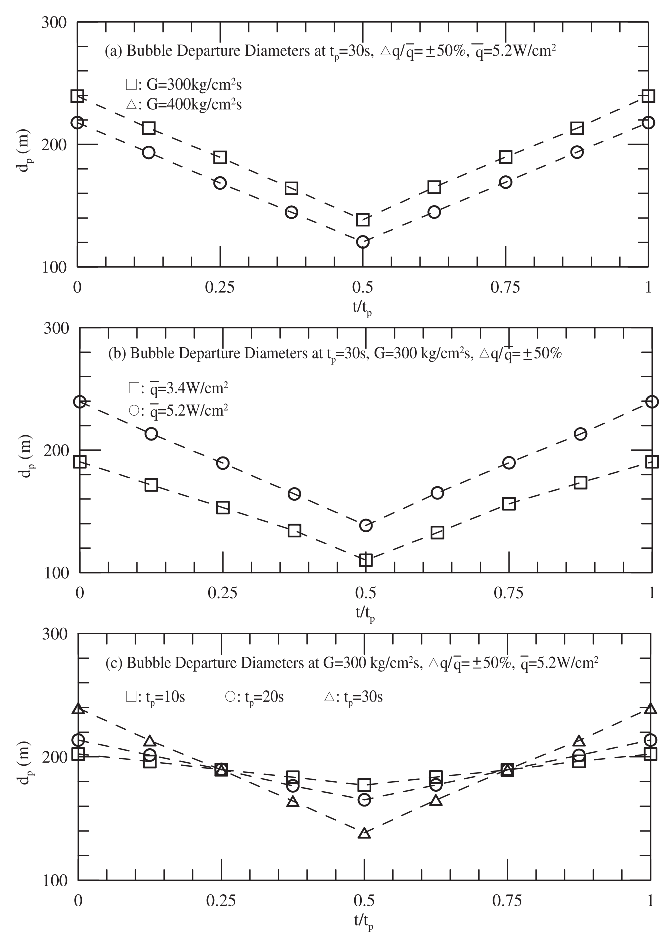

Fig. 10. Mean bubble departure diameters for transient oscillatory saturated flow boiling at $\Delta q/\bar{q} = \pm 50\%$ for various G(a), $\bar{q}$(b) and t_p(c).

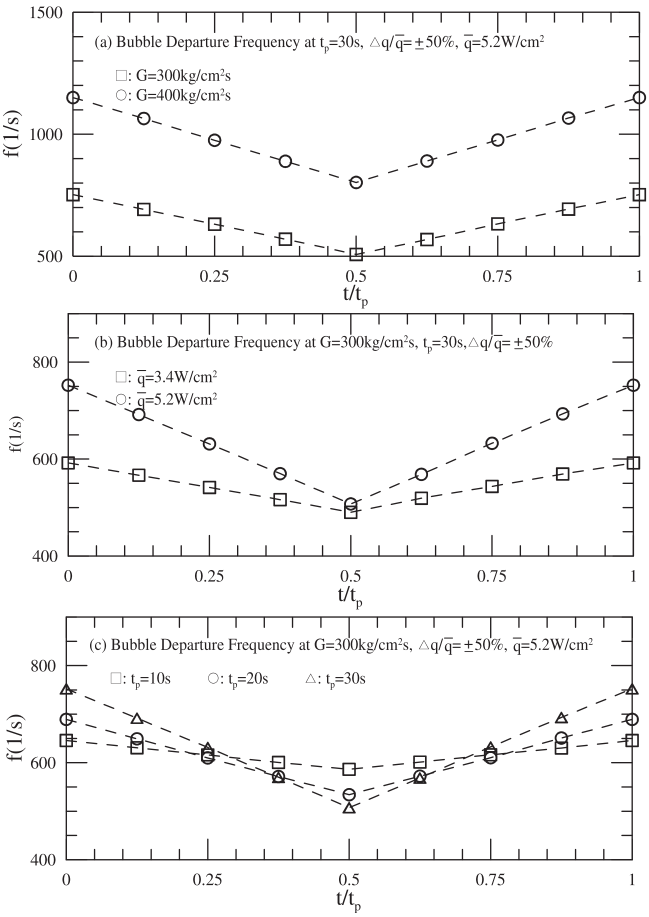

Fig. 11. Mean bubble departure frequency for transient oscillatory saturated flow boiling at $\Delta q/\bar{q} = \pm 50\%$ for various G(a), $\bar{q}$(b) and t_p(c).

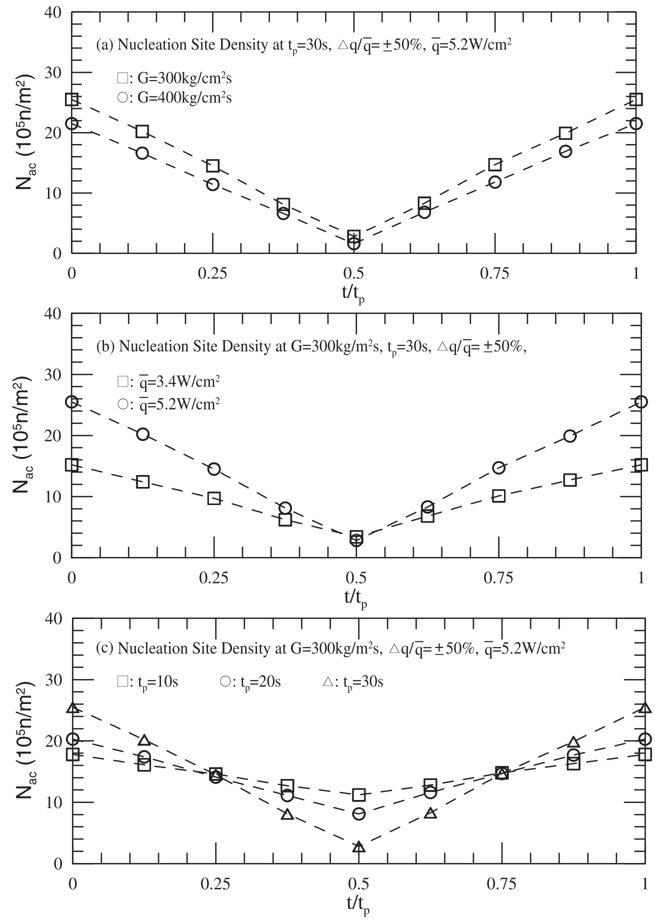

Fig. 12. Mean active nucleation site density for transient oscillatory saturated flow boiling at $\Delta q/\bar{q} = \pm 50\%$ for various G(a), $\bar{q}$(b) and t_p(c).

transient oscillatory saturated flow boiling. It reflects the fact that the coolant at a higher mass flux and hence at a higher speed tends to sweep the nucleation bubbles more quickly away from the heating surface. Moreover, for given G, $\bar{q}$ and t_p the size of the departing bubbles decreases almost linearly with time in the first half of the periodic cycle in which the heat flux is at the low level of $\bar{q} - \Delta q$. The decrease in the bubble departure diameter with time when the heat flux is at the low level is conjectured to result mainly from the smaller liquid inertia force due to the slower displacement of liquid coolant during bubble growth at lower liquid superheat for a lower wall superheat [23]. Hence the bubbles attaching the heated surface can be swept away by the liquid flow earlier at the low heat flux level. While in the second half of the cycle an opposite process is noted since the imposed heat flux is maintained at the high level of $\bar{q} + \Delta q$. Besides, at a higher mean imposed heat flux the departing bubbles are larger, as evident from the results in Fig. 10(b). The effects of the heat flux oscillation period on the time variations of d_p are further illustrated in Fig. 10(c). Note that an increase in the period of the heat flux oscillation causes a stronger variation of the bubble departure diameter with time. This can be attributed to the larger amount of the energy accumulation in and heat removal from the heated plate for a longer t_p, resulting in stronger oscillations of the plate temperature and hence the bubble characteristics with time.

Next, the data shown in Fig. 11 indicate that in the transient oscillatory flow boiling the bubble departure frequency increases substantially with the mass flux (Fig. 11(a)). The increase of f with G is ascribed again to the higher drag on the bubbles attaching to the heated surface by the liquid coolant moving at a higher speed for a higher G. This in turn causes an earlier departure of the bubbles from the surface, resulting in a higher departure frequency. For given G, $\bar{q}$ and t_p the bubbles depart from the heated surface at a nearly linear decreasing rate in the first half of the periodic cycle in which the imposed heat flux is at the low level. Apparently, in the second half of the cycle in which the imposed heat flux is at the high level the bubble departing rate increases also almost linearly. It should be pointed out that the time variations of the bubble departure frequency are stronger for a longer period and a higher amplitude of the imposed heat flux oscillation and for a higher mean imposed heat flux. But the effects of the coolant mass flux on the oscillation amplitude of the bubble departure frequency are relatively mild.

Then, the space-average active nucleation site density on the heated surface affected by the imposed heat flux oscillation is illustrated in Fig. 12. Note that in the transient oscillatory flow boiling the active nucleation site density also decreases almost linearly with time in the first half of the periodic cycle in which the imposed heat flux is at the low level. The reverse process appears in the second half of the cycle in which the heat flux is at the high level for given G, $\bar{q}$ and t_p. At a longer period and a higher amplitude of the heat flux oscillation and at a higher mean imposed heat flux the temporal variation of N_{ac} is stronger. Besides, at a lower coolant mass flux the time variation of N_{ac} is slightly stronger.

Finally, based on the present data for the persistent boiling of FC-72 the dependence of the quantitative bubble characteristics on the heat flux oscillation can be approximately expressed as $d_p \propto q^a, f \propto q^b$ and $N_{ac} \propto q^c$ when the time lag in the T_w oscillation is neglected. Here the exponents a, b and c range respectively from

0.11 to 0.23, 0.11 to 0.17 and 0.37 to 0.55. This result clearly indicates that the time oscillatory flow boiling heat transfer gets better at increasing heat flux since d_p, f and N_{ac} all increase with q, as noted from the data for the boiling heat transfer coefficient given in Fig. 4(c) and Fig. 5(c).

5. Concluding Remarks

The transient oscillatory flow boiling heat transfer and associated bubble characteristics of saturated FC-72 liquid flow over a small heated circular flat copper plate flush mounted on the bottom of a rectangular channel subject to a time periodic heat flux in the form of rectangular waves have been experimentally investigated. The effects of the mean level, amplitude and period of the imposed heat flux oscillation on the periodic FC-72 flow boiling heat transfer and associated bubble characteristics such as the mean bubble departure diameter, bubble departure frequency, and active nucleation site density have been examined in detail. Major results obtained can be summarized as follows:

1. The time-average boiling curves for the transient oscillatory saturated flow boiling of FC-72 are not affected to a noticeable degree by the amplitude and period of the imposed heat flux oscillation. In fact, they resemble that for the stable flow boiling.
2. In the transient oscillatory saturated flow boiling of FC-72 subject to the imposed time-periodic heat flux oscillation, significant temporal oscillations in the heated surface temperature, boiling heat transfer coefficient, bubble departure diameter and frequency, and active nucleation site density appear. These physical quantities also oscillate time periodically and at the same frequency as the heat flux oscillation. Besides, at a higher mean imposed heat flux at $t_p = 10$ and 20 s and for a larger amplitude of the heat flux oscillation they exhibit relatively stronger oscillations. Meanwhile, a longer period of the heat flux oscillation causes stronger oscillations in these quantities. Moreover, a slight time lag in T_w oscillation is seen. Furthermore, reductions in the size of the departing bubbles, active nucleation site density and bubble departure frequency with time result when the imposed heat flux is reduced to the low level. We also note the presence of the intermittent boiling for the mean imposed heat flux close to that for the ONB in the stable boiling. And a regime map is provided to delineate the boundaries among single-phase liquid flow, intermittent boiling and persistent boiling.

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