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Experimental study of transient pool boiling heat transfer under sinusoidal power excursion

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1. Introduction

Reactivity-initiated accident (RIA) is a postulated nuclear power plant accident that involves an exponential power excursion within the fuel rods because of the instantaneous extraction of a control rod in a nuclear reactor core. Under such accidents, due to the rapid heating, it is expected that the mechanism of transition to film boiling under transient condition is totally different from that under a common steady-state condition [1-4]. Such different mechanism could affect the heat transfer at the clad-to-coolant interface. In this sense, the transient heat transfer under high burnup conditions is important to understanding of fuel damage mechanisms, and thus a lot of studies have been carried out to explore the transient boiling under exponentially escalating power condition [1-4]. Most of these studies were performed with a thin wire heater in a pool of stagnant water in order to focus on the fundamental physics and facilitate control of variables, i.e. heater material, thickness, surface characteristics. It was found that the heat transfer coefficient for nucleate boiling and film boiling as well as the critical heat flux, under a transient input power, could vary with the rate of power rise.

However, these studies were performed under exponentially or linearly escalating power condition [1-4], although the actual pulse under RIAs has a single sine shape, that is, an exponential power increase and consequent decrease due to the negative reactivity feedback from the temperature rise and void generation.

In this study, the transient pool boiling experiment was conducted under sinusoidal power excursion on a thin zirconium wire heater. The behavior of vapor bubbles and vapor film during transition from nucleation to film boiling was observed using a high-speed video camera. Then, the transient boiling heat transfer characteristic of saturated water under sinusoidal power input condition was investigated.

2. Experiment

2.1. Setup of pool boiling experiment

The pool boiling experimental facility consisted of a thin wire heater, current conductors, a rectangular boiling chamber, a hot plate, a PT-100 RTD, and a reflux condenser, as shown schematically in Fig. 1(a). The heater was made of zirconium with diameter of 1.14 mm and effective length of 60 mm. Both ends of the wire heater were connected to two corresponding current conductors, the resistance of which is large enough to avoid Joule heating.

2.2. High speed DC power supply and data acquisition system

Voltage and current to the wire heater were supplied using a DC pulse-controlled power supply that is able to create various current or voltage signal forms such as ramp-shaped, rectangular, and sine wave functions. The maximum output power of the DC power supply is 15 kW and the typical slew time is less than 30 ms for 10-90% full scale, allowing fast transient power output. As shown in Fig. 1(b), the voltage input was supplied with sine wave function.

The voltage drop across the heater was obtained from current conductors at the ends of the heater, and current was obtained by measuring the voltage across a calibrated shunt resistor. A function generator was used to generate a simultaneous trigger signal to both power supply and high speed camera. The voltages through the heater and shunt resistor, trigger signal and camera output signal were simultaneously measured using a 4 channel data acquisition system (DAS). The maximum sampling rate of the DAS was 50 kS/s for each channel, which is fast enough to measure the voltage and current applied to heater during transient power input. The voltage measurement range of the DAS was ±60V at 24 bit resolution, allowing high voltage measurement. The maximum voltage and period of a single pulse corresponding to the fastest transient in this study were 10V and 60 ms, respectively.

2.3. Analysis of heat flux and temperature behavior with time

From the measurements of voltage (U) and current (I) through the heater, the input heat flux as a function of time was obtained. The current was calculated by the measured voltage through the shunt resistance. Through an energy balance in the wire heater, the heat flux to the bulk liquid (q''_b) was then estimated as

$$q''_b = \frac{D}{4}Q - \rho c \frac{D}{4}\frac{dT_a}{dt} \tag{1}$$

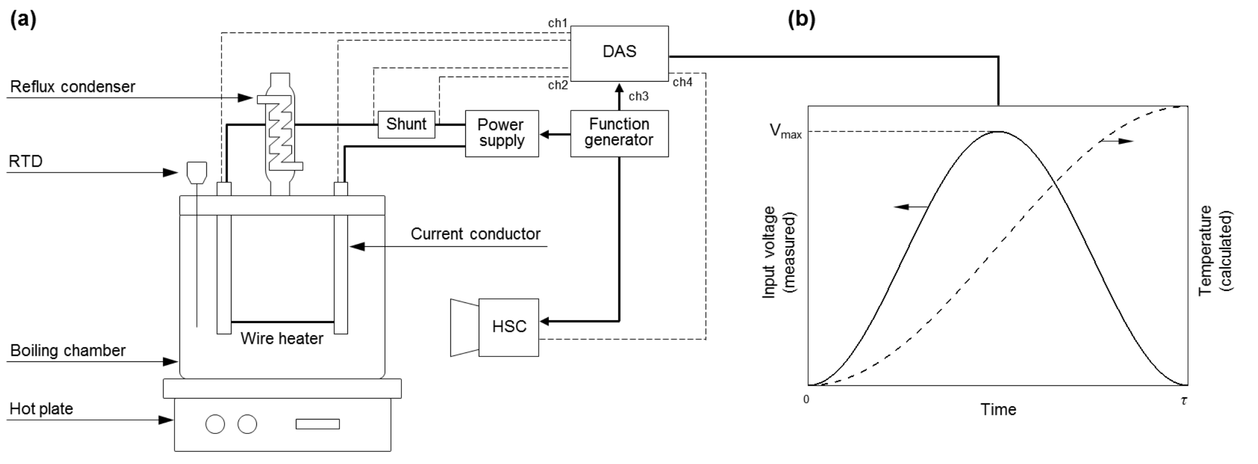

Fig. 1. (a) Setup of boiling experiment and (b) typical input voltage and surface temperature under sinusoidal power condition

where Q, A, D, ρ, c, and T_a are the input heat generation rate, the surface area, the diameter, density, specific heat and the average temperature of the wire, respectively.

The average temperature was calculated from the pre-calibrated relation between electrical resistivity and temperature of zirconium, and the resistivity was calculated from voltage and current recorded by the DAS, and active heater dimension.

Assuming the surface temperature around the wire heater to be uniform, the surface temperature can be obtained by solving the 1-dimensional unsteady heat conduction equation:

$$\frac{\partial T}{\partial t} = a\left[\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right] + \frac{Q}{\rho c} \qquad (2)$$

Boundary conditions are as follows:

$$\left.\frac{\partial T}{\partial t}\right|_{r=0} = 0, \quad -k\left.\frac{\partial T}{\partial r}\right|_{r=R} = q_b''$$

$$T_a = \frac{\int_0^R T(2\pi r)dr}{\int_0^R (2\pi r)dr} = \frac{2}{R^2}\int_0^R Trdr$$

where a is the thermal diffusivity and R is the radius of wire.

3. Results and discussion

All the experiments presented here were conducted with the saturated water under atmospheric condition. The zirconium wire was used as a heater, which has the average roughness of 44±3 nm, and the contact angle of 82±3°. Before each experiment, the water was boiled vigorously at least for 30 minutes to remove the dissolved gas. Every experimental case was performed at least twice to confirm the repeatability of data. The test matrix consists of the various heating rate conditions, corresponding to Fig. 2, and it is characterized by the maximum input voltage (V_{max}) and the pulse width (τ), which determine the heating rate of the wire heater. The test condition referred the PATRICIA-RIA experiments that consists in both PWR Hot Zero Power conditions and pool conditions similar to those of the RIA experiments performed in the NSRR reactor. The heating rate ranged from 2,200 K/s to 4,900 K/s and from 6,000 K/s and 12,000 K/s in the PWR-HZP condition and pool condition, respectively [5]. In the present study, the heating rate of the heater comprised between 2,200 K/s to 12,000 K/s. Preliminary tests were conducted to find the conditions under which data can be obtained without the deformation of the wire heater for the whole pulse period.

3.1. Typical characteristics of transient boiling

Some representative data on wall superheat change rate, heat fluxes, and heat transfer coefficient under sinusoidal power condition are shown in Fig 3. For the fast transient cases, most of heat transferred to the heater is consumed to heat up the heater and the rest is

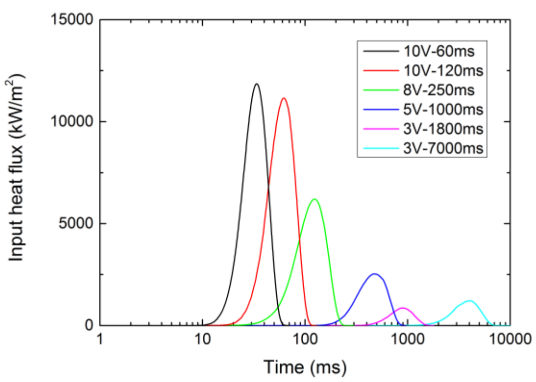

Fig. 2. Pulse characteristics in transient pool boiling.

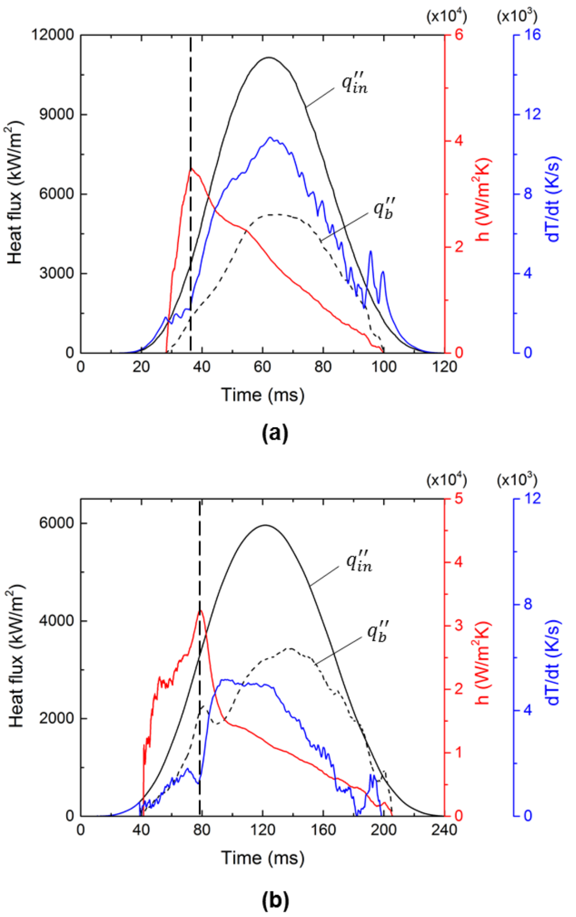

Fig. 3 Time traces of the heat fluxes, the derivative of wall superheat, and the heat transfer coefficient during the transient boiling: (a) 10V-120 ms, (b) 8V-240 ms

transferred to the bulk liquid to initiate boiling. The boiling heat flux (q''_b) increases and then decreases with the sinusoidal heat input (q''_{in}). The wall superheat consistently increases during the boiling processes due to the increase in heat input at the initial phase and the film boiling at the later phase of the whole pulse period, but the temperature increase rate (dT/dt) depends on the boiling regime. The heat transfer coefficient (h) is also closely related to the boiling regime. It is characterized by a reduction of the local heat transfer coefficient due to the replacement of liquid by the vapor film on the heater surface. Therefore, the transition to film boiling, namely critical heat flux, can be determined by the change of heat transfer coefficient. In addition, the slope in the derivative of wall superheat can be also changed at the entry into the film boiling that results in the low heat transfer coefficient and thus the sudden change in the slope of wall superheat.

Figure 4 shows the transient CHFs versus pulse width. Note that the maximum voltage is different in every case (see Fig. 2). The CHF values decrease and then sharply increase with decrease of pulse width from quasi-steady condition, which is consistent with typical trend

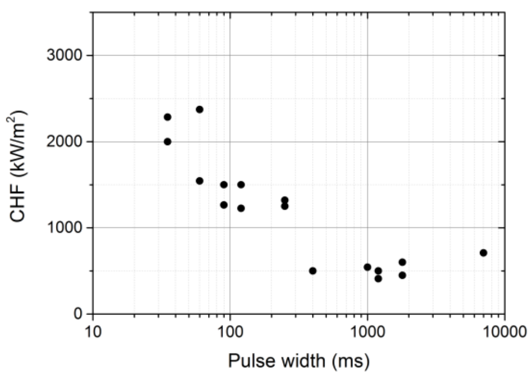

Fig. 4. Transient CHF values vs. pulse width

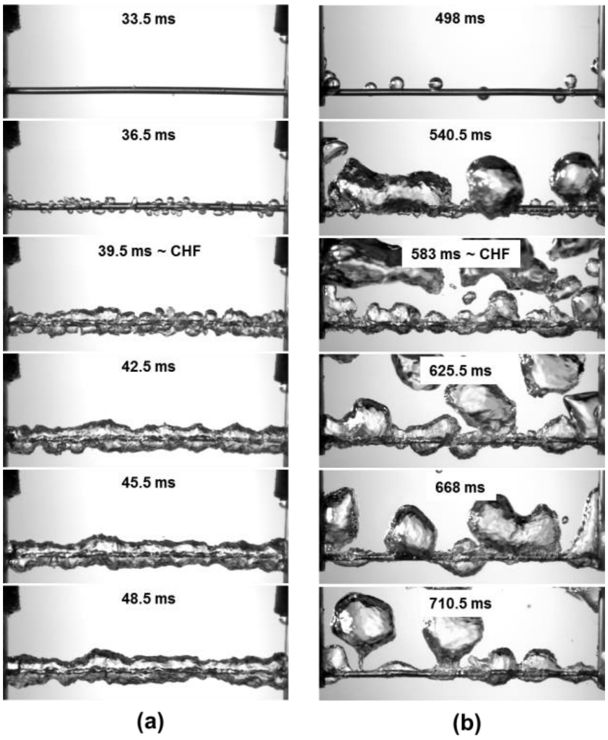

Fig. 5. Visualization results for (a) fast transient and (b) quasi-steady conditions

presented in previous studies [1,3,4]. Such data demonstrated that there exist another mechanisms of CHFs for fast transient condition that is different from that for steady-state condition.

3.2. Fast vs. slow transition boiling heat transfer

The observation of the vapor bubbles and vapor film adjacent to the heater surface during the transient boiling processes was attempted to examine the details of the transition phenomena at the CHF. Figure 5 shows the representative visualization results for both fast transition boiling (10V-60ms) and quasi-steady boiling (3V-1800ms). The processes of transition to film boiling are completely different from each other. For the quasi-steady condition, the vapor bubbles nucleated sparsely on the heater surface. The nucleating bubbles grow and then depart from the surface, while other bubbles are formed at the different sites. As the heat flux increases, the neighboring bubbles are merged and departed from the surface. The process is repeated until the CHF is reached. On the other hand, under the fast transient condition, the bubble departure that is often observed in quasi-steady condition is not observed, but instead numerous bubbles are simultaneously formed on the heated surface and instantly merged into an elongated vapor bubble, which immediately leads to the film boiling. To date, the mechanism of these semi-direct transition from the single-phase regime to the film boiling has not been clearly identified and further study is needed.

4. Conclusion

The transient boiling heat transfer experiment on the horizontal wire heater immersed in a pool was performed under sinusoidal power excursion with various input power increase rates.

The heater surface temperature, and heat flux to water, and boiling heat transfer coefficient during the transient condition were obtained through the measurement of heater electrical parameters. Based on these data, the transient critical heat flux were determined. It was found that the CHF values decrease and then sharply increase with decrease of pulse width from quasi-steady condition. To examine the mechanism of the transition to film boiling during the fast transient condition, the vapor bubble and vapor film on the heater surface were observed using a high-speed video camera. In the case of the fast transient, the semi-direct transition from the single-phase regime to the film boiling occurs with an explosive vapor bubble generation as if the nucleate boiling regime does not exist.

The examination of heat transfer characteristics and the observation of the dynamic behavior of the vapor bubble provide the evidence that there is a significant difference in the transient heat transfer mechanism from the steady-state process. Therefore, more detailed analysis is necessary to investigate the transient heat transfer mechanism.

In addition, the present work was limited to the horizontal wire in the saturated water pool under atmospheric pressure condition. Further studies should be focused on the effect of inclination of the wire, liquid subcooling, flow rate and pressure on transient boiling.

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