Preliminary test of transient pool boiling with fast pulse power

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1. Introduction

As a part of a 'Multi-Physics Coupled Safety Assessment of Loss-Of-Coolant Accident (LOCA) and Reactivity Initiated Accident (RIA) phenomena' project in KAERI, we are investigating the boiling characteristics for Reactivity Initiated Accident (RIA) application in light water reactors [1,2]. To have a better knowledge of the boiling applied fast pulse power, experimental apparatus for transient pool boiling using joule-heated wire has been developed. The reference test is described herein, from the steady-state to transient (6 cases), and representative results are presented.

2. Methods and Results

2.1 Test apparatus, sample and data reduction

Pool boiling test apparatus, consisting of the liquid pool, test zig, direct current pulse-controlled power supply, reflux condenser, circulating bath, shunt resistance, high speed data acquisition system, and high speed camera, has been set up to investigate the boiling characteristics depending on rapidly applied pulse power coming from the Joule-heating method to horizontal Zirconium wire. Test condition is saturation temperature of water and atmospheric pressure. Radius R and length L of wire is 0.57, and 60 mm, respectively. By measuring the voltage V and current I at test section using voltage tap and shunt resistance, the heat flux by boiling q''_{boiling} is obtained by the energy balance relation in eq. (1-3):

$$q''_{\text{boiling}} = q''_{\text{input}} - q''_{\text{int}} \qquad \text{Eq. (1)}$$
$$q''_{\text{input}} = VI/(2\pi RL) \qquad \text{Eq. (2)}$$
$$q''_{\text{int}} = \rho C_p (R/2)(\mathrm{d}T/\mathrm{d}t) \qquad \text{Eq. (3)}$$

where q''_{input}, q''_{int}, ρC_p, $\mathrm{d}T/\mathrm{d}t$ is the heat flux applied by power supply, heat flux causing the increase in internal energy of test section, het capacity of test material, change rate of wall temperature, respectively. Average wall superheat, ΔT_{sat} [K] = $T_w - T_{\text{sat}}$, is evaluated by the resistance change according to the temperature, which is calibrated by the four-wire method under temperature-controlled chamber (Fig. 1). In transient boiling beyond ΔT_{sat} = 250ºC, average wall superheat is predicted by polynomial extrapolation based on the literatures [3-4]. The resistivity-temperature correlation obtained by the calibration and prediction is matched within 3.6% and the deviation is due to the heterogeneous property of Zirconium wire containing 4.5% Hafnium in this study [3]. Maximum error of q''_{input} and ΔT_{sat} measurement is 5.5%, and 6.6%, respectively.

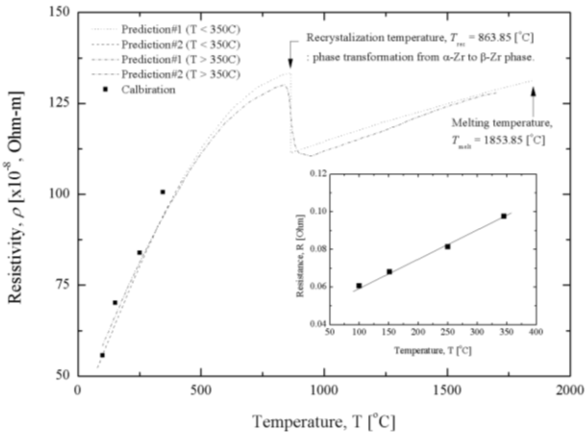

Fig. 1. Calibration of resistance-temperature to predict the average wall superheat.

2.2 Repeatability test under the steady-state and transient boiling experiment

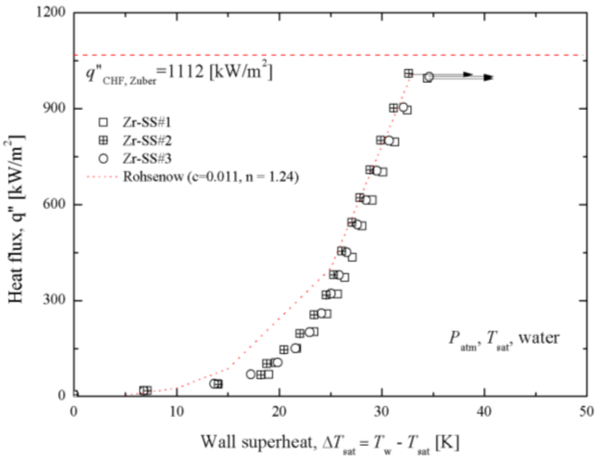

Fig. 2. Repeatability test obtained by steady-state pool boiling.

Prior to parametric investigation in transient boiling, we checked the repeatability at steady-state and transient boiling experiment (Fig. 2-3). With good repeatability of the steady-state results, critical heat flux and nucleate boiling heat transfer coefficient show a well matched to the prediction model [5-6] in eq. (4-5):

$$q''_{CHF,Zuber} = 0.131 h_{lv}\rho_v[\sigma_{lv}g(\rho_l-\rho_v)/\rho_v^2]^{0.25} \quad \text{Eq. (4)}$$

$$q''_{Rohsenow} = \mu_l h_{lv}[g(\rho_l-\rho_v)/\sigma_{lv}]^{0.5}[C_{p,l}(\Delta T_{sat})/(c h_{lv} Pr_l^n)]^3 \quad \text{Eq. (5)}$$

where h_{lv}, ρ_l, ρ_v, σ_{lv}, μ_l, g, $C_{p,l}$, ΔT_{sat}, c, Pr_l, and n is the latent heat of vaporization, density of liquid and vapor, surface tension, viscosity of liquid, gravitational acceleration, specific heat of liquid, wall superheat, surface-fluid factor (0.011), Prandtl number of liquid, and empirical constant (general value from unity to 1.7, 1.24 in the experiment), respectively.

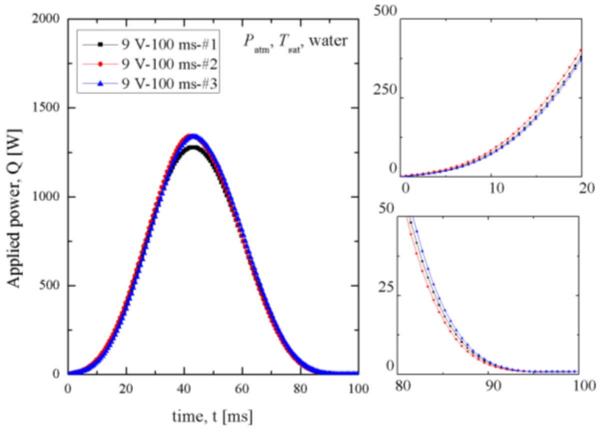

Fig. 3. Repeatability test obtained by transient pool boiling.

In transient pool boiling, the pulse shape is sine function with different frequency and amplitude. The reference condition is 9V-100ms, which indicates the applied voltage and pulse width, respectively, and shows a good agreement at an ascent and descent phase in transient pool boiling. Error of maximum power and pulse width is within 5% and 1%, respectively.

2.3 Transient pool boiling depending on pulse characteristics.

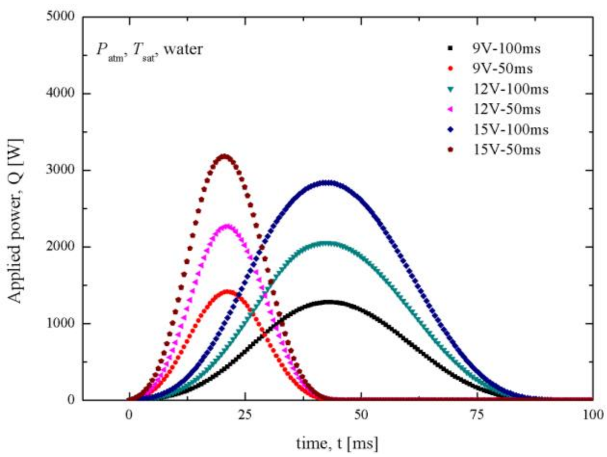

Fig. 4. Pulse characteristics in transient pool boiling

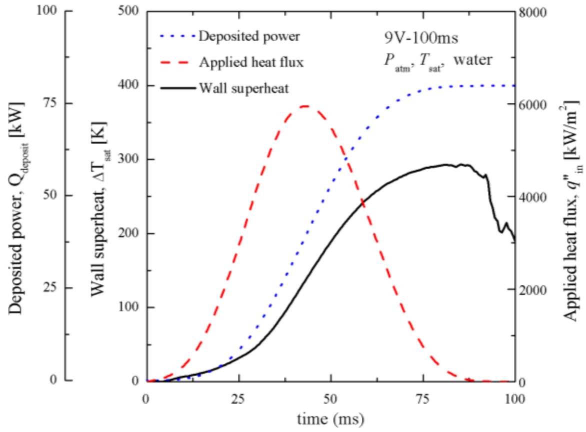

Fig. 5. Time-dependent deposited power, applied heat flux and average wall superheat in transient pool boiling.

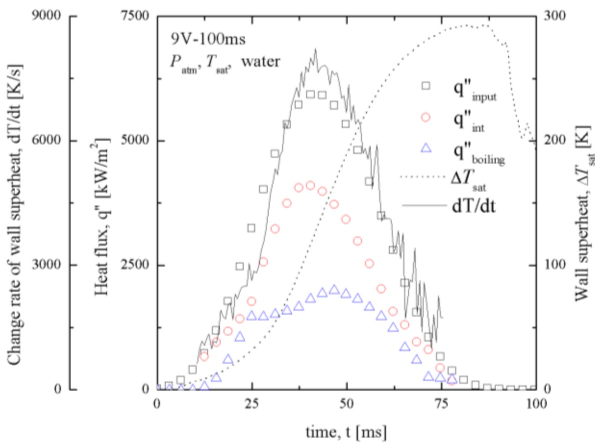

Fig. 6. Heat flux partitioning analysis in transient pool boiling.

Table I. Summary of deposited power, critical heat flux and maximum average wall superheat in pool boiling.

	9 V	12 V	15 V	SS
Deposited power, $Q_{deposit}$ [kW]				
100 ms	80	120	180	-
50 ms	43	69	98	
Maximum heat flux, q''_{MAX} [kW/m^2]				
100 ms	1,945	3,977	7,737	1,013
50 ms	4,196	4,182	4,136	
Critical heat flux, q''_{CHF} [kW/m^2]				
100 ms	1,667	1,662	3,837	1,013
50 ms	4,196	4,182	4,136	
Maximum average wall superheat, ΔT_{sat} [K]				
100 ms	292	400	444	31.9
50 ms	133	250	375	

Test matrix in transient pool boiling is consist of two case of pulse width (50 and 100 ms corresponding to the Full-Width at Half- Maximum FWHM 19 and 38 ms, respectively) and three case of pulse power (1346±68, 2161±181, and 3011±171 W corresponding to the applied voltage 9, 12, and 15 V, respectively) (Fig. 4). For example, the reference case (9V–100ms) shows that the increase rate in wall superheat is slower than that of the deposited power of test wire, and is due to the time-lag of transient heat conduction (Fig. 5). Heat flux partitioning analysis by Eq. (1) indicates that most of the heat transferred to the test wire is consumed by the increase in wall superheat of test wire (Fig. 6). Initial stage in boiling heat flux (within 25 ms) shows an asymptotic increase, and is also explained by the transient heat conduction around the liquid coolant [7].

An increase in pulse time and pulse power result in increase in maximum wall superheat of test wire (Table I). Maximum wall superheat is 444K at the case of maximum deposited power: 15V-100ms. The critical heat flux in transient boiling is larger than that of the steady state condition under all cases. At the pulse width 50 ms, the critical heat flux reaches the critical value (~4,200 kW/m^2) as opposed to that of the pulse width 100 ms cases. Also, it is note that the maximum heat flux is all larger than the critical heat flux at the pulse width 100 ms cases, and is observed at the high wall superheat condition.

2.4 High speed visualization

Compared to the steady-state, the transient boiling shows a rapid transition of boiling regime from the nucleation to the film boiling. For example, most of the transient boiling tests under pulse width 100 ms show the *taylor*-type wavelength in film boiling after 50 ms (Fig. 7). As the deposited power increases, the void fraction around the test wire seems to be increased. Governing physic of the critical heat flux is well known as the hydrodynamic instability or local dry-out in case of the steady-state pool boiling [8], and the difference between the transient and steady-state is clearly distinguishable by visualization. With assumption that the critical heat flux occurs at the half of the pulse width in transient pool boiling (e.g., Fig. 6), it is expected that the transient heat conduction around the test surface will play a major role of critical heat flux determination. This observation is identical to the prediction model of transient critical heat flux [9,10].

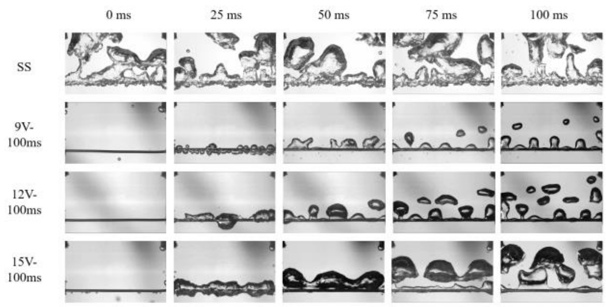

Fig. 7. High speed visualization under pool boiling: the steady-state (SS) and transient at pulse width 100 ms.

3. Conclusions

Depending on pulse characteristics, the maximum wall superheat, critical heat flux and maximum heat flux are determined in transient pool boiling experiment. As the pulse power or pulse time increase, the deposited power increases, causing an increase in maximum wall superheat. The critical heat flux in all transient boiling is larger than that of the steady state experiment. As the pulse power increases, the maximum heat flux is observed at the high wall superheat condition, which is distinguishable to the critical heat flux at the pulse width 100 ms cases. High speed visualization elucidates that the increase in deposited power results in increase in growth rate of vapor bubble at instantaneous nucleation. This causes a rapid transition from the nucleate to film boiling regime. Final application of these results and experiment will become as the reference condition for several parametric studies, accordingly: (*i*) the effect of surface oxidation, (*ii*) surface wettability, and (*iii*) thermo-physical properties of test materials.

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