7. Y. M. Yang and J. R. Maa, Dynamic surface effect on the boiling of mixtures, *Chem. Engng Commun.* **25**, 47–62 (1984).
8. N. Zuber, On the stability of boiling heat transfer, *Trans. ASME* **80**, 711–720 (1958).
9. J. W. Westwater, J. J. Hwalek and M. E. Irving, Suggested standard method for obtaining boiling curves by quenching, *I&EC Fundam.* **25**, 685–692 (1986).
10. H. S. Lin, Studies on pool boiling heat transfer by quenching with sphere, M.S. Thesis, Chem. Engng Dept., National Cheng Kung University, Tainan, Taiwan (1990).
11. J. F. Chen, Studies on pool boiling heat transfer of binary mixtures by quenching with sphere, M.S. Thesis, Chem. Engng Dept., National Cheng Kung University, Tainan, Taiwan (1992).
12. Y. L. Tzan and Y. M. Yang, Pool boiling of binary mixtures, *Chem. Engng Commun.* **66**, 71–82 (1988).
13. J. S. Ded and J. H. Lienhard, The peak pool boiling heat flux from a sphere, *A.I.Ch.E. Jl* **18**, 337–342 (1972).

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Dryout under oscillatory flow condition in vertical and horizontal tubes—experiments at low velocity and pressure conditions

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1. INTRODUCTION

DENSITY wave oscillation in boiling channels induces a drastic reduction of the critical heat flux (CHF) from the value under stable operating conditions [1, 2]. The increase in the amplitude of the oscillation may enhance the initiation of the premature dryout, and the decrease in the period of oscillation may enhance the rapid cooling and/or rewetting after the premature dryout. The CHF problems under flow oscillations should be analyzed taking account of the effects of these two factors. The period and the amplitude of the density wave oscillation are closely related to each other and are strong functions of the operating conditions, such as a mass flux and a heat flux, as well as a system configuration. One of the approaches to provide the fundamental understanding of the phenomena is to conduct the CHF experiment imposing a forced flow oscillation with a predetermined period and amplitude on a mean flow. Although such approach has been conducted almost 30 years ago by Sato *et al.* [3] and Ishigai *et al.* [4], sufficient understanding has not been obtained so far owing to the limitations of the experimental range. Thus systematic experiments have been conducted to verify the effects of the amplitude and the period of the flow oscillation on the CHF using vertical and horizontal boiling channels, and experimental data of the CHF with the forced flow oscillation are presented in this report.

2. EXPERIMENT

The main parts of the test loop are a reserve tank of ion-exchanged water, a gear pump, a calming section, a test section, a separator, and a flow oscillator as shown in Fig. 1. The water in the reserve tank was degassed by boiling prior to the experiments. The test section was a SUS304 tube of the dimension 5.0 mm I.D., 6.0 mm O.D. and 900 mm in length, and was heated by Joule heating of the A.C. power. The steam–water separator was opened to the atmosphere and thus all the experiments were conducted at the atmospheric pressure. The tube wall temperatures were measured using C-A thermocouples of 0.1 mm diameter at every 50 mm location along the test section. The pressure drops at the calming section and the test section were measured with D.P. cells. The pressure drop in the calming section was used for monitoring the flow oscillation.

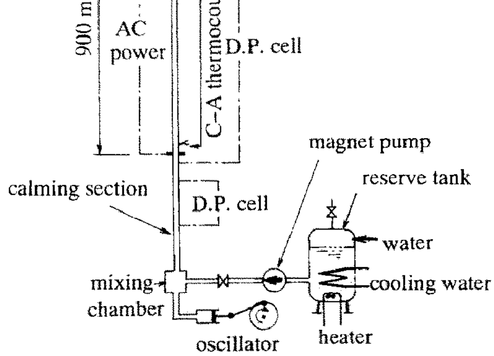

FIG. 1. Experimental apparatus.

NOMENCLATURE

G	mass flux	q_{cro}	critical heat flux under steady state condition
G_o	mean mass flux	t	time
ΔG_{max}	oscillation amplitude of mass flux	ΔT_{sub}	inlet subcooling.
P	pressure		
q	heat flux	Greek symbol	
q_{cr}	critical heat flux	τ	oscillation period.

The flow oscillator unit was mounted at the mixing chamber. The oscillator unit was composed of a cylinder and a piston which was driven by a geared motor with a linkage mechanism. The mean flow G_o was supplied by the gear pump and the fluctuation component ΔG was generated by this oscillator unit. Then the total mass flux G entered into the test section is given by

$$G = G_o + \Delta G = G_o + \Delta G_{max} \cos(2\pi t/\tau). \quad (1)$$

In the present investigation, two series of experiments were conducted, i.e. the vertical flow and the horizontal flow experiments. In the case of the horizontal flow experiment, the test section as well as the calming section shown in Fig. 1 was set horizontally. Throughout the experiments, the CHF condition was determined when the tube wall temperature detected by the thermocouples reached 200°C.

The experimental range was as follows: the exit pressure was the atmospheric pressure and the inlet subcooling was 20.0 K throughout the present experiment. The mean mass flux was in the range from 70 to 450 kg m^{-2} s^{-1}, and the heat flux was up to 514 kW m^{-2}. The normalized amplitude $\Delta G_{max}/G_o$ and the period τ of the flow oscillation were from $\Delta G_{max}/G_o = 0.209$ to 3.77 and from $\tau = 2.0$ to 6.0 s, respectively.

3. CHF UNDER STEADY STATE CONDITION

Prior to the experiments under oscillatory flow conditions, the CHF data, i.e. the dryout heat flux in this case, were obtained under steady state conditions. The experimental data of CHF agreed approximately with Katto's correlation [5] for relatively low mass flux and Mcbeth's one [6], but deviated successively from those correlation lines with the increase in the mass flux. No significant difference was observed between the CHF data for the horizontal flow and for the vertical flow, while the former were slightly lower than those for the latter. This suggests that the CHF in the horizontal flow is not induced by the phase stratification but is caused by the liquid film dryout [7, 8] in the present range of experiments.

4. CHF UNDER OSCILLATORY FLOW CONDITION

4.1. *General feature of temperature fluctuation*

When the heat flux was low and the amplitude of the flow oscillation was also low enough, i.e. $\Delta G_{max}/G_o < 1$, the wall temperature retained almost constant value or showed small fluctuation. When the heat flux increased beyond a certain limit and/or the normalized amplitude became large so as to induce the flow reversal process, the wall temperature in the region near the test section exit began to pulsate with large amplitudes. This pulsation of the temperature represents the initiation of the premature dryout. The region with the premature dryout extended upstream with the increase in the heat flux.

This phenomenon is postulated as follows: the volume of the vapor generated in the heated section is much larger than the liquid volume moving downward during the flow reversal process. Most of the vapor flows upward and is mixed with the liquid entering from the riser. Under the CCFL (counter-current flow limitation) condition, this two-phase mixture will be almost stagnant in the heated section. Thus the quality of the two-phase mixture increases beyond a certain limit, which leads to the breakup of the liquid film at the tube wall. Then the temperature increases rapidly to a certain level, after which a rapid rewetting due to the water flowing up from the heated section inlet makes it decrease again. This process is repeated. Further increase in the heat flux induces the wall temperature to rise beyond the critical condition, i.e. the CHF condition.

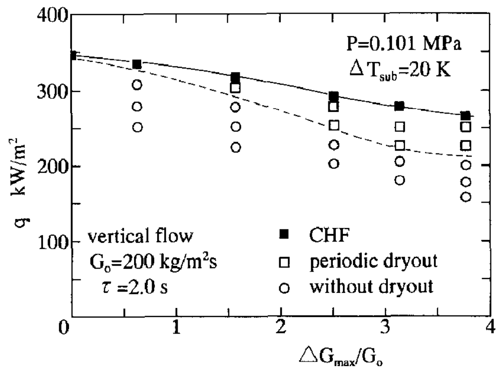

FIG. 2. Mode of temperature fluctuation (vertical flow, $\tau = 2$ s).

Then the behavior of the wall temperature is classified into three modes: almost constant temperature and/or small fluctuation without dryout, periodic dryout with a relatively small increase in the wall temperature, and the CHF condition. These three modes for the vertical flow are represented on the heat flux q vs the normalized amplitude $\Delta G_{max}/G_o$ plane in Fig. 2. The broken line represents the transition from the mode without dryout to the mode of the periodic dryout, and the solid line represents the CHF condition. The CHF value and the heat flux at the transition of the mode decrease with the increase in the normalized amplitude. Such tendencies are observed also in the horizontal flow experiment, while the CHF and the heat flux at the transition of the mode are slightly lower than those in the vertical flow.

4.2. *Critical heat flux*

The CHF value q_{cr} under the oscillatory flow condition is normalized by the steady state CHF value q_{cro} and is plotted against the normalized amplitude $\Delta G_{max}/G_o$ in Figs. 3 and 4. The value of q_{cr}/q_{cro} decreases with the increase in the value of $\Delta G_{max}/G_o$. The increase in the oscillation period τ makes the reduction in q_{cr}/q_{cro} large. The CHF value for $\tau = 6$ s reaches about 40% of the steady state value. The reduction of the CHF value for $G_o = 100$ kg m^{-2} s^{-1} at $\tau = 2$ s is only 5% of the steady state value, while the reduction of the CHF value increases with the increase in the mean mass flux G_o. When the oscillation period becomes large, the effect of the mean mass flux on the reduction of the CHF value becomes less significant. In the present range of the experiment, the reduction in q_{cr}/q_{cro} in the horizontal flow is larger than that in the vertical flow, which is typically observed for relatively

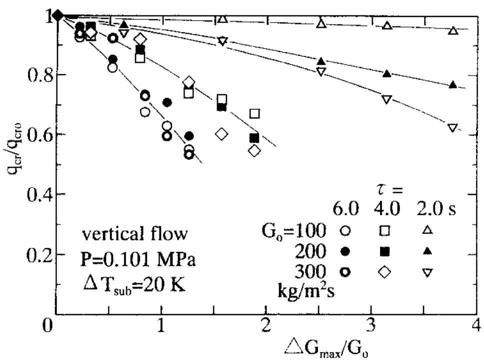

FIG. 3. Reduction of CHF (vertical flow).

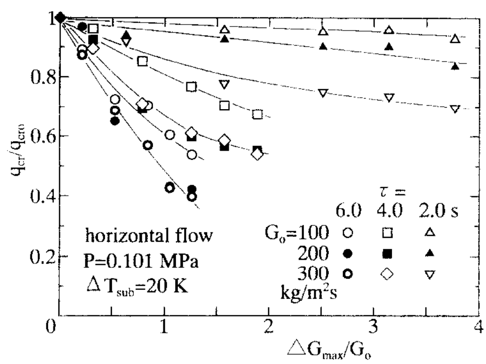

FIG. 4. Reduction of CHF (horizontal flow).

large values of the mean mass flux and the oscillation period. Phase stratification may play an important role in the CHF phenomena under such conditions.

5. CONCLUSION

Experimental investigation on the critical heat flux was conducted under the forced flow oscillation condition. The mode of temperature fluctuation was classified into three types and the effects of the amplitude and the period of the flow oscillation on the CHF were discussed. The reduction of the CHF from the steady state value increases with the increase in the amplitude and in the period of the flow oscillation.

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REFERENCES

1. A. E. Bergles, R. F. Lopina and M. P. Fiori, Critical-heat-flux and flow pattern observations for low-pressure water flowing in tubes, *Trans. ASME, J. Heat Transfer* **89**, 69–74 (1967).
2. K. Mishima, H. Nishihara and I. Michiyoshi, Boiling burnout and flow instabilities for water flowing in a round tube under atmospheric pressure, *Int. J. Heat Mass Transfer* **28**, 1115–1129 (1985).
3. T. Sato, Y. Hayashida and T. Motoda, The effect of flow fluctuation on critical heat flux, *Proc. 3rd Int. Heat Transfer Conf.*, Chicago, Vol. 4, pp. 226–233 (1966).
4. S. Ishigai *et al.*, Critical heat flux of oscillatory flow in a vertical tube, Preprint of the 43rd Annual Conf. of the JSME-Kansai, Paper No. 408, pp. 23–25 (1968).
5. Y. Katto, A general correlation of critical heat flux for the forced convection boiling in vertical uniformly heated round tube, *Int. J. Heat Mass Transfer* **21**, 1527–1542 (1978).
6. T. Ueda, *Two-phase flow*, pp. 290–293. Yokendo, Tokyo (1981).
7. J. M. Robertson, Dryout in horizontal hairpin waste-heat boiler tubes, *A.I.Ch.E. Symp. Ser.* No. 131, Vol. 69, pp. 55–62 (1973).
8. V. Kefer, W. Koehler and W. Kastner, Critical heat flux (CHF) and post dryout heat transfer in horizontal and inclined evaporator tubes, *Int. J. Multiphase Flow* **15**(3), 385–392 (1989).