Applied Physics Letters

Can flow oscillations during flow boiling deteriorate the heat transfer coefficient?

Cite as: Appl. Phys. Lett. **113**, 154102 (2018); https://doi.org/10.1063/1.5046429
Submitted: 27 June 2018 . Accepted: 07 September 2018 . Published Online: 11 October 2018

I.W. Park, J. Ryu, M. Fernandino, and C. A. Dorao

APPLIED PHYSICS LETTERS **113**, 154102 (2018)

Can flow oscillations during flow boiling deteriorate the heat transfer coefficient?

I.W. Park, J. Ryu, M. Fernandino, and C. A. Dorao[a)]
Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim 7491, Norway

(Received 27 June 2018; accepted 7 September 2018; published online 11 October 2018)

Two-phase flow instabilities have been identified as one of the impediments for achieving high heat flux in boiling systems due to their potential heat transfer deterioration. However, most of the fundamental characteristics of two-phase flow instabilities and the mechanisms leading to the heat transfer deterioration remain uncharted. In particular, up to what extent self-induced oscillations can deteriorate the heat transfer coefficient is not well understood. Here, we measure the flow boiling heat transfer coefficient under controlled oscillatory flow conditions. We show that flow oscillations can deteriorate the heat transfer coefficient significantly, but the deterioration depends on the amplitude and period of the oscillations. In particular, the deterioration is primarily a consequence of the dry-out at the wall that in turn increases the averaged wall temperature. *Published by AIP Publishing*. https://doi.org/10.1063/1.5046429

Flow boiling inside tubes is characterised by a complex interplay of hydrodynamic and thermal effects where the dominant mechanisms controlling heat transfer remain not understood.[1] Under particular conditions, two-phase flow instabilities can be observed. These transient and dynamic events can induce mechanical and thermal fatigues. Two typical two-phase flow instabilities are pressure drop oscillations (PDOs) and density wave oscillations (DWOs). The former are characterised by long period oscillations while the latter by short period oscillations. In addition, the amplitude of the oscillations is strongly dependent on the characteristics of the external system, i.e., the mass flux-pressure drop response of the device driving the flow in the system. Although two-phase flow instabilities have been attributed to be one of the impediments for achieving high heat flux in boiling systems, most of their fundamental characteristics remain uncharted.[2] A large number of studies have investigated alternatives for controlling and suppressing the oscillations for overcoming the drawbacks attributed to two-phase flow instabilities.[3–5] However, up to what extent the oscillations can deteriorate the heat transfer coefficient is not understood as only a few studies have focused on the deterioration of the heat transfer coefficient during two-phase flow instabilities.[6,7] In particular, it has been reported that in experiments with controlled flow oscillations, the critical heat flux is a decreasing function of the amplitude and period of the flow oscillation and reaches almost 40% of the steady state value.[8] In the case of pressure drop oscillations, it has been observed that the flow oscillations deteriorate the heat transfer coefficient in the case of helical tubes compared to the stable conditions.[6] On the other hand, controlled flow rate oscillations in the form of a triangular wave with an amplitude lower than 30% of the mean mass flux do not show a noticeable influence on the heat transfer coefficient.[9] A major challenge when studying the influence of two-phase flow instabilities on the heat transfer coefficient is that the period and amplitude of the oscillations depend on the external system and the characteristics of the test section.[2,10] In this letter, we measure the heat transfer coefficient of controlled sinusoidal flow oscillations. We show that flow oscillations can deteriorate the heat transfer coefficient, but the deterioration is strongly dependent on the amplitude and period of the oscillations.

To investigate the deterioration of the heat transfer coefficient under oscillatory flow, a test section consisting of a 5 mm ID stainless steel pipe heated by the Joule effect is used. The facility is equipped with a conditioning section to heat up the working fluid (R134a) to the desired local thermodynamic quality where the heat transfer coefficient is determined by 4 thermocouples installed at the outer wall of the pipe and one inner thermocouple for determining the fluid temperature. The oscillation of the flow was induced by controlling the pump speed in a sinusoidal profile. The details of the experimental facility, experimental procedures, calibration tests, and uncertainty analysis are presented in the supplementary material. In the case of oscillatory flows, the dynamic response of the tube wall temperature can be affected by the wall heat capacity. Therefore, the measured temperature at the outer wall can suffer from damping and phase lag. The thermal penetration depth can be estimated by

$$\delta = \sqrt{\frac{2\alpha_w}{\omega}}, \tag{1}$$

where α_w represents the thermal diffusivity of the tube material and ω the angular frequency. The thermal penetration is 11 mm for oscillations with a period τ of 1 s, and the penetration depth increases with the oscillation period. The present experiments are able to capture the variation of the inner wall temperature as the wall-thickness of the test section is 1.5 mm. Considering a lumped-capacitance approximation of the response of the tube wall, the thermal time constant of the wall is defined as

[a)]Electronic mail: carlos.dorao@ntnu.no

$$\tau_t = \frac{\rho_w Cp_w (D_o^2 - D_i^2)}{h\,4\,D_i}, \tag{2}$$

where Cp_w is the thermal capacity, ρ the density, D_o the external diameter, D_i the internal diameter, and h the heat transfer coefficient from the wall to the fluid. This gives an estimation of $\tau_t \approx 15$ s for the heat transfer coefficient corresponding to post-dryout conditions, while $\tau_t \approx 2$ s for an averaged heat transfer coefficient in the two-phase flow region.

When describing oscillatory flow problems, the dimensionless frequency or Womersley number

$$Wo = r\sqrt{\frac{\omega}{\nu}} \tag{3}$$

can be evaluated, where r is the internal radius of the pipe and ν the kinematic viscosity. For $Wo < 1$, the characteristic time scale for viscous diffusion, r^2/ν, is shorter than that for the forced oscillation, i.e., $r^2/\nu < 1/\omega$, so there is sufficient time for the flow to adjust through viscous diffusion to the imposed oscillation. Therefore, the flow can be considered as quasi-steady flow. For $Wo > 1$, the flow will not be able to follow the imposed oscillation and the flow will experience a phase-shift in time relative to the forcing term. In the present study, for oscillations with periods of 130 s and 10 s, the corresponding Womersley numbers are 2.7 and 9.9, respectively, which implies that as the period decreases, the flow departs significantly from the quasi-steady conditions. Finally, another relevant parameter during transient flows is the Stokes layer thickness or oscillatory boundary layer given as

$$\delta_{ST} = \sqrt{\frac{2\omega}{\nu}}. \tag{4}$$

For oscillations with periods of 130 s and 10 s, the corresponding Stokes layer thicknesses are 2.6 mm and 0.7 mm, respectively, which implies that by reducing the period of the oscillation, the penetration of the variation of the flow towards the wall is significantly reduced.

In order to determine whether flow oscillations can deteriorate the heat transfer compared to stable conditions, the temporal averaged heat transfer coefficient, h, is computed, where

$$h = \frac{1}{T}\int_0^T \frac{q''}{T_{wall} - T_{fluid}}\,dt, \tag{5}$$

with T_{wall} and T_{fluid} being the internal wall temperature and fluid temperature, respectively, and q'' the heat flux. In particular, T_{fluid} is assumed to be the saturation temperature at the working pressure, i.e., $T_{sat}(P)$. However, it will be shown that this assumption is not appropriate in the case of large amplitude oscillations. The averaged heat transfer coefficient is based on at least 10 cycles in the case of the oscillatory flow.

Figure 1 shows measurements during stable and oscillatory conditions of the averaged heat transfer coefficient as a function of the averaged thermodynamic quality. The

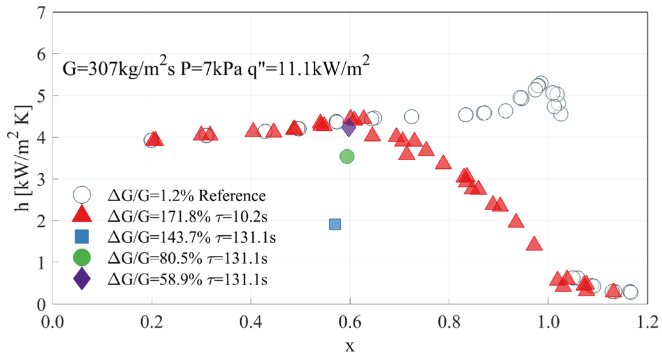

FIG. 1. Deterioration of the heat transfer coefficient during controlled flow oscillations in a horizontal heated pipe of 5 mm ID with refrigerant R134a.

amplitude of the oscillations is characterised in terms of a normalised oscillation amplitude defined as the peak-to-peak amplitude divided by the mean mass flux, i.e., $\Delta G/G$, and the period of the oscillation τ. These values are computed using Fast Fourier Transform. These experiments show the complexity of assessing whether flow oscillations deteriorate the heat transfer coefficient as it depends on the local averaged quality, amplitude, and period of the oscillation for a given working condition. In particular, the quality at the inception of the heat transfer deterioration, x_i, depends on the amplitude and the period of the oscillation. For qualities above x_i, the deterioration of the heat transfer coefficient increases monotonously as the thermodynamic quality increases, while for qualities below x_i, no effect of the oscillation is observed. In order to understand the underlying mechanisms responsible for the heat transfer deterioration, the effect of oscillations with different amplitudes and periods is studied. In Fig. 2, the time evolution of the wall and fluid temperatures, instantaneous heat transfer coefficient, and mass flux, and in Fig. 3, the limit cycles of the heat transfer and wall temperatures in terms of the mass flux are shown. It is important to note that the mass flux is measured in the flowmeter at the inlet of the test section while the temperature and heat transfer are measured downstream. Furthermore, as the fluid starts boiling inside the test section, the compressibility of the vapour introduces a time lag and dumping effects that are difficult to quantify. These issues need to be added to the previously mentioned ones related to the response of the tube wall.

Figure 2(a) shows that for oscillations with a period τ of 131 s, the heat transfer coefficient is not affected for amplitudes $\Delta G/G$ below 60%, the effect that is observed in Fig. 3(a) and Fig. 3(e) in terms of the limit cycle of the temperature and heat transfer coefficient, respectively. In particular, in Fig. 3(a), the steady state heat transfer coefficient is included in the plot where three distinctive regions are observed. Below a mass flux of 110 kg/m^2 s, dryout occurs, for mass fluxes in the range of 110–200 kg/m^2 s, nucleate boiling is dominant, and above 200 kg/m^2 s, convective flow boiling contributes to the heat transfer. The limit cycle of the heat transfer coefficient approaches the steady state heat transfer coefficient but remains at a lower value. Considering that during the convective flow boiling, the heat transfer coefficient is controlled by the conductive sublayer,[1] the lower heat transfer coefficient implies that the momentum

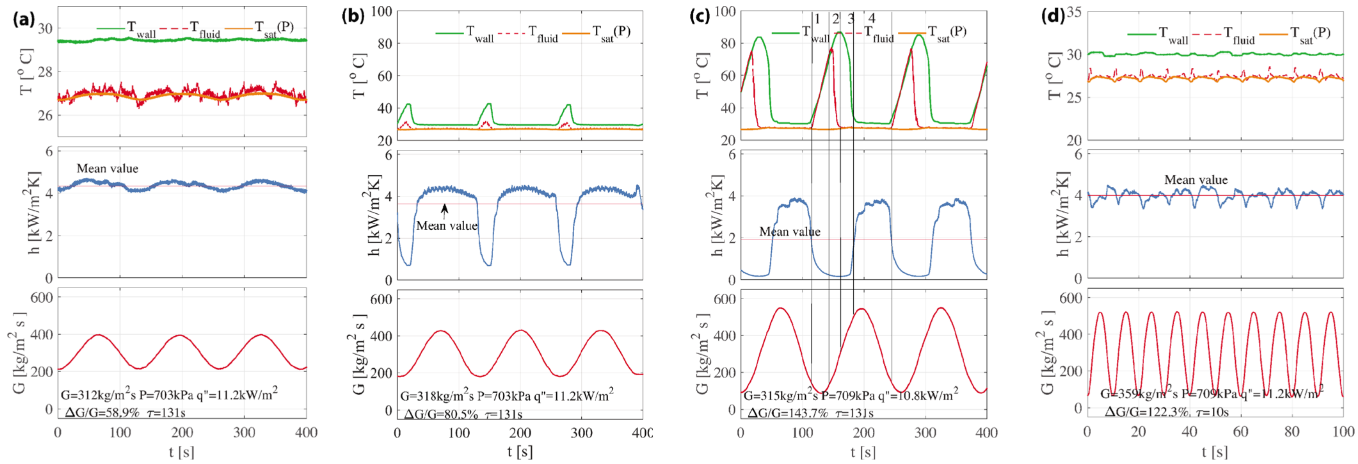

FIG. 2. Effect of the flow oscillation on the temperature and local heat transfer coefficient. (a)–(c) For a period τ of 131 s and an amplitude of 59%, 80% and 131%, (d) for a period τ of 10 s and an amplitude of 131%. Multimedia views: https://doi.org/10.1063/1.5046429.1; https://doi.org/10.1063/1.5046429.2; https://doi.org/10.1063/1.5046429.3

transfer to the conductive sublayer is not efficient during the oscillations, i.e., the conductive sublayer does not reach the velocity equivalent to the steady state condition. Increasing the amplitude of the oscillations, Figs. 2(b) and 3(f), it is possible to observe a clear deterioration in the heat transfer coefficient as the mass flux reaches a minimum. In this case, the wall and fluid temperature shows an increase at the minimum of the mass flux. In this condition, the local quality based on the minimum of the mass flux is above 1.1, which implies that the flow reaches a condition of dryout at the wall which is clearly observed in the reading of the fluid temperature that departs from the saturation temperature. Increasing further the amplitude of the oscillations, the heat transfer deterioration increases as shown in Figs. 2(c) and 3(g). The maximum heat transfer coefficient during the oscillation is slightly lower than in the previous cases corresponding to the nucleate boiling condition. This can be attributed to the high wall temperature reached during the minimum of the mass flux which triggers bubble formation at the wall. During the flow oscillation, it is possible to identify four stages in the case of large flow oscillations, Fig. 2(c). In the first stage, when the mass flux goes to the minimum of the oscillation, a sudden increase in both wall and fluid temperatures is observed. The heat transfer coefficient based on the saturation temperature decreases due to the increase in the wall temperature. In the second stage, as the mass flux

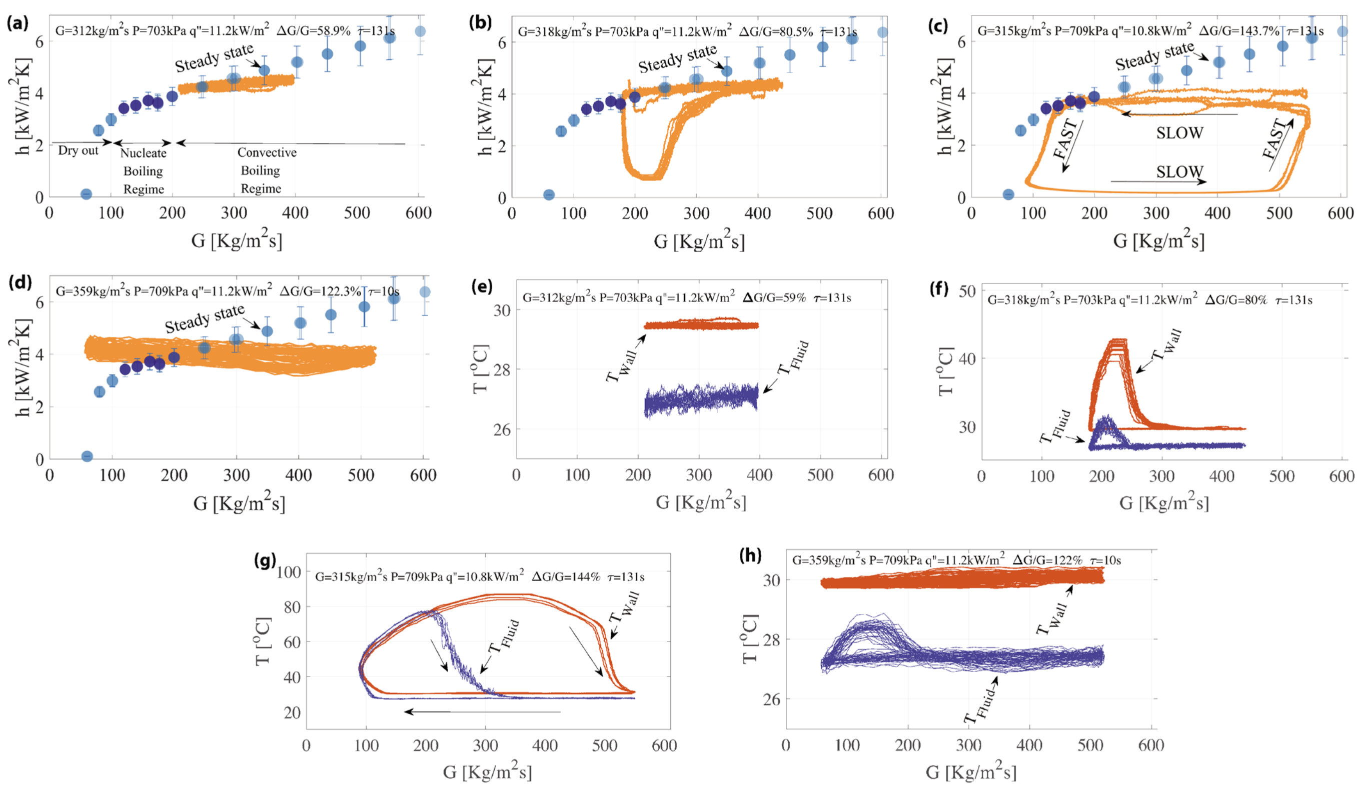

FIG. 3. Limit cycles of the heat transfer coefficient and wall and fluid temperature. The symbols in (a)–(d) correspond to the steady state heat transfer coefficient.

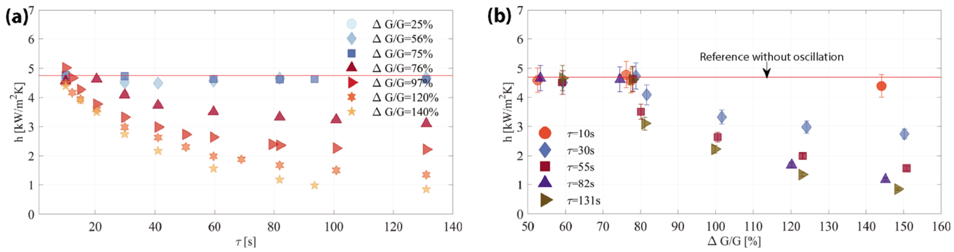

FIG. 4. Deterioration of the heat transfer coefficient. (a) Oscillations with fixed amplitudes and (b) oscillations with fixed periods.

increases from the minimum value, the fluid temperature starts to decrease while the wall temperature increases further. The temperature at the wall increases as the heat transfer coefficient remains low during this phase. But at the core of the pipe, where the fluid temperature is measured, fluid at a lower temperature arrives as the mass fluxes increases. Furthermore, in this stage, the dynamics of the pipe plays an important role, but only a few studies have discussed the influence of the wall inertia during flow instabilities.[11] In the third stage, the wall temperature decreases as the fluid temperature is again at the saturation temperature and the flow boiling heat transfer regime extracts heat more efficiently. In the last step, the temperature of the wall and fluid remains constant corresponding to the nucleate boiling condition.

The previous experiments have shown that heat transfer deterioration occurs when the amplitude of the oscillation reaches the condition of dryout. Furthermore, the deterioration is related to the fraction of the time during the dryout condition. In the next experiment, the influence of the period of the oscillation is studied. Figure 2(d) shows that upon changing the period of $\tau = 131$ s–$\tau = 10$ s, no comparable deterioration is observed. The evolution of the fluid temperature in Fig. 3(h) indicates that the heat transfer process remains efficient at this period, implying that the wall remains wet during the flow oscillations. This can be attributed to the damping of the oscillation by the boiling fluid and the dynamic of the wall, in addition to the no efficient heat transfer/momentum transfer to the boundary layer during the oscillations as expected for a large Womersley number and a very thin Stoke boundary layer.

The previous experiments show that the heat transfer deterioration during flow oscillation is a rather complex problem and that for amplitudes and period below a given threshold, the oscillation might not affect the average heat transfer coefficient. In order to obtain a better picture of these thresholds, the dependency on the amplitude and period of the oscillations is studied in more detail in Fig. 4. The heat transfer coefficient shows a noticeable deterioration for amplitudes above 76% and periods above 10 s. This result agrees with previous experiments showing that for controlled flow rate oscillations in the form of a triangular wave with an amplitude lower than 30% of the mean mass flux, no noticeable influence on the heat transfer coefficient was observed.[9,12]

In summary, the deterioration of the heat transfer coefficient during flow boiling in the case of controlled flow oscillations is shown experimentally. It is observed that flow oscillations can deteriorate the average heat transfer coefficient, but the deterioration depends on the amplitude and period of the oscillation. In particular, the deterioration is not noticeable until the amplitude and period of the oscillations reach a given threshold. The deterioration of the heat transfer coefficient during flow oscillation is attributed to the dry-out of the wall during the low mass flux part of the oscillation. Therefore, self-induced oscillations occurring during two-phase flow instabilities can be detrimental to the heat transfer coefficient but only if the amplitude of the oscillations is above a given value. This result indicates that the presence of two-phase flow oscillations does not directly imply a deterioration of the heat transfer performance.

See supplementary material for the details of the heat transfer experiments and experimental database.

The authors gratefully acknowledge the NTNU-SINTEF Gas Technology Centre for the Ph.D. Fellowship (Il-Woong Park).

[1]C. Dorao, S. Drewes, and M. Fernandino, "Can the heat transfer coefficients for single-phase flow and for convective flow boiling be equivalent?," Appl. Phys. Lett. **112**, 064101 (2018).
[2]I. W. Park, M. Fernandino, and C. A. Dorao, "On the occurrence of superimposed density wave oscillations on pressure drop oscillations and the influence of a compressible volume," AIP Adv. **8**, 075022 (2018).
[3]Y. Zhu, D. S. Antao, D. W. Bian, S. R. Rao, J. D. Sircar, T. Zhang, and E. N. Wang, "Suppressing high-frequency temperature oscillations in microchannels with surface structures," Appl. Phys. Lett. **110**, 033501 (2017).
[4]A. K. Vutha, S. R. Rao, F. Houshmand, and Y. Peles, "Active control of flow boiling oscillation amplitude and frequency using a transverse jet in crossflow," Appl. Phys. Lett. **108**, 134104 (2016).
[5]W. Li, X. Qu, T. Alam, F. Yang, W. Chang, J. Khan, and C. Li, "Enhanced flow boiling in microchannels through integrating multiple micro-nozzles and reentry microcavities," Appl. Phys. Lett. **110**, 014104 (2017).
[6]L.-J. Guo, Z.-P. Feng, and X.-J. Chen, "Transient convective heat transfer of steam water two-phase ow in a helical tube under pressure drop type oscillations," Int. J. Heat Mass Transfer **45**, 533–542 (2002).
[7]M. Sørum and C. A. Dorao, "Experimental study of the heat transfer coefficient deterioration during density wave oscillations," Chem. Eng. Sci. **132**, 178–185 (2015).
[8]M. Ozawa, H. Umekawa, K. Mishima, T. Hibiki, and Y. Saito, "CHF in oscillatory flow boiling channels," Chem. Eng. Res. Des. **79**, 389–401 (2001).
[9]S. Wang, C. Chen, and T. Lin, "Oscillatory subcooled flow boiling heat transfer of R-134a and associated bubble characteristics in a narrow annular duct due to flow rate oscillation," Int. J. Heat Mass Transfer **63**, 255–267 (2013).
[10]I. W. Park, M. Fernandino, and C. A. Dorao, "Experimental study on the characteristics of pressure drop oscillations and their interaction with short-period oscillation in a horizontal tube," Int. J. Refrig. **91**, 246–253 (2018).
[11]E. Manavela Chiapero, M. Fernandino, and C. Dorao, "On the influence of heat flux updating during pressure drop oscillations—A numerical analysis," Int. J. Heat Mass Transfer **63**, 31–40 (2013).
[12]C. A. Chen, T. F. Lin, W. M. Yan, and M. Amani, "Time periodic evaporation heat transfer of R-134a in a narrow annular duct due to mass flow rate oscillation," Int. J. Heat Mass Transfer **118**, 154–164 (2018).