AIP Advances

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Cite as: AIP Advances **11**, 125208 (2021); https://doi.org/10.1063/5.0060523
Submitted: 19 June 2021 • Accepted: 07 November 2021 • Published Online: 06 December 2021

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Submitted: 19 June 2021 • Accepted: 7 November 2021 •
Published Online: 6 December 2021

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ABSTRACT

The heat transfer rate during nucleate flow boiling conditions inside a horizontal heated pipe is assumed to increase with the heat flux until the boiling crisis while being independent of the mass flux. Contrary to this, we present experimental observations of a heat transfer deteriorated regime prior to the occurrence of the boiling crisis. We show that in this regime, the heat transfer coefficient becomes independent of the heat flux, and experimentally, we identify the limits of this boiling regime that elucidate how the near-wall interaction of the bubbles can hinder the heat transfer process. Furthermore, we show that in order to avoid this heat transfer deteriorated regime, the mass flux needs to exceed a threshold value, which drastically reduces as the working pressure decreases. This fact offers useful insights on how to design thermal management systems, and it is more important that the role of the mass flux during nucleate flow boiling needs to be reconsidered.

Flow boiling inside pipes has motivated vast research since the early 1940s, and although ubiquitous in industrial and everyday life applications, the physics of flow boiling remains under continuous scrutiny. When liquid flows inside a heated pipe close to its saturation temperature, vapor is generated. At high heat fluxes and relatively low mass fluxes, nucleate flow boiling is the dominant heat transfer mechanism and bubbles produced at the wall are attributed to the control of the heat transfer. In this regime, the heat transfer coefficient is proportional to the heat flux and almost independent of the mass flux and thermodynamic quality[1–3] [Fig. 2(a)]. An increase in the heat flux in this regime will have little effect on the wall temperature as more nucleation cavities will be activated, keeping the wall temperature almost unchanged. Furthermore, the independence of the heat transfer coefficient on the thermodynamic quality suggests that the heat extracted from the surface is not influenced by the increase in the flow velocity induced by the vapor generation. This suggests that the processes of bubble nucleation, bubble departure, and surface rewetting play a major role in the heat transfer process.

This nucleate boiling regime is assumed to be limited at high heat fluxes by the boiling crisis[4] that is caused by a sudden vapor layer that blankets the entire heating surface, resulting in a vapor film regime. The thermal conductivity of the vapor causes a significant degradation of the heat transfer process and an escalation of the surface temperature[5] that can be critical for the safety of many thermal management systems.

The above-mentioned description[4] suggests that in the nucleate boiling regime, the heat transfer coefficient increases as the heat flux is increased until reaching the boiling crisis. However, experimental studies approaching the critical pressure[6–8] have reported a distinctive decrease in the heat transfer coefficient as the thermodynamic quality increases or a lower heat transfer coefficient than expected. This trend has been attributed either to the role of forced convection[9] suppressing the bubble nucleation mechanism or to partial dry-out of the wall[10,11] that results in vapor accumulation that in turn breaks the contact between the liquid and the hot surface. Furthermore, studies involving micro-channels have suggested that the decreasing trend of the heat transfer coefficient vs the thermodynamic quality is a consequence of the reduction in the momentum of liquid waves,[9] due to incipient dry-out in the annular film resulting from high vapor shear,[12,13] or due to an increased period of intermittent dry-out.[12] These observations have suggested that the

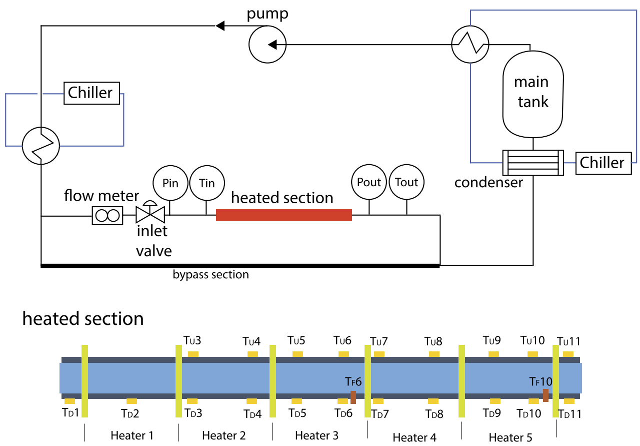

FIG. 1. Schematic diagram of the test facility and test section.

assumed proportionality of the heat transfer coefficient to the heat flux until the boiling crisis can be questionable particularly at working pressures close to the critical one, and the cause of this remains speculative.

In this work, we show that during nucleate boiling conditions, a deteriorated heat transfer regime is observed before the occurrence of the sudden heat transfer deterioration corresponding to the boiling crisis. This condition is attributed to a dominance of the buoyancy force over the drag force acting on the vapor phase close to the wall that prevents an optimal rewetting of the surface.

To investigate the heat transfer process, flow boiling experiments are performed. The test section consists of a 5 mm ID stainless steel pipe, heated with Joule effect. The facility is equipped with a conditioning section to heat up the working fluid (R134a) to the desired local thermodynamic quality (see Fig. 1). The heat transfer coefficient is computed based on the averaged temperature difference between the wall and fluid at four positions around the pipe at 1700 mm from the entrance of the pipe. The thermodynamic quality at the measurement location is controlled by the power of the pre-heating section. Further details are presented in the supplementary material.

Figure 2(a) shows the heat transfer coefficient at a working pressure of P = 700 kPa where the nucleate flow boiling regime and the convective boiling[14] regime are easily identified. In the convective flow boiling case, the increase in the heat flux shows little effect on the heat transfer coefficient. On the contrary, in the nucleate boiling regime, the heat transfer coefficient increases proportional to the heat flux. Furthermore, the heat transfer coefficient is independent of the thermodynamic quality below 0.9 where the dry out starts occurring. From this point, the temperature of the wall increases significantly compared to the fluid temperature, and the heat transfer coefficient shows a sharp transition to the heat transfer coefficient corresponding to the all-vapor case. Figure 2(b) shows the heat transfer coefficient at a higher working pressure of P = 1350 kPa. For the cases of mass fluxes of 300 and 400 kg/m^2 s, the heat transfer coefficient is almost identical and shows independence of the thermodynamic quality and mass flux, as expected for the nucleate boiling regime. However, if the mass flux is reduced below 200 kg/m^2 s, the heat transfer coefficient shows a drastic reduction. However, it remains significantly higher than the corresponding pure convective flow boiling (shown as continuum lines) and the level of deterioration looks to be independent of the heat flux. It is also noted that even when the heat flux increases from 30 to 37 kW/m^2, the heat transfer coefficient remains almost constant. This fact suggests that it is neither a transition to the convective flow boiling or a boiling crisis and it is in agreement with previous observations.[6–8] In particular, it is important to note that the trend does not correspond to boiling crisis, which will lead to a sudden increase in the temperature due to the formation of a vapor film.

From a practical point of view, this result suggests that the heat transfer can be deteriorated during nucleate boiling if the mass flux is below a given threshold. Furthermore, this result suggests that when studying the heat transfer coefficient, particularly in the nucleate boiling regime, the independence of the mass flux needs to be evaluated.

To explain the deterioration observed for lower mass fluxes, we can evaluate the forces that will detach the bubbles forming at the wall. In the case of a horizontal pipe, the dominant forces

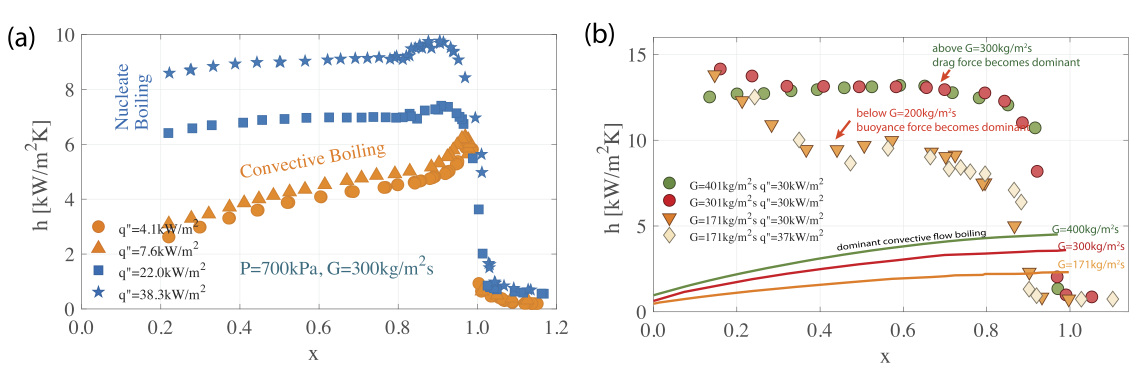

FIG. 2. (a) Heat transfer coefficient corresponding to nucleate flow boiling and convective flow boiling in terms of the thermodynamic quality for a constant mass flux and working pressure. Reproduced from C. Dorao, S. Drewes, and M. Fernandino, Appl. Phys. Lett. **112**, 064101 (2018) with the permission of AIP Publishing. (b) Heat transfer coefficient measurements showing deterioration at low mass fluxes during nucleate boiling. The solid lines represent the calculated convective boiling heat transfer coefficient.[14]

acting on the bubble attached to the surface are the drag force $F_d = C_d \pi d^2/32\rho_l(dd/dt)^2$, surface tension force $F_s = \pi d_w \sigma \sin(\theta)$, inertial force $F_i = 11\pi d^3\rho_l(d^2d/dt^2)/96$, pressure force $F_p = (4\sigma/d + p_v)\pi\, d_b^2/2$, and buoyancy force $F_b = \pi d^3(\rho_l - \rho_v)g/6$. For the inertial force, the vapor inertia is negligible, but the liquid around the bubble is moved by the growth of the bubble. As the growth of the bubble decreases after the initial formation phase, the inertia of the liquid works trying to pull the bubble away from the surface. After the initial bubble formation, the buoyancy and surface tension forces become dominant. While for the bottom surface the forces act against each other detaching the bubble from the surface when the buoyancy exceeds the surface tension, on the upper wall they act in the same direction, contributing to maintaining the bubble attached to the surface. In the axial direction, the dominant forces are the drag flow force $F_D = 1/2C_d\rho_l U{*}^2\pi/4d^2$ and the surface tension force $F_S = \sigma d_w(\sin(\theta_a) + \sin(\theta_r))$. As the bubble is not occupying the full channel, the local velocity close to the wall is lower than the superficial velocity $U^* \propto Gx/\rho_v + G(1-x)/\rho_l$. For the bubbles formed at the top surface, the drag force plays a major role in detaching the bubble. At very low thermodynamic quality, the isolated droplets are easily removed if $F_D > F_S$, but when the thermodynamic quality increases, the accumulation of vapor in the top surface reduces the influence of the drag force, resulting in progressive deterioration of the heat transfer coefficient. However, as the thermodynamic quality increases, U^* increases allowing to counterbalance the further accumulation of vapor. This will allow to avoid a further heat transfer coefficient deterioration. When the thermodynamic quality reaches a value close to 0.7, the limitation of the liquid for rewetting the surface triggers the dry-out of the surface. The heat transfer coefficient approaches the vapor single-phase flow coefficient as the thermodynamic quality approaches 1. For the mentioned reasons, when the mass flux is reduced, the drag force is not able to remove efficiently the bubbles forming at the top wall, favoring the progressive accumulation of vapor close to the top wall of the pipe, which affects the average heat transfer coefficient. This effect can be observed in Fig. 3(a) where the temperature difference between the top and bottom walls corresponding to Fig. 2(b) is shown. It is possible to see that for $G = 300$ kg/m^2 s, the temperature difference between the top and bottom surface remains constant, suggesting that the surface is properly rewetted allowing an optimal heat transfer process. However, for $G = 171$ kg/m^2 s, three clear trends are observed. First, the temperature difference increases for low qualities, which can be attributed to the partial accumulation of vapor in the top surface. This accumulation of vapor deteriorates the heat transfer as bubbles start to interact between each other. This effect is enhanced as the thermodynamic quality increases [Fig. 3(b)]. At a given thermodynamic quality, a balance between the accumulation and removal of bubbles is observed. As a consequence of this balance, the temperature difference remains almost constant until reaching a high thermodynamic quality. At high thermodynamic qualities, the dry-out process starts and the temperature difference increases proportional to the thermodynamic quality.

To further study the heat transfer deterioration, a new experiment is performed keeping the mass flux constant while the heat flux is reduced stepwise, as shown in Figs. 4(a) and 4(b). The values of the mass flux considered are above the value corresponding to stratified flow. The heat transfer process at the bottom surface [Fig. 4(b)] is

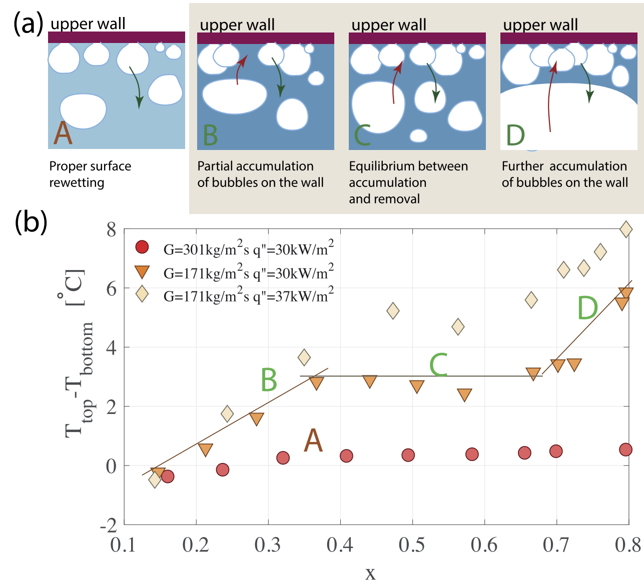

FIG. 3. (a) Possible interpretation of the vapor interaction at the top wall. (b) Temperature difference between the top and bottom surfaces corresponding to the data shown in Fig. 2(b). The higher temperature difference in the case of $G = 171$ kg/m^2 s and $P = 1350$ kPa indicates that the cooling of the top surface is limited. The initial growth of temperature difference until $x = 0.4$ indicates a growing accumulation of bubbles. After $x = 0.4$, a constant cooling rate is achieved.

independent of the mass flux and $q'' \propto \Delta T^2$, as discussed in the literature.[3] The buoyancy force on the bottom surface contributes to a proper liquid rewetting. At the top surface [Fig. 4(a)], it is possible to observe a similar trend than that observed at the bottom surface for G = 301 kg/m^2 s. However, for lower mass fluxes, $q'' \propto \Delta T$, which implies that the heat transfer coefficient remains constant and equal to the value corresponding to the point where the branch started. The value of the heat flux at such a point is defined as a threshold heat flux q_t''. The increase in the heat flux observed in Fig. 4(a) is not implying an sudden increase in the wall temperature; then, it is not possible to assume the occurrence of a dry-out process. Then, the deterioration of the heat transfer coefficient can be a consequence of deficient liquid rewetting. This liquid deficiency is more pronounced at the top surface, as expected, since contrary to what happens at the lower surface, buoyancy forces push the vapor toward the upper surface, as shown in the inset of Fig. 4(b). In particular, the removal of vapor depends strongly on (i) the rate at which the bubbles are formed, which is related to the heat flux applied on the surface, and (ii) the bubble size, which is related to the density ratio and thus the working pressure and mass flux.

The previous analysis suggests that the nucleate boiling heat transfer process can be hindered if the mass flux is lower than a threshold value, as shown in Fig. 2(a). To understand how the working conditions can influence this threshold, a sequence of experimental studies was performed. In this case, the mass flux, the local quality (x = 0.5), and the working pressure are kept constant while the heat flux is reduced stepwise. The threshold values of the heat flux are plotted in terms of the mass flux in Fig. 4(c) and in terms

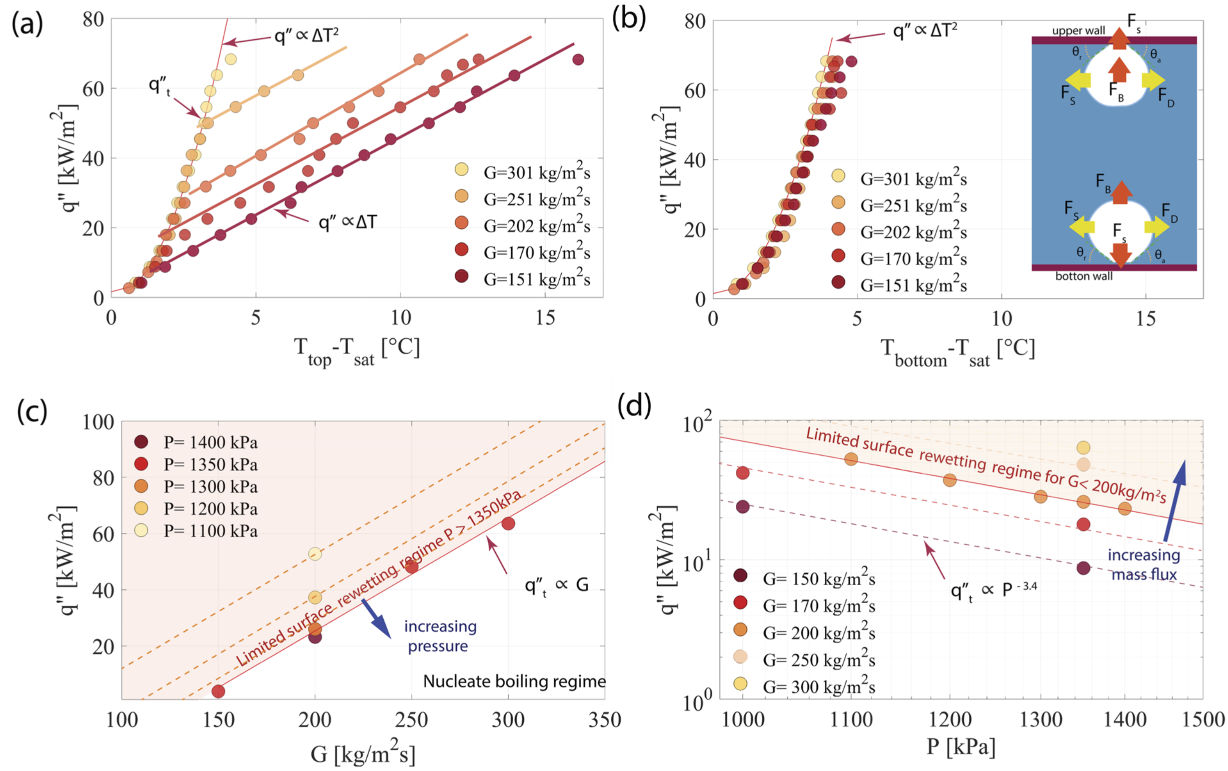

FIG. 4. (a) and (b) Heat transfer process at the top and bottom surfaces, respectively, at P = 1350 kPa for different mass fluxes. (c) q′′–G map defined in terms of the critical values of q′′ for a constant working pressure for identifying the normal nucleate boiling regime and the limited surface rewetting regime. (d) q′′–P map defined in terms of the critical values of q′′ for a constant mass flux for identifying the normal nucleate boiling regime and the limited surface rewetting regime.

of the working pressure in Fig. 4(d). These two plots identify two regions limited by q_t'' corresponding to the working conditions. For heat fluxes below the threshold value, the nucleate boiling regime is observed and $q'' \propto \Delta T^2$, which implies that the heat transfer coefficient increases as the heat flux increases. Furthermore, the wall temperature is slightly affected by the increase in the heat flux. However, for heat fluxes above the threshold value, the nucleate boiling process is deteriorated and $q'' \propto \Delta T$, which implies that the heat transfer coefficient remains almost constant even when the heat flux increases. In particular, this implies that the wall temperature increases linearly with the applied heat flux, representing a major issue for thermal management systems. For the studied conditions, the threshold heat flux scales with $P^{-3.4}$ for a constant mass flux and thermodynamic quality and with G for a constant working pressure and thermodynamic quality. The maps from Figs. 4(c) and 4(d) help to reconsolidate contradictory results from previous studies where the heat transfer coefficient has shown unexpected trends. These unexpected trends are expected if the heat flux is above q_t''. The maps are also suggesting that the increase in the heat flux requires a systematic increase in the mass flux if the working conditions are close to q_t''.

In summary, we show that in the case of flow boiling, the mass flux plays a major role in achieving an optimal dominant nucleate boiling, thus allowing a high heat transfer rate. The results presented in this work suggest that although the heat transfer coefficient related to nucleate boiling is independent of the mass flux, the optimal heat transfer process requires a minimum mass flux for avoiding vapor accumulation at the wall. In this way, in the quest of thermal management system for high heat fluxes, the relationship between mass flux, heat flux, and pressure during nucleate boiling needs to be reconsidered.

See the supplementary material for the details of the heat transfer experiments.

The Marie Sklodowska-Curie Actions Individual Fellowship grant (Subhanker Paul) by the ∗European Union Horizon 2020 Research and Innovation Program for the project HisTORIC (Grant No. 789476) is gratefully acknowledged. Funding for this work from the Research Council of Norway under FRINATEK Project No. 275652 is gratefully acknowledged.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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