The overlooked role of pressure oscillations on heat transfer deterioration during self-sustained flow oscillations

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The naturally occurring oscillations during flow boiling inside a heated pipe under specific conditions are known to hinder the system performance. Although substantial research has been done to reveal the occurrence and control mechanisms of such oscillations, the heat transfer mechanism remains a puzzle to be solved. In particular, it is believed that the heat transfer deterioration can be attributed to the flow velocity variation, namely the amplitude and period of the oscillations. Here we show that the heat transfer deterioration does not necessarily depend on the flow velocity variation. Using controlled experiments we investigate the underlying mechanisms of the heat transfer deterioration during flow oscillations. We show that the associated pressure oscillations play a dominant role in triggering the heat transfer deterioration. In the absence of pressure oscillations, even a high amplitude flow velocity oscillation does not deteriorate the heat transfer rates in the studied conditions.

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Flow boiling has been a promising means for achieving high heat transfer rates since the steam age, gaining high relevance in the industrial era, with a renewed interest as a tool for removing high heat fluxes in modern equipment. Due to its high relevance, the complexity of the boiling phenomenon has motivated vast research[1–5]. The efficacy of the heat transfer process is given by the heat transfer coefficient h (kW/m^{2}K) which is the ratio of the heat flux q" (kW/m^2) to the temperature difference between the surface and the bulk fluid. The nonlinear nature of flow boiling can lead to the occurrence of self sustained oscillations, i.e. oscillations of flow and pressure. Two well known cases of these two-phase flow instabilities (TPFIs) are density wave oscillations DWOs[6](characterised by short periods) and pressure drop oscillations PDOs[7](characterised by long periods). The occurrence of these self sustained oscillations have resulted in a serious technological bottleneck due to the deterioration of the heat transfer coefficient[8–10] which sets limits in the operation of the systems for avoiding such conditions. For the last 80 years, research works[11–14] have been performed for understanding the occurrence and control of such complex nonlinear phenomenon, but many fundamental questions remain unsolved. One particular issue has been about the underlying mechanism responsable of the heat transfer deterioration during these mentioned self-sustaining oscillations. As a result of this, systems today are designed to operate at lower efficiency to avoid the occurrence of such oscillations.

In the particular case of DWO, the period of the oscillations can be closer to twice the fluid transit time for low inlet subcooling and even longer at high inlet subcooling[15]. Research has been motivated by the need to understand the conditions for their occurrence[15–18], the characteristics of the oscillations and parameters affecting them[13,18,19], and in particular their effect on the heat transfer capability of the flow[10,11]. The latter has been a source of major debate and studies due to its impact on the operation of high heat flux systems.

Early experimental studies have identified that during DWO the heat transfer is deteriorated and even triggers an early critical heat flux[11,20,21]. It has been suggested that the heat transfer deterioration is a consequence of the large variation of the flow velocity[9,11,20,21]. This results in the creation of a vapor blanket over the surface[21] or temporary dryout[17] based on the observed temperature variations of the surface with the flow oscillations. During the first half-cycle of the oscillation when the flow rate is low, the accumulated vapor on the surface creates a temporary dryout leading to a reduction in the instantaneous heat transfer rate and thus increasing the wall temperature. During the next half-cycle of the oscillation, when the flow rate becomes high, it removes the vapor from the surface and enhances the instantaneous heat transfer rate. However, the high flow rate during the next half-cycle is not able to compensate for the influence of the temporary dryout, leading to a deterioration in the average heat transfer rate. A recent study[22] based on controlled flow oscillations mimicking the amplitude of the DWOs has argued that the variation of the amplitude of the flow oscillation is not a sufficient condition for the heat transfer deterioration.

In this work, we show that in the case of naturally occurring self-sustained DWOs, the associated pressure

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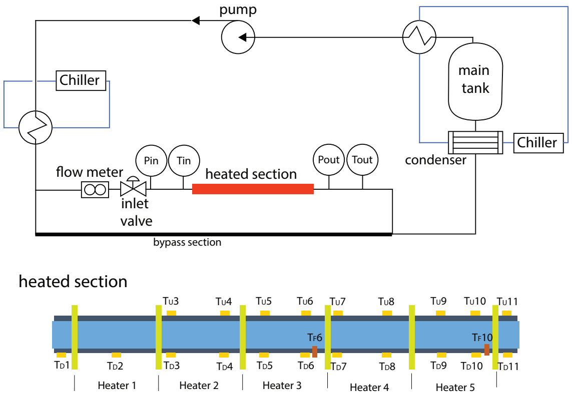

FIG. 1. Schematic diagram of the test facility and test section.

oscillations play a dominant role over the velocity oscillations to trigger the deterioration in the heat transfer rates. The dominant accumulation of vapor on the surface is not necessarily a consequence of the flow velocity oscillation. Also, the amplitude and period of flow velocity oscillations are not the sole entities in triggering the heat transfer deterioration during such flow oscillations.

To investigate the heat transfer mechanism, an experimental facility designed for the study of transient flows has been used, see Fig.1. The facility consists of a 2 m long horizontal stainless steel pipe of 5 mm internal diameter and 8 mm outer diameter which is heated with Joule effect. The working fluid is refrigerant R134a. A Micropump GC-M35 is used which provides a not pulsating flow. Four flow conditions are considered in this study: (a) The steady flow condition has been achieved by controlling an inlet valve before the test section which stabilizes the flow preventing the occurrence of two-phase flow instabilities, (b) self-sustained density wave oscillations condition where a bypass section is used to mimic the constant pressure drop condition[23–25] normally used in the numerical studies, (c) controlled flow oscillations with similar flow amplitude and period than the DWOs were set by controlling the driver of the pump, (d) controlled pressure fluctuations were introduced by controlling the inlet valve to the test section. The test section is instrumented with thermocouples distributed about every 215 mm at the top and bottom of the test section. In particular, 4 thermocouples are installed at 1117 mm and at 1917 mm from the inlet, in order to compute the heat transfer coefficient. In this work the heat transfer coefficient at 1917 mm from the inlet is presented. The temperature of the fluid is estimated based on the inlet conditions and by two internal thermocouples installed at these locations. Further details can be found in previous publications[10,17,19] and in the supplementary material.

Heat transfer comparison. To compare the heat transfer rates among the steady flow, flow-controlled oscillations, and the self-sustained naturally occurring DWOs as shown in Fig. 2, the following methodology is adopted for the experiments. First, the heat transfer coefficient is obtained for DWOs. The power is gradually decreased in a stepwise manner, which changes the amplitude and period of the DWOs. Next, the heat transfer coefficient of flow-controlled oscillations of the same amplitude and period as of the DWOs is measured. Numerical studies of oscillatory single-phase flows can be found in the literature[26,27]. Finally, the heat transfer coefficient for steady flow is measured.

Fig. 2a shows the heat transfer coefficient corresponding to the DWO's, flow controlled oscillations and steady state flow. The corresponding amplitude of the mass flux, inlet pressure, fluid temperature and wall-fluid temperature difference are presented in Fig. 2c.

The heat transfer coefficient for the DWOs is lower than the one corresponding to flow-controlled oscillations and steady flow. In particular, the amplitude of the mass flux for the DWO's and the flow controlled oscillations ΔG are similar. This fact suggests that the amplitude of the mass flux is not a sufficient condition of the heat transfer deterioration observed. Further it challenges existing theories. To understand the possible cause of the heat transfer deterioration, Fig. 2b shows the time evolution of the selected conditions. It is possible to observed that in the case of the DWOs, the pressure is also oscillating which is not the case for the flow-controlled case and steady flow case. Further, examining Fig. 2c it is possible to see that the amplitude of the pressure at the entrance of the test section ΔP_{in} and the wall-fluid temperature difference $T_{wall} - T_{fluid}$ are well correlated. For the conditions in the experiments in 2, the oscillations the fluid properties are varying no more than 2%, but the saturation temperature can vary up to $1.3°C$.

It is possible to assume that the underlying cause of the heat transfer deterioration due to the pressure oscillations is related to an accumulation of vapor on the surface. To investigate this effect, the flow structure at the outlet of heated test section is shown in Fig 2d. The experiments were performed at a heat flux of 41.9kW/m^2 and mass flux of 350 kg/m^{2}s and a fluid temperature of 2^{o}C at the inlet of the test section. Clearly, during the DWO's the flow varies between mist and annular flow with a short phase of dryout condition at the wall. During the flow controlled oscillation, the flow structure is not really affected. In Fig 2e, the limit cycle of the oscillations in terms of P-G and T_{fluid}-P maps are presented. The oscillation in the pressure is strongly couple with the fluid temperature. This effect can be the trigger of sudden vapour generation and accumulation, and the subsequent heat transfer deterioration.

This comparison between the flow control case and the steady flow case suggests that the amplitude and period of the oscillation is not a sufficient condition for the heat transfer deterioration observed in the DWOs. This result suggests that the role of the pressure oscillations on the heat transfer deterioration has been overlooked. Although not acknowledged in previous studies[8,9], experimental data does show a strong link between pressure oscillation and wall temperature as well.

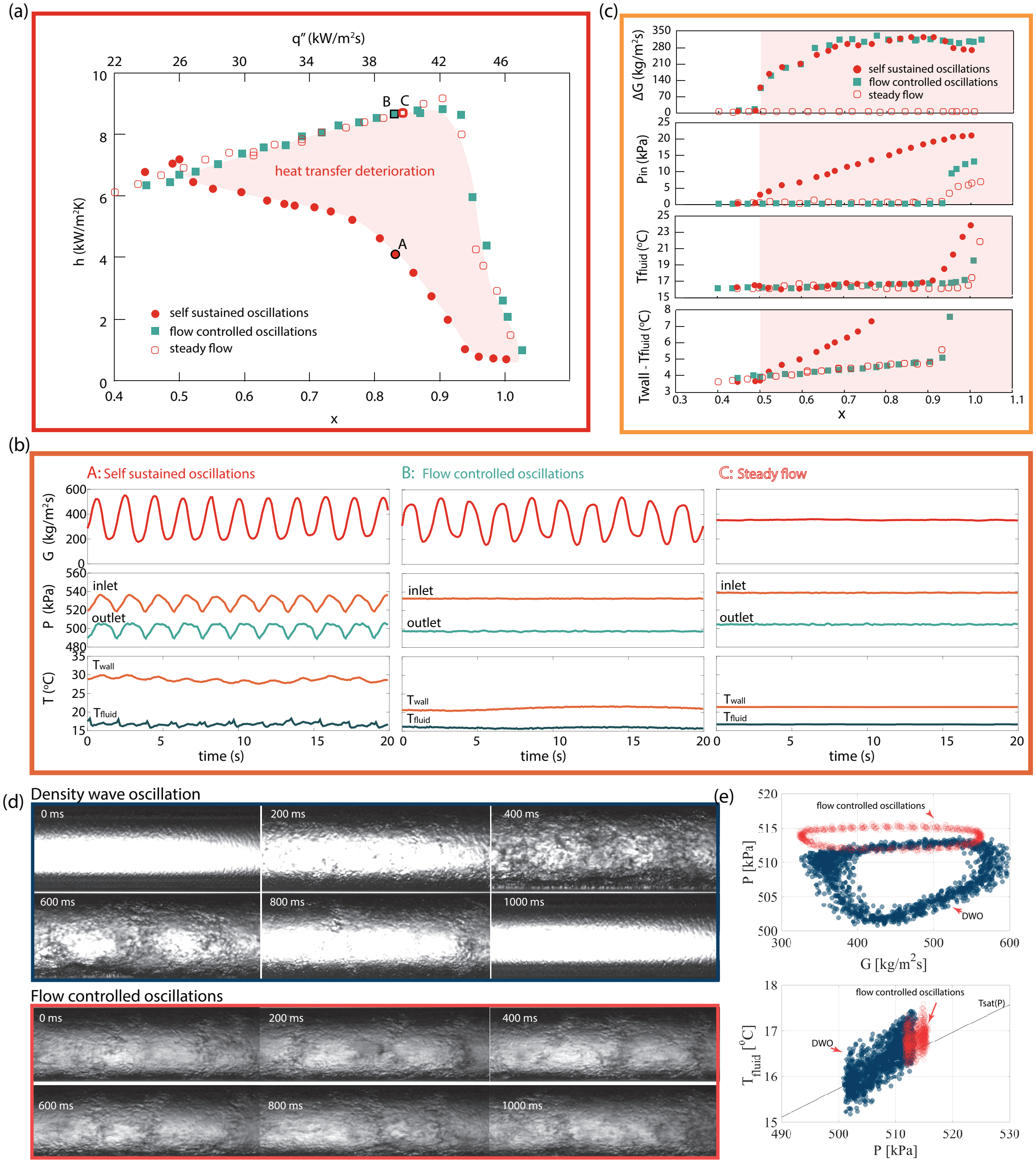

FIG. 2. **(a)** Heat transfer coefficient measurements ($G_{mean} = 350 kg/m^2s, P = 500 kPa$) for steady flow, controlled flow oscillation and self-sustained oscillation. The self-sustained oscillation shows lower heat transfer coefficient than the steady flow and the flow controlled oscillation cases. **(b)** Instantaneous mass flux, pressure, and temperature at the fluid and wall at selected conditions. **(c)** The amplitude of the mass flux, inlet pressure and temperatures corresponding to (a). **(d)** Flow visualisation of the DWO's and flow controlled oscillations at the outlet of test section. **(e)** Limit cycles of the flow oscillations.

Confirmation of the influence of pressure oscillations. If the pressure oscillations are the cause of the heat transfer deterioration, this suggests that a possible mechanism is the sudden formation and accumulation of vapor at the wall during the minimum of the pressure cycle. For confirming the role of the pressure oscillations on the heat transfer deterioration, two experiments have been designed. The first experiment triggers local pressure oscillations in a steady flow, see Fig. 3a. It is possible to observe that the perturbations of the pressure have a strong effect on rising the wall temperature and thus deteriorating the heat transfer coefficient compared to the

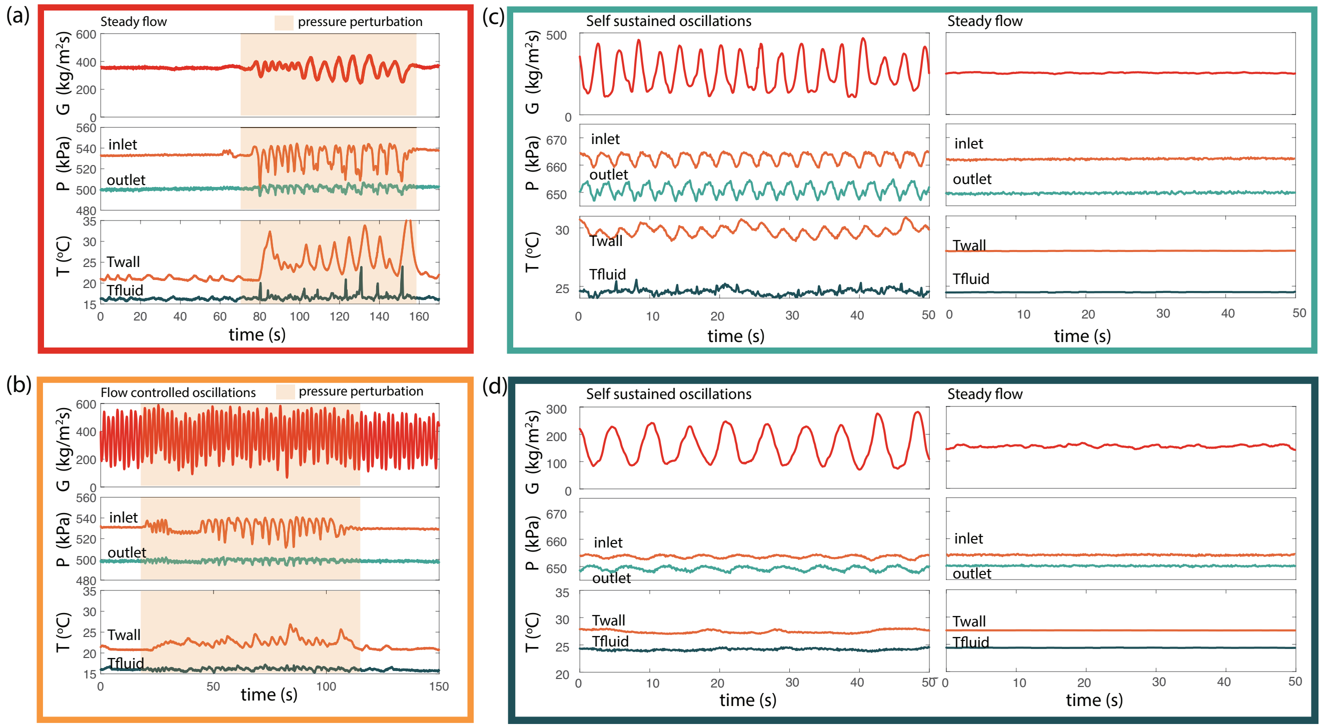

FIG. 3. **(a)** When a pressure perturbation is applied to the steady flow to mimic the pressure oscillations, it increases the wall temperature. **(b)** Similar to the previous case when a pressure perturbation is applied to the flow velocity oscillations, the wall temperature increases. The two cases shown in (a) and (b) confirm that the pressure oscillation plays a dominant role in deteriorating the heat transfer rate. **(c)** DWO case where the instantaneous wall temperature is higher than the corresponding steady flow case implying heat transfer deterioration. Note that the amplitude of the pressure oscillation is significant. **(d)** DWO case where the instantaneous wall temperature is almost the same to the steady flow case implying no heat transfer deterioration. Note that the amplitude of the pressure oscillation is negligible.

steady flow. In the second experiment, see Fig. 3b, the goal was to recreate the conditions of the self-sustained DWOs. For this case, the pump controlled case was set with flow velocity oscillations and then pressure oscillations were triggered by an oscillating valve. In this case, the pressure fluctuations increase the wall temperature and thus deteriorate the heat transfer coefficient.

For testing the influence of pressure oscillations on the heat transfer deterioration during the DWOs, Fig. 3c and Fig. 3d compare the heat transfer characteristics with and without pressure oscillations, respectively. In Fig. 3c and Fig. 3d it is possible to see that DWOs with negligible pressure oscillations are not deteriorating the heat transfer. Thus, from this results it is possible to confirm that the heat transfer deterioration in DWOs is related to the particular characteristics of the associated pressure oscillations, and this is related to the feedback between the mass flux and the characteristics of the external system, i.e. the driving of the flow. Note that the amplitude and period of pressure oscillations in a system strongly depend on the external configuration of the system[28–30], namely the characteristics of the pump, valves, and the overall flow loop. In particular, the effect of the slope of the pump characteristic curve and the bypass on the amplitude of the oscillations is evident from previous research[28–31]. Therefore, this study concludes that the self-sustained oscillations when triggered by an external system with minimum pressure oscillations, i.e. controlling the demand curve of the pump, do not cause heat transfer deterioration. This suggests that in the quest of thermal management in two-phase flow engineering applications that frequently encounter flow oscillations, a proper characterisation of the external system is required. This ensures minimising the pressure oscillations by the appropriate adjustment of the external configuration of the system.

In summary, we show that during self-sustained flow oscillations, in particular during density wave oscillations, the associated pressure oscillations activate the physical mechanisms leading to heat transfer deterioration. In the absence of pressure oscillations, a high amplitude flow velocity oscillation does not deteriorate the heat transfer. Therefore, it is postulated that to avoid heat transfer deterioration during flow oscillations, the pressure oscillations in the system need to be minimised.

Suplementary Material

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

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

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