On the occurrence of superimposed density wave oscillations on pressure drop oscillations and the influence of a compressible volume

Il Woong Park, Maria Fernandino, and Carlos A. Dorao

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On the occurrence of superimposed density wave oscillations on pressure drop oscillations and the influence of a compressible volume

Il Woong Park, Maria Fernandino, and Carlos A. Dorao[a]
Kolbjørn Hejes v1b, 7491 Trondheim, Norway

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Although two-phase flow instabilities are attributed to be one of the impediments for achieving high heat flux in boiling systems, most of their fundamental characteristics remain uncharted. In particular, pressure drop oscillations and density wave oscillations are two types of dynamic two-phase flow instabilities that can cause large variations in pressure and temperature. Under particular working conditions, both oscillations have been observed to interact, resulting in long-period pressure drop oscillations with superimposed short-period density wave oscillations. However, in this situation, the amplitude of the density wave oscillations is typically larger than the corresponding to a pure density wave oscillation. Here, we show that a compressible volume in the system, essential for the occurrence of pressure drop oscillations, plays a major role in amplifying the amplitude of the superimposed density wave oscillations. https://doi.org/10.1063/1.5040113

I. INTRODUCTION

Flow boiling is characterized by a complex interplay of hydrodynamic and thermal effects that can exhibit flow instabilities. These two-phase flow instabilities can result in transient and dynamic events that can induce mechanical and thermal fatigues, in addition, to deteriorate heat transfer in boiling systems.[1,2] In order to overcome the drawbacks of the flow instability, recent studies show the efforts for controlling and suppressing the oscillations.[3–5] Two typical types of dynamic two-phase flow oscillations are density wave oscillations and pressure drop oscillations which are characterized by short and large period oscillations respectively.[6–8] Since the 60s research has been carried out for unveiling the physics of the process and developing suitable models for predicting and controlling the occurrence of such instabilities.

Under particular working conditions, density wave and pressure drop oscillations can interact establishing a long-period oscillation with superimposed short-period oscillations at the minimum of the long-period oscillations. However, the corresponding superimposed density wave oscillation shows a larger amplitude compared with the pure density wave oscillation. For example, in previous studies, it is possible to observe that the amplitude of the superimposed density wave oscillation has been amplified about five to ten times.[9–11]

Only a few studies have been focused on understanding the interplay of density wave and pressure drop oscillations. Briefly, a typical boiling system where two-phase flow oscillations may occur consists in a heated section, inlet and outlet valves (or orifice plates) is characterized by a compressible volume due to the presence of vapor in the system. This compressible volume is typically represented in experimental studies with a surge tank connected upstream of the test section. Liu and Kakaç (1991)[12] suggested that superimposed density wave oscillations could occur due to complete boiling during the pressure increase stage in the pressure drop oscillation limit cycle. Menteş et al.

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[a] Author to whom correspondence should be addressed. Electronic mail: carlos.dorao@ntnu.no

(1989) explained that the superimposed density wave oscillations could be triggered by a sudden change in the mass flow rate due to bubbles crossing the orifice in the inlet valve.[13] Moreover, in this case, the sudden change of the pressure is accompanied by a change in the mass flux. Using linear frequency domain stability models, Yin et al. (2006) showed that pressure drop oscillations occur due to the compressible volume at the heater inlet, while density wave oscillations are not affected by the latter.[14] In summary, in the previous studies, the superimposed oscillations have been attributed either to the complete boiling during pressure drop oscillations,[12] or sudden change of the mass flux in the orifice valve during the pressure drop oscillations[13] or the interaction of the oscillations.[14] In this letter, we show that the compressible volume in the surge tank upstream of the test section plays a major role in controlling the amplitude of the superimposed density wave oscillations.

II. EXPERIMENTAL SECTION

To investigate the interplay of density wave and pressure drop oscillations an experimental facility was constructed consisting of a horizontal test section of 5mm ID stainless steel pipe heated with Joule effect using R134a as working fluid, Figure 1. A surge tank was located just upstream of the test section to control the available compressible volume in the system. Details of the experimental facility, experimental procedures, calibration tests and uncertainty analysis are presented in the supplementary material.

III. RESULTS AND DISCUSSIONS

Figure 2(a) and 2(c) show a reference case for the superimposed density wave oscillations during pressure drop oscillations. The selected conditions of the experiment were a mass flux of 700 kg/m^{2}s, subcooling of 37.5 K, the inlet pressure of 7.0 kPa and 0.0043 m^3 of compressible volume in the surge tank. For this experiment, the valve connected to the surge tank was opened for triggering the pressure drop oscillations. In this case, it is possible to observe short-period, high-amplitude density wave oscillations superimposed on the long-period pressure drop oscillations. In order to exclude the effect of the compressible volume on the pressure drop oscillations, the approach consisted in mimicking the mass flux oscillations observed during the pressure drop oscillations by controlling the pump while maintaining the surge tank closed. Figure 2(b) and 2(d) show the profile of the mass flux

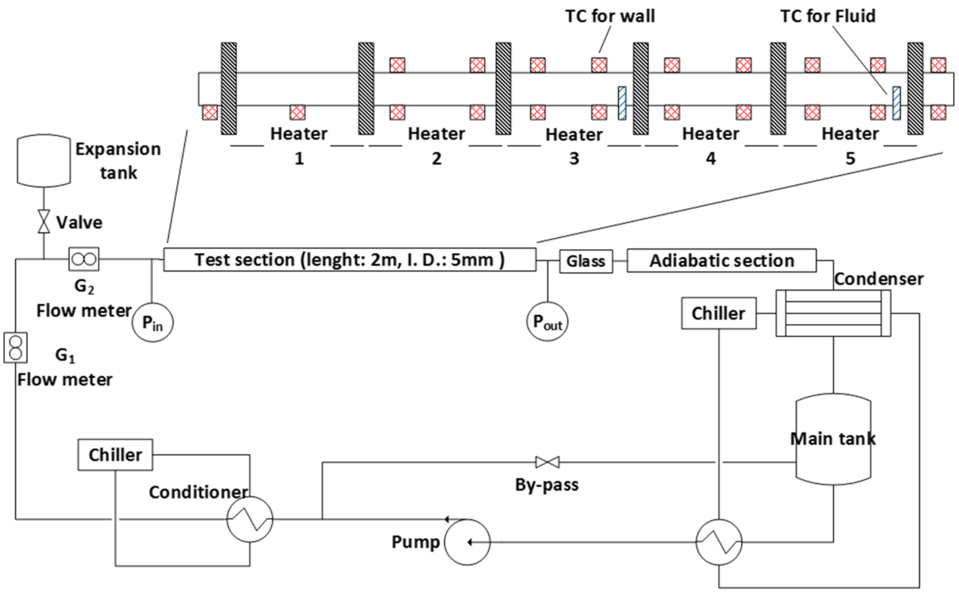

FIG. 1. Sketch of the experimental facility and test section.

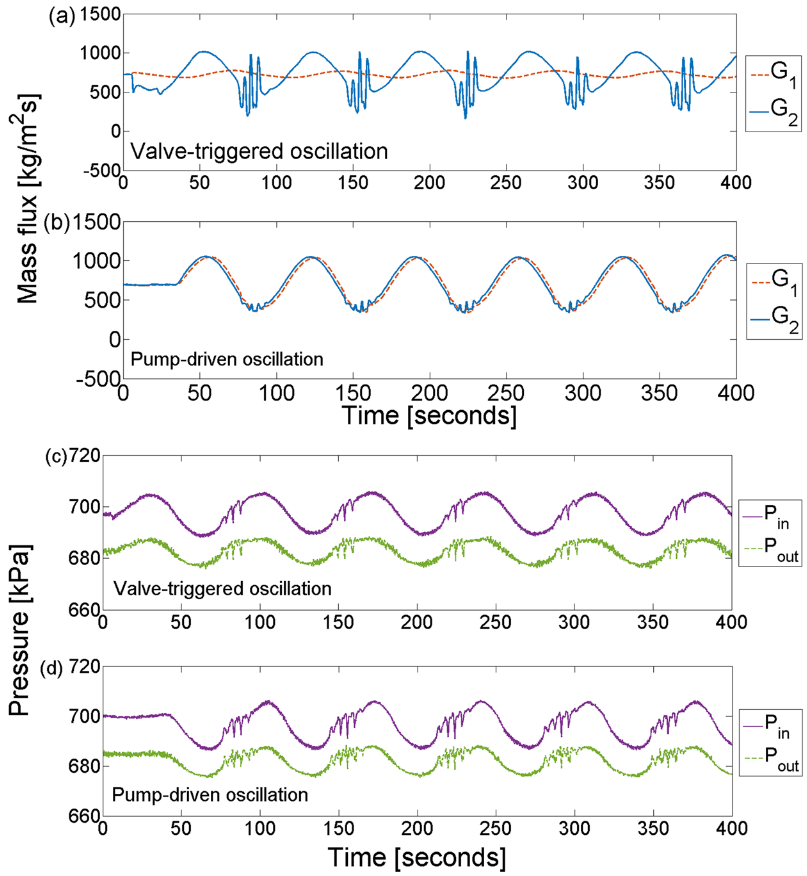

FIG. 2. Mass flow rate and pressure of valve-triggered oscillation (a, c) and pump-driven oscillation (b, d).

and the pressure under the pump-driven oscillatory condition. Comparing these two cases, i.e. the pressure drop oscillations with superimposed density wave oscillations and the mimicked pressure drop oscillations by controlling the flow with the pump, the amplitude of the mass flux oscillation during the density wave oscillations was significantly suppressed. However, it is possible to see short-period superimposed oscillations in the evolution of the pressure. This shows that the occurrence of the superimposed density wave oscillations during pressure drop oscillations does not depend on the presence of a compressible volume.

The previous experiments suggest that the compressible volume controls the amplitude of the density wave oscillations, amplifying it. In order to confirm this, the following experiment was performed. For a particular initial condition of 300 kg/m^{2}s of mass flux, 0.0043 m^3 of compressible volume and 30.0 K of subcooling (where pressure drop oscillation cannot occur even if the valve for the expansion tank is opened) the influence of the compressible volume on the pure density wave oscillations is studied. The valve for the compressible volume was opened (at 50 and 250 seconds) and closed (at 150 seconds and 350 seconds) as shown in Figure 3(a) and 3(d). The profiles of the mass flux and pressure evolution are depicted in Figure 3(b) and 3(e) for the closed valve and in Figure 3(c) and 3(f) for the opened valve. With the compressible volume not connected, density wave oscillations do not fully develop and only small amplitudes (~20 kg/m^{2}s) are observed. However, with the compressible volume connected, density wave oscillations develop fast reaching large amplitudes (~700 kg/m^{2}s). This experiment confirms the role of the compressible volume not only for the occurrence of pressure drop oscillations but also in the amplification of the density wave oscillations. In particular, this experiment shows that the occurrence of large-amplitude density wave oscillations superimposed on pressure drop oscillations is a consequence of the presence of the compressible volume.

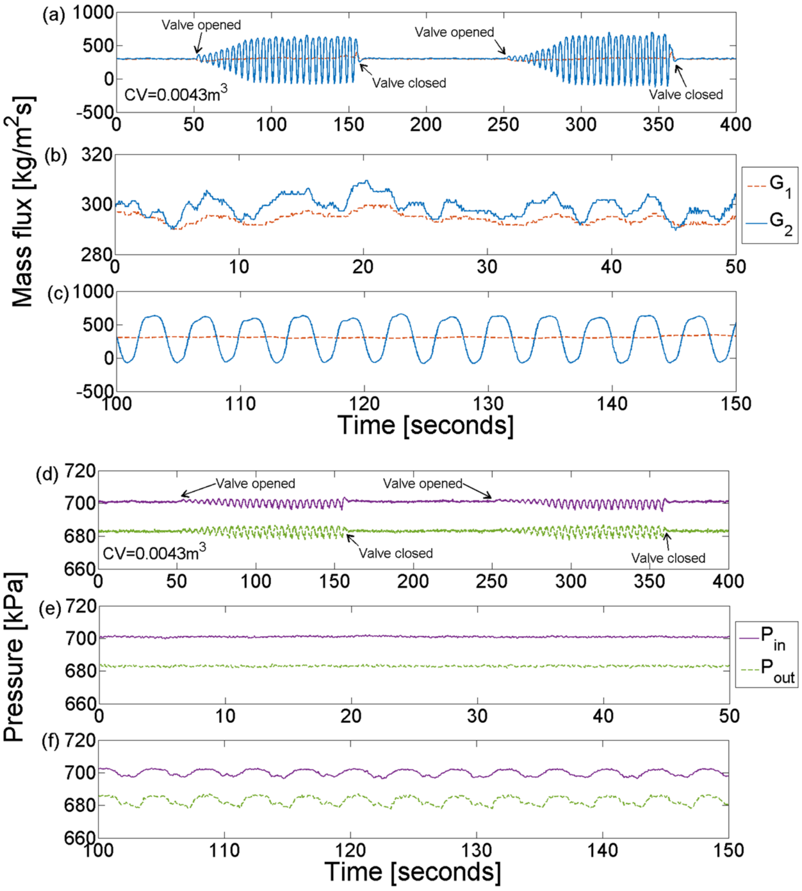

FIG. 3. Effect of the existence of the compressible volume on mass flux (a-c) and pressure (d-f) during density wave oscillations. The valve for the compressible volume was opened at 50 and 250 seconds and it was closed at 150 and 350 seconds.

In the next part of this study, the influence of the compressible volume on the magnitude of the amplitude of pure density wave oscillations is studied. Compressible volumes of 0.0013 m^3 and 0.0094 m^3 are tested as shown in Figure 4. It is observed that the compressible volume is essential

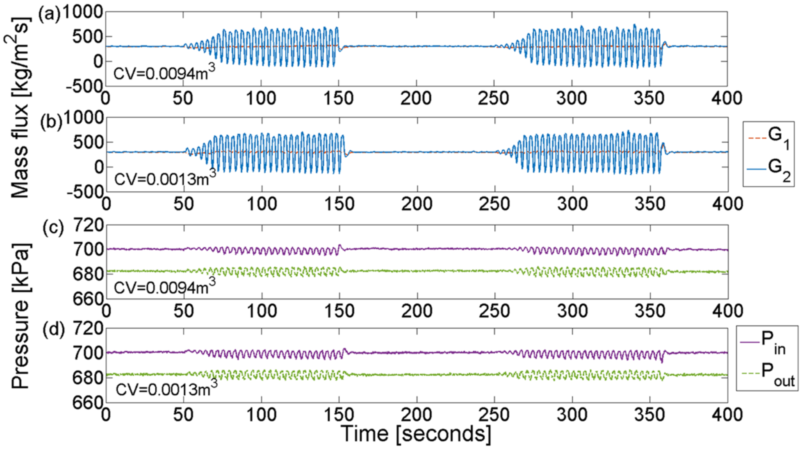

FIG. 4. Mass flux and pressure during amplified density wave oscillations with 0.0094 m^3 (a, c) and 0.0013 m^3 (b, d) of compressible volume. The valve for the compressible volume was opened at 50 and 250 seconds and it was closed at 150 and 350 seconds.

for the large amplitude of the density wave, but it is not possible to observe a dependency of the amplitude of the density wave on the value of the compressible volume for the studied cases.

Now, under pressure drop oscillations condition, the influence of the magnitude of the compressible volume on the amplitude of the density wave oscillations is studied by setting the compressible volume at 0.0013 m^3, 0.0043 m^3 (corresponds to the reference case in Figure 2(a)) and 0.0094 m^3, with a mass flux of 700 kg/m^2s and 37.5 K of subcooling as the initial conditions. As shown in Figure 5, the magnitude of the compressible volume influences the characteristics of both the pressure drop and superimposed density wave oscillations. In the case of the large compressible volume (Figure 5(a) and (b)), a larger amplitude of mass flux oscillations and the longer period of pressure drop oscillations were observed as compared to the low compressible volume case. Moreover, the amplitude of the superimposed density wave oscillations is more enhanced when the compressible volume is large. On the other hand, superimposed density wave oscillations disappeared in the case of small compressible volume, as shown in Figure 5(c) and (d). According to the findings above, it seems like the rate of change of the mass flux was not large enough to be considered as a sudden perturbation for triggering density wave oscillations. The small amplitude of the pressure drop oscillations was a consequence of the level of the compressible volume. This shows that the operating conditions could change the profile of the pressure drop oscillations while the occurrence of the superimposed density wave oscillations is controlled by the rate of change of the mass flux during pressure drop oscillations.

Superimposed density wave oscillations can be triggered by the sudden perturbation of the pressure drop which causes the perturbation of the flow rate. In the last part of this study, it is studied whether the pressure drop oscillations can be considered as a sudden perturbation of the mass flux for

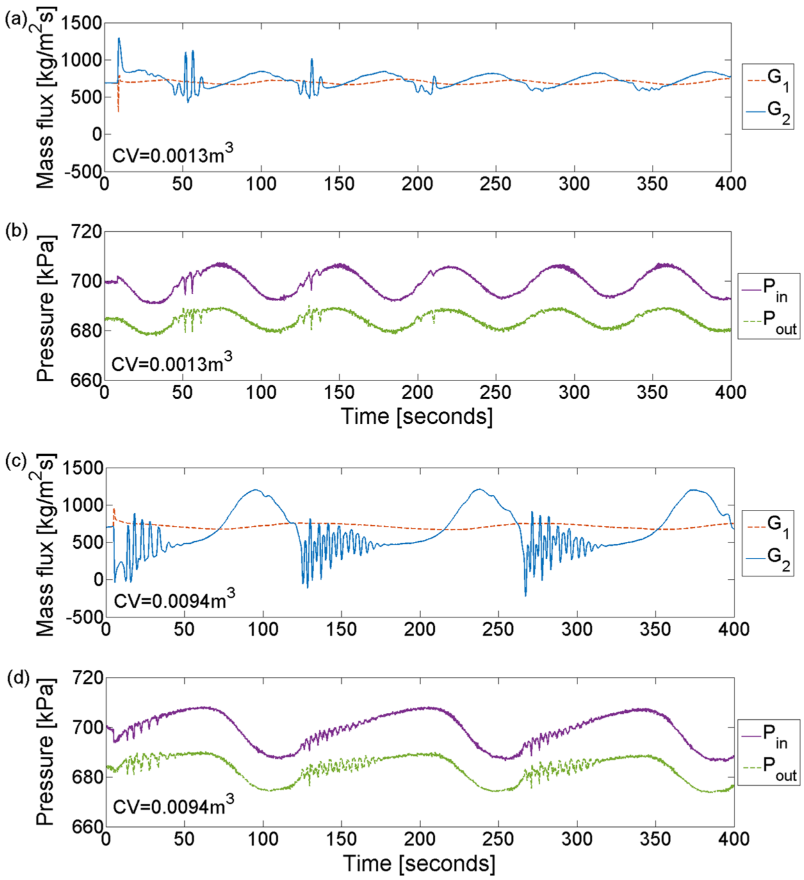

FIG. 5. Mass flux and pressure during pressure drop oscillations with 0.0094 m^3 (a, b) and 0.0013 m^3 (c, d) of compressible volume.

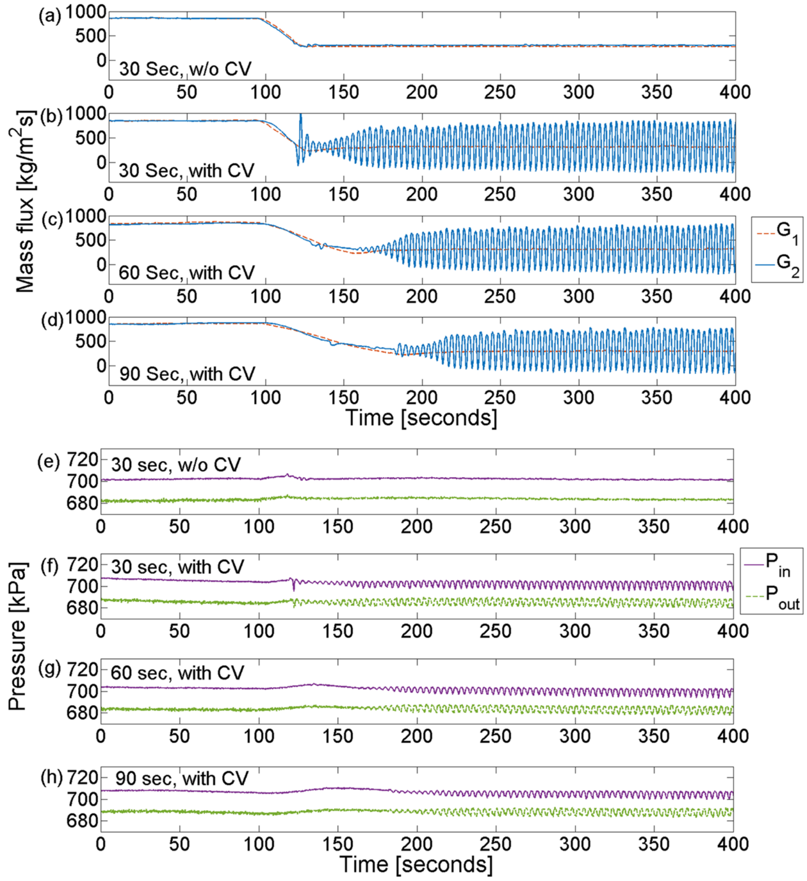

FIG. 6. Occurrence of density wave oscillations by reducing the mass flux without compressible volume during 30 seconds (a, e), with compressible volume during 30 seconds (b, f), 60 seconds (c, g), and 90 seconds (d, h).

triggering density wave oscillations. It is assumed that the superimposed density wave oscillations could instantly develop when the rate of change in the mass flux is fast enough. The experiment consists in suppressing the oscillatory condition of the pressure drop oscillations and mimicking the decreasing profile of the mass flux under the pressure drop oscillations by controlling the mass flux with the pump. As initial conditions, 850 kg/m^{2}s of mass flux, 30.0 K of subcooling and 7.0 kPa of inlet pressure were selected. The mass flux was varied decreasingly from 850 to 300 kg/m^{2}s as shown in Figure 6. The same variation of mass flux was performed in a time interval of 30 seconds (Figure 6(a) and 6(b)), 60 seconds (Figure 3(c)) and 90 seconds (Figure 6(d)). The corresponding profiles of the pressure are also depicted in Figure 6(e), 6(f), 6(g) and 6(h). The valve between the compressible volume and the test section was closed in the case of Figure 6(a) while the valve was opened in the case of Figure 6(b–d). As shown in Figure 6(a), small perturbations of the mass flux were observed in this case. However, density wave oscillations did not develop under these conditions (i.e. no compressible volume) even though the mass flux was varied fast. As observed in Figure 6(b), density wave oscillations can develop instantly during the mass flux decreasing. In the other cases (Figure 6(c) and 6(d)), density wave oscillations were gradually developed after the decrease in mass flux is finished. Interestingly, the large-amplitude peak observed just after the sudden drop of the mass flux in Figure 6(b) is similar to the large-amplitude oscillations observed during the superimposed density wave oscillations in Figure 2(a) and 5(a). This could imply that a fast change in the mass flux during a pressure drop oscillation can be considered as a sudden perturbation and is an essential condition for the occurrence of the superimposed density wave oscillations.

The objectives and findings for each experiment are summarized in order to present overall picture clearly as shown in table I.

TABLE I. List of the objective of the experiments and finding from each experiment.

Figure	The objective of the experiments	Finding from the experiments
2	Mimicking of the valve-triggered (self-induced) oscillations by controlling the pump	Mass flux of superimposed density wave oscillations amplified for valve-triggered cased.
3	Decoupling of the effect of the existence of the compressible volume from the pressure drop oscillations	Amplitude of the density wave oscillation is amplified because of the existence of the compressible volume.
4	Identifying the effect of the level of the compressible volume on the pure density wave oscillations	There is no dependency of the amplitude of the pure density wave oscillations.
5	Identifying the effect of the level of the compressible volume on the superimposed density wave oscillations	Level of the compressible volume affect the characteristics of superimposed density wave oscillations and pressure drop oscillations.
6	Decoupling the effect of the transition of the mass flux from the oscillatory flow	Essential condition for the superimposed density wave oscillations is the fast change in the mass flux.

It can be noticed that an effective method has not been developed for the complete elimination of the two-phase flow oscillations.[15] Thus, investigation on two-phase flow instability is still necessary. It is shown for the first time that density wave oscillations over imposed on pressure drop oscillations are having a larger amplitude compared to pure density wave oscillations as a consequence of the expansion tank. Besides, it is shown for the first time that the rate of change of the flow plays a major role in triggering the density wave oscillations. These two findings can provide a new insight into the physics of two-phase flow instabilities.

IV. CONCLUSION

In summary, in this study superimposed density wave and pressure drop oscillations were decoupled with an experimental technique for identifying the characteristics of the oscillations. It was found that density wave oscillations can be superimposed on pressure drop oscillations when the large-period oscillations corresponding to the pressure drop oscillations imposes a fast rate of change in the mass flux. The amplitude of the mass flux oscillations during density wave oscillations can be amplified due to the existence of the compressible volume which is the essential condition for pressure drop oscillations. The level of the compressible volume can affect the characteristics of the pressure drop oscillations, while the latter can, in turn, trigger the density wave oscillations when accompanied by a fast change in mass flux.

SUPPLEMENTARY MATERIAL

See supplementary material for the details of the experimental setup and procedure.

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