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Effect of heating profile on the characteristics of pressure drop oscillations

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ABSTRACT

The effect of the heating profile on the characteristics of pressure drop oscillations (PDO) are studied. The experiments are performed in a 2 m horizontal test section of 5 mm I.D. and R134a as working fluid. The PDOs are characterised by a low frequency oscillation with a superimposed high frequency oscillation at the minimum of the flow oscillation for some conditions. This work has focused on identifying how the heating profile can modify the presence of the high frequency oscillations. In particular it was observed that the high frequency oscillations appear in a given range of heat flux, while at low and high heat fluxes with a uniform heating profile the high frequency oscillations vanish. In addition, a decreasing power distribution can increase the presence of high frequency oscillations, and at high heat fluxes only high frequency oscillations are observed.

1. Introduction

Two phase flow instabilities have been extensively studied during the past decades (Boure et al., 1973; Tadrist, 2007; Durga Prasad et al., 2007; Kakac and Bon, 2008; Liang et al., 2010) due to its relevance in different areas such as refrigeration systems, boiling water reactors and steam generators. The induced oscillations of the flow rate and system pressure are undesirable as they can cause mechanical vibrations, thermal fatigue, transient burn-out of the heat transfer surface, degradation of the heat transfer performance and problems of system control.

Pressure drop oscillations (PDOs) are a particular case of two phase flow instabilities. They are dynamic instabilities caused by a Hopf bifurcation (Padki et al., 1992). A PDO occurs in a system having compressible volume upstream or within the heated section and when the system operates in the negative slope region of the N-shape curve, namely pressure drop vs. flow rate curve (Boure et al., 1973). PDOs have a long period (of the order of several seconds) and produce big excursions of the flow resulting in large variations in the local wall temperature (thermal oscillation). PDOs exhibit a long oscillatory period which is characterised by relaxation oscillations similar to the van der Pol oscillator (Grasman, 2011). In particular, the thermal capacity of the pipe wall plays a major role in the dynamics of the oscillations. A criterion for determining the impact of the wall thermal capacity in the PDOs was given in Manavela Chiapero et al. (2013).

The necessary conditions for the occurrence of this type of oscillations are Padki et al. (1992): (i) internal characteristic curve with negative slope; (ii) external characteristic curve steeper than internal curve; and (iii) upstream compressible volume (e.g. surge tank) in the flow circuit. The standard way to eliminate pressure-drop oscillations is to make the slope of internal characteristic curve positive (e.g. internal throttling). PDOs have been widely studied theoretically, e.g. Stenning and Veziroglu (1965), Doáan et al. (1983), Padki et al. (1991), Padki et al. (1992), Mawasha et al. (2001), and experimentally, e.g. Ozawa et al. (1979), Yünco and Yildirim (1991), Feng (), during the last decade. Gaining a better understanding of two phase flow instabilities and in particular PDOs has become particular relevant in mini- and micro-channels (Bogojevic et al., 2009; Kim and Mudawar, 2014; Lee et al., 2014) as these oscillations can affect the performance of the unit severely.

A summary of the research done on pressure drop instabilities and remaining challenges has been recently presented by Manavela Chiapero et al. (2012). It was acknowledged that the characterisation and understanding of the PDOs is essential due to its relevance in two phase systems ranging from large scale industrial equipment to microscale cooling devices. Previous research studies have identified that a compressible volume in the system can affect the characteristics of the oscillations. In this context, Guo et al. (2001) has shown that the location of the compressible volume upstream or downstream of the test section can modify the characteristics of the oscillation. Furthermore, the PDOs can exhibit high frequency oscillations similar to density wave oscillations (DWO) for some particular conditions. Liu and Kakac (1991) have observed that PDO with superimposed DWO occurs at the negative slope region of the characteristic curve. The interaction of the PDO and DWO has been studied numerically in Yin et al. (2006), Schlichting et al.

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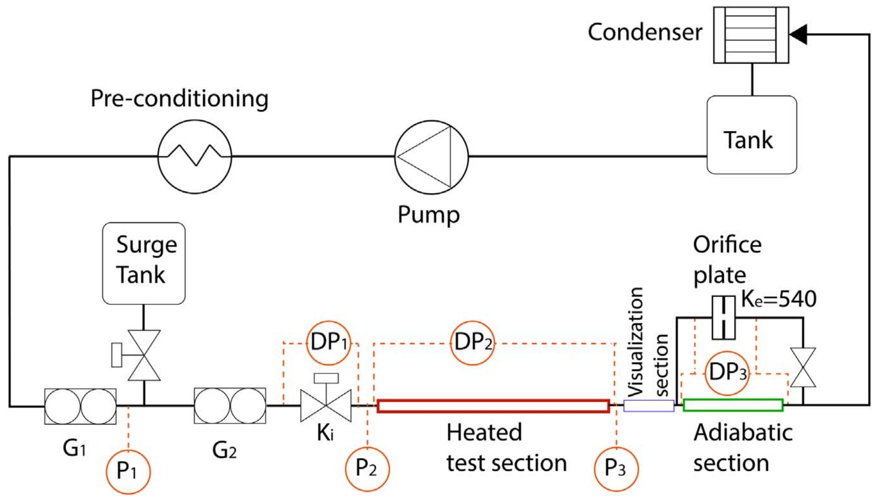

Fig. 1. Sketch of the test facility.

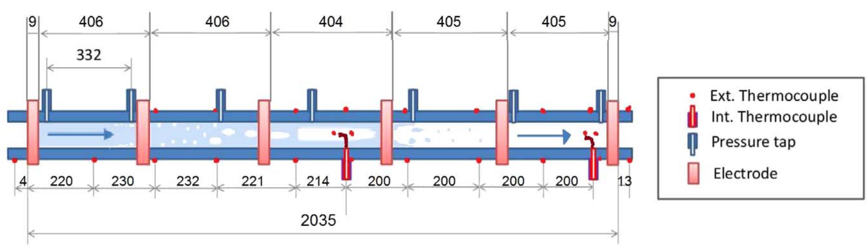

Fig. 2. Sketch of the heated test section.

(2010). In particular, Yin et al. (2006) has shown that if a compressible volume exists upstream of the boiling section, four modes of instability region exist: a pure DWO, a transition region, a region with PDO with superimposed DWO, and a pure PDO. This work has also pointed out to the need of well controlled experimental data for validation of the numerical models and for improving the understanding of the interactions between the instabilities modes, and in particular that available information on interacting instability modes is very limited on the literature. Recently, Manavela Chiapero et al. (2014) has pointed out to the limited research regarding the different modes of oscillation for PDO in parallel boiling channels. In particular in this experimental work considering two parallel channels no pressure drop oscillations with both channels following the typical limit cycle were found for the studied conditions. The oscillation mode detected consisted in one channel performing the usual limit cycle, while the other was always oscillating in the superheated vapour region confirming previous numerical predictions (Manavela Chiapero et al., 2013). Park et al. (2015) performed an experimental study about the effects of the mass flow and inlet subcooling on the period and amplitude of PDOs considering a uniform heated test section. The work has identified 4 types of behaviours during the test, namely: (i) no oscillation, (ii) decreasing flow oscillation, (iii) dominant long-period oscillation, and (iv) long-period oscillation followed by short-period oscillation.

In this work, the effect of the heating profile in the characteristics of the pressure drop oscillations is experimentally studied. The goal is to investigate the effect on the wave form of the oscillations and how the heating distribution can affect the occurrence of high frequency oscillations observed in the PDOs. The study is done in a horizontal straight tube evaporator of 5 mm ID and 2 m long, using refrigerant R134a as working fluid.

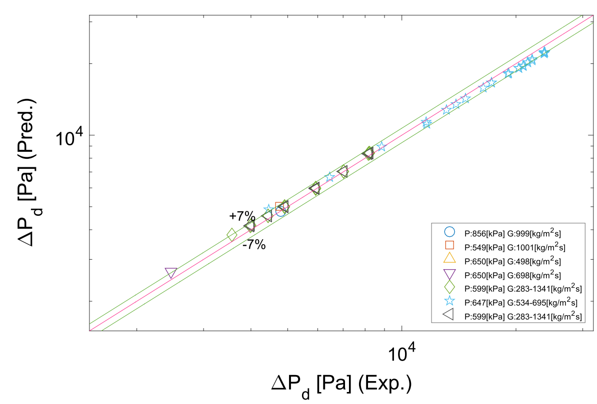

Fig. 3. Single phase flow validation.

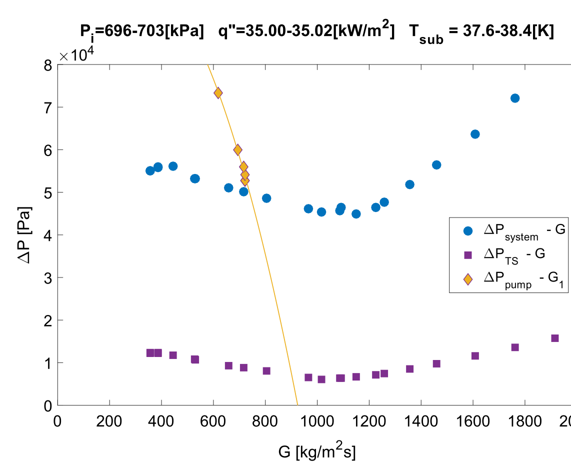

Fig. 4. N-shape curve of the heated section (ΔP_{TS}) and the flow loop (ΔP_{system}).

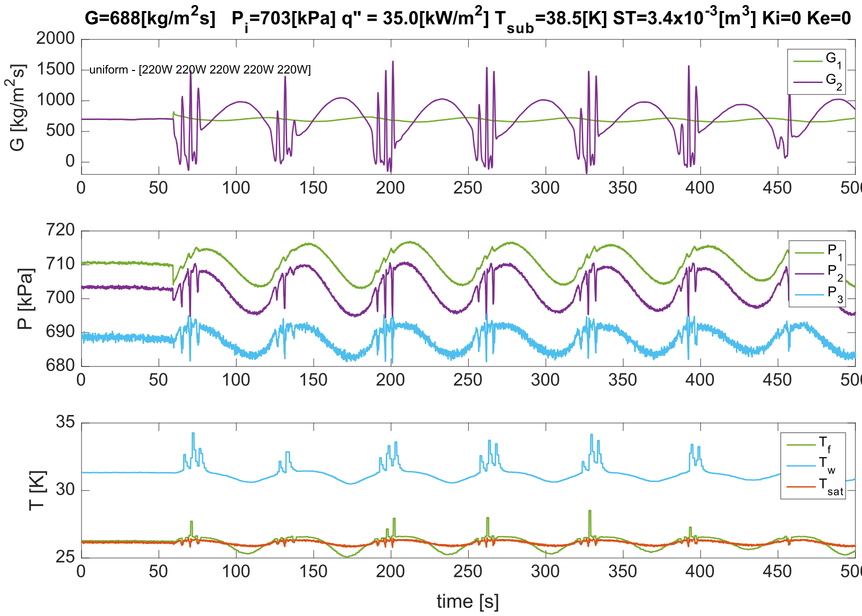

Fig. 5. Example of the evolution of main variables during a PDO.

2. Material and methods

The facility is a closed loop consisting of a main tank, a pump, a conditioner, a surge tank, a heated test section, a visualisation glass, an adiabatic test section and a condenser. The working fluid (R134a) is circulated by a magnetically couple gear pump. The pressure in the loop is controlled by the saturation conditions at the main store tank. A pre-heater or conditioner adjusts the inlet temperature of the refrigerant before entering the test section. The pre-heater is a shell and tube heat exchanger with glycol in the shell side.

For these experiments, the flow is measured with two Coriolis mass flow meter one located after the pump and one between the surge tank and the heated test section. Before the heated section a manually operated valve is installed, while after the heated section it is possible to select an orifice plate or an adiabatic section. The heated section is a stainless steel tube with 5 mm I.D. and 8 mm O.D.and 2035 mm long, (Fig. 1). The tube is heated by Joule effect with a rectified sine wave and is insulated to reduce heat loss to the surroundings. In order to have control of the heating profile, the heating is done by 5 independent sections of 40 cm long, (Fig. 2). The test section is equipped with 7 pressure taps for differential pressure drop measurements, a number of external (wall temperature) thermocouples, and 2 internal thermocouples to study heat transfer to the fluid. The pressure taps are connected to two pressure transducers by a network of valves which allows for a custom point of measurement. An additional third pressure differential transducer measures the overall test section pressure drop. Ten thermocouples are distributed along the outside bottom wall of the test section while there are seven on top. In particular, position 6 (at 1117 mm from the inlet) and 10 (at 1917 mm from the inlet) include thermocouples on the top, bottom, both sides of the wall plus an in-flow internal thermocouple. All the variables are logged with a National Instruments NI RIO data acquisition system. The temperatures, absolute pressures, pressure differences and mass flow rates were acquired at a frequency of 10 Hz.

The surge tank is a tank with a capacity of 9.5×10^{-3} m^3 with an inner diameter of 219 mm. The tank is pressurised with N_2 which control the level of refrigerant the surge. The inlet valve and the exit orifice is installed in a pipe of internal diameter of 12.7 mm. Considering the mass flux in this pipe, the inlet valve fully opened has a minor loss coefficient Ki =400. In order to indicate in the figure that the valve was fully opened, the legend of Ki =0 will be used instead of the real value. If the adiabatic section is used instead of the orifice, the legend of Ke =0 will be used.

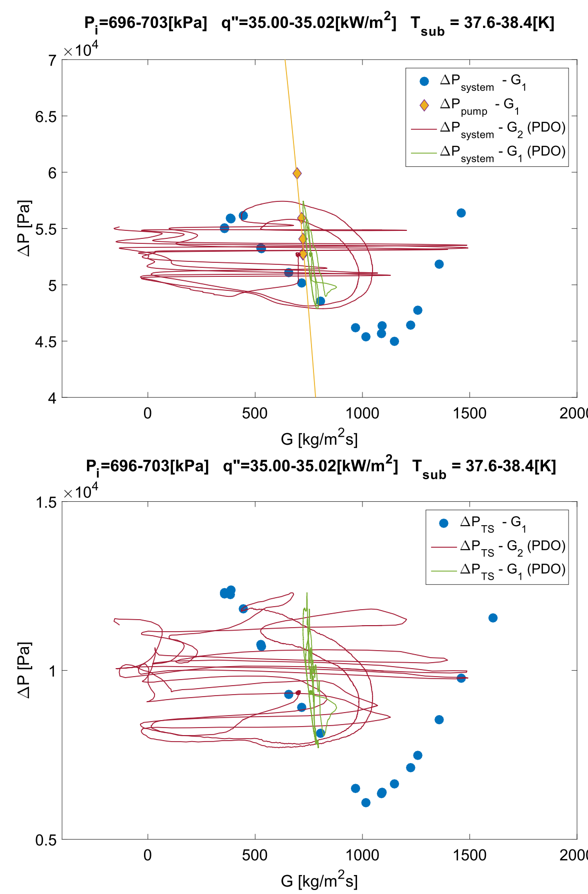

Fig. 6. N-shape curve of the heated section (ΔP_{TS}) and the flow loop (ΔP_{system}).

2.1. Measurements and accuracy of measurements

For the temperature measurement, type-T thermocouples with 0.5 mm diameter have been used with an accuracy of 0.1 K (in-house calibration). The absolute pressure at the inlet and outlet of the heated section was used for determining the saturation temperature, T_{sat}, of the fluid based on the equilibrium properties calculated with software REFPROP.

The inlet and outlet pressures are measured with absolute pressure transducers with an accuracy of 0.04% at full-scale (25 bar) given by the supplier. The two-phase total pressure drop along each test section is measured with a differential pressure transducer with an accuracy of 0.075% at full-scale (50 kPa) given by the supplier. For the heat flux, q", the error coming from the propagation is the error associated with the voltage and current measurements. Nevertheless, the thermal heat transfer to the fluid under stationary conditions was calibrated against the electrical value for different temperatures and conditions for single-phase liquid considering the heat exchange with the surrounding arriving to a final accuracy of 3%.

The vapour quality is obtained by performing a heat balance along the test section as shown below

$$x(z) = \frac{\int_{z0}^{z} q''\pi D_i dz - G\ A\ cp_l\ T_{sub}}{G\ A\ h_{lv}} \quad (1)$$

Here $x(z)$ is the fluid quality at point $z\,[m]$ along the heated section, $G\,[kg/m^2\ s]$ is the mass flux, $A\,[m^2]$ is the cross section area of the pipe, $cp_l\,[J/kgK]$ is the liquid phase heat capacity of the fluid, $h_{lv}\,[kg/m^2\ s]$ is the enthalpy of vaporisation and $T_{sub}\,[K]$ the inlet subcooling. A mass flow rate accuracy of 0.2% of the reading was given by the supplier.

2.2. Single–phase validation and uncertainties

The system was tested with single–phase flows and these results were compared with known correlations. The single phase friction factor, f, was compared with the Colebrook correlation which is typically used for Reynolds number between 4000 and 10^8,

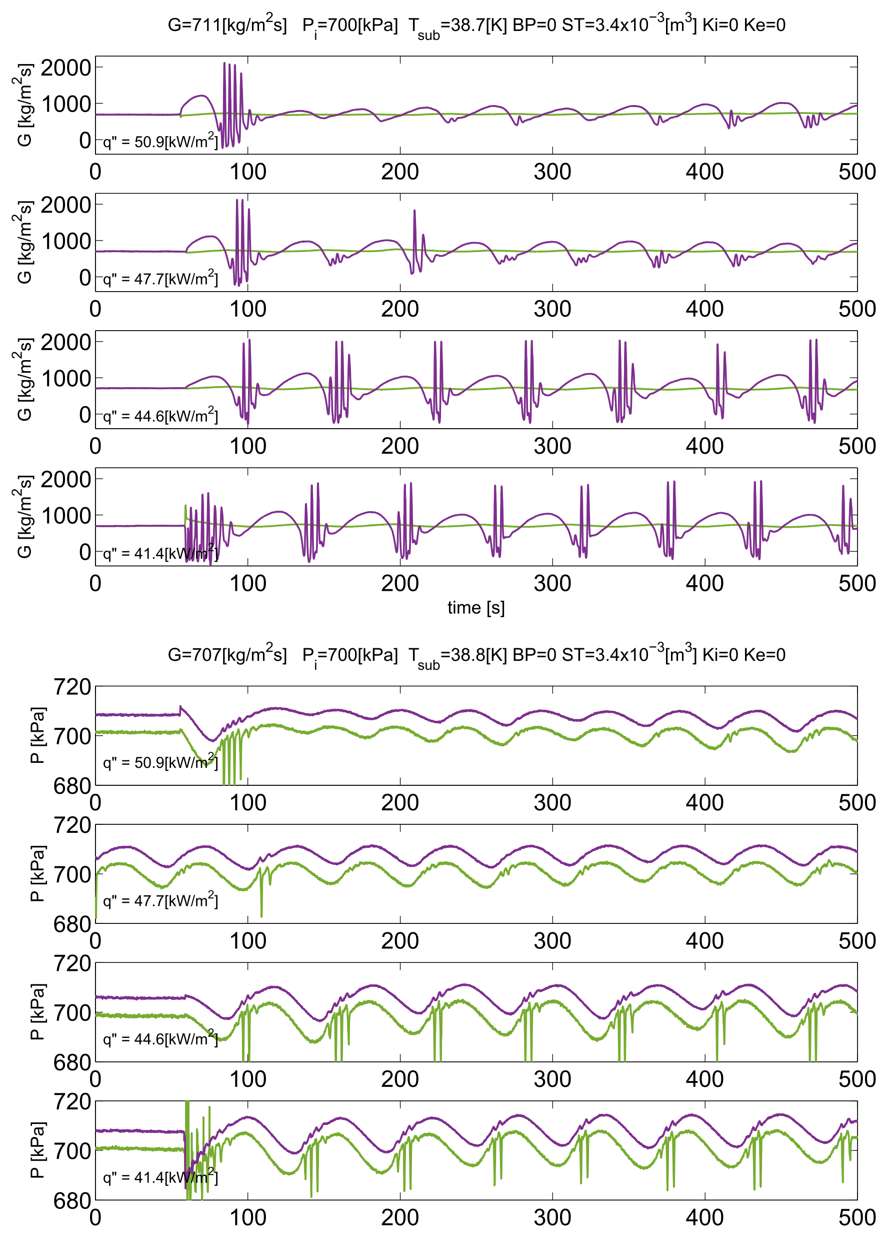

Fig. 7. Effect of the heat flux on the characteristics of the PDO.

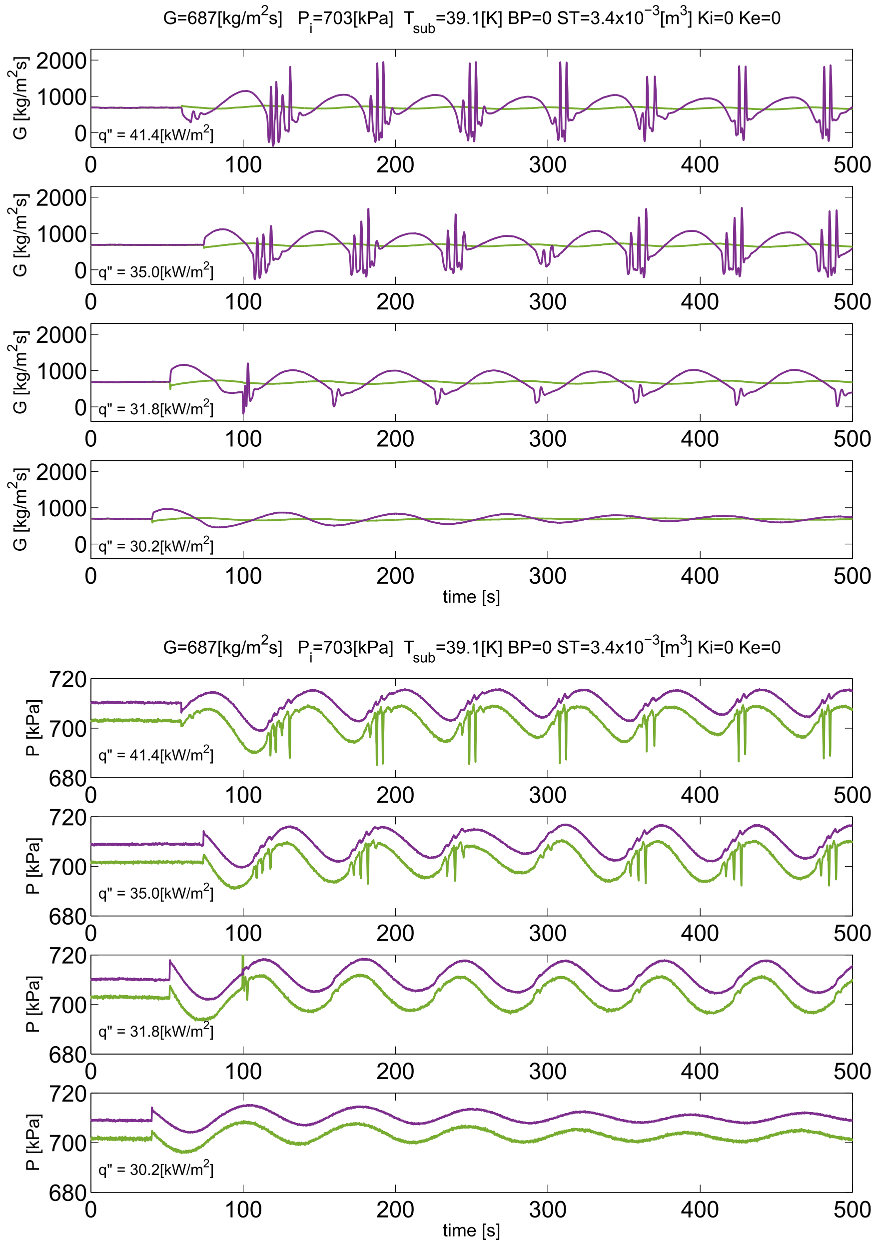

Fig. 8. Effect of the heat flux on the characteristics of the PDO.

$$\frac{1}{\sqrt{f}} = -2.0 log\left(\frac{\epsilon/D_i}{3.7} + \frac{2.51}{Re\sqrt{f}}\right) \tag{2}$$

where ϵ is the roughness. The friction factor was determined with an error of about 5% and with a difference between the experimental and predicted one lower than 10% for a roughness of 7 μm for the reported range, see Fig. 3. The figure shows the predicted and measured pressure drop over the diabatic test section.

2.3. Internal and external system characterisation

Fig. 4 shows part the N-shape curve of the heated section, ΔP_{TS}, and of the flow loop (including the heated section), ΔP_{system}, for one operational condition used in this work. Manavela Chiapero et al. (2014) have discussed the effect of different parameters on the shape of the N-shape. In Fig. 4, the N-shape curve was obtained by reducing the mass flux in steps while keeping the conditions at the inlet of the heated section fixed for an inlet pressure of P = 700 kPa, a heat flux of

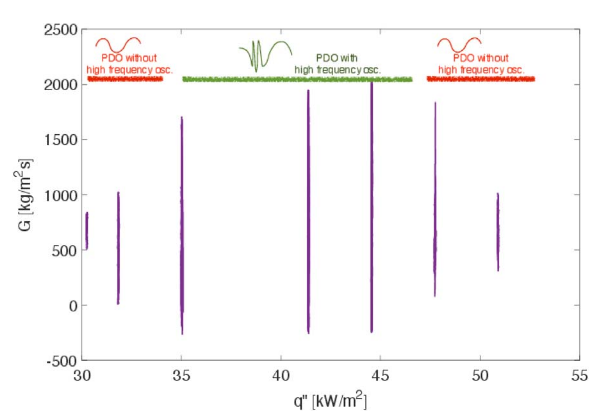

Fig. 9. Effect of the heat flux on the amplitude of the PDO. The vertical lines are the variation of the amplitude after t = 150 s.

$q'' = 35\ \mathrm{kW/m^2}$, and inlet subcooling of $T_{sub} = 38$ K. The flow loop pressure drop ΔP_{system} is measured after the pump and before the storage tank, while the pressure drop in the test section ΔP_{TS} is measured before and after the 2 m heated section.

The response of the pump to an increment in the pressure drop in the flow loop is also shown in Fig. 4. ΔP_{pump} represents the pressure drop along the flow loop, i.e. equivalent to ΔP_{system}. In this case, the experiment was performed by maintaining the conditions at the inlet of the test section constant. In order to change the operational point, the valve at the inlet of the test section was closed in steps for increasing the pressure drop of the loop.

2.4. Pressure drop oscillation. Reference case

Fig. 5 shows the evolution of the main variables during a pressure drop oscillation. After maintaining the facility at a stable condition for about 1000 s, the valve connected to the surge tank is opened ($t = 60$ s in the figure), and the PDO is trigged. The mass flux before the surge tank G_1 and in the heated test section G_2 are shown. G_1 is computed with the cross-section of the test section in order to compare the evolution. In addition the average wall temperature (T_w), the fluid temperature (T_f) and corresponding saturation temperature T_{sat} at 1917 mm from the inlet of the heated section are shown.

The limit cycle of the oscillation in the flow loop and test section for 2 cycles is presented in Fig. 6. It is possible to see that the limit cycle corresponding to $\Delta P_{system} - G_1$ follows closely the response of the pump.

Limited attention has been given to the characterisation of the flow loop and its impact on the oscillations. Considering that the pressure drop along the system controls the flow both representations of the oscillations might be recommended for analyzing the oscillations.

2.5. Effect of the heat flux on the PDOs

Figs. 7 and 8 show the effect of varying the heat flux while the inlet pressure $P = 700$ kPa, mass flux $G = 700\ \mathrm{kg/m^2\,s}$, and inlet subcooling $T_{sub} = 39$ K were kept constant. For this case, the volume in the surge tank was fixed to $ST = 3.\ 410^{-3}\ \mathrm{m^3}$. The pressure before the surge tank, i.e. P_1, and before the test section, i.e. P_2, are also presented. For a

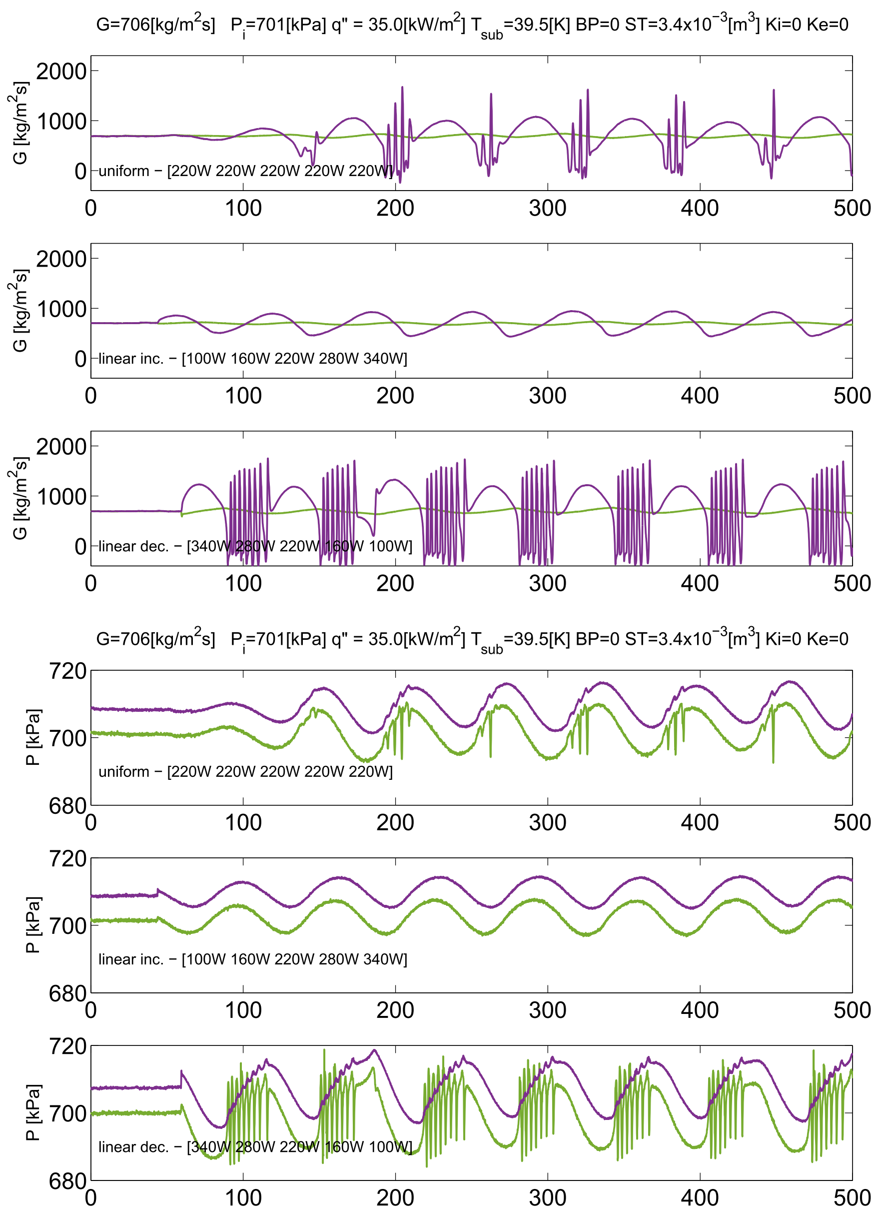

Fig. 10. Effect of the heating profile on the PDOs for cases A, B and C.

given range of heat fluxes, the PDO can present high frequency oscillations similar to density wave type of oscillations (Liu and Kakac, 1991).

Fig. 9 shows the variation of the mass flux as a function of the heat flux for Figs. 7 and 8. In the figure, each vertical line represents a time series for $t > 150$ s and for 7 cycles. The PDO occurs in the range of heat fluxes 30–50 kW/m^2.

2.6. Effect of heating profile on the PDOs

In this section, the effect on the PDO of changing the heating profile is presented. In the first case, three different heating profiles are considered with the same total power of 1100 W. The cases are defined as:

A. uniform [220 W 220 W 220 W 220 W 220 W]
B. linear increasing [100 W 160 W 220 W 280 W 340 W]
C. linear decreasing [340 W 280 W 220 W 160 W 100 W]

where the bracket represents the power in each heater (Fig. 10). Imposing a linear increasing power distribution results in PDOs without the high frequency oscillations observed in the uniform heating case. However, by imposing a linear decreasing power distribution, the number of high frequency oscillations increases from 3 to 7 or 8 per oscillation. In Fig. 7 it has been observed that by increasing the heat flux for a uniform heating, the high frequency oscillations vanish indicating that the distribution of compressible volume in the heated section plays a major role in the wave form of the oscillation.

In order to see the effect of increasing the power at the first and second sections of the heated pipe, the following cases are defined:

A. First section [380 W 180 W 180 W 180 W 180 W]
B. First and second sections [350 W 350 W 133 W 133 W 133 W]

while the total power remains in 1100 W. For these two cases (Fig. 11), it is also observed from 6 to 8 high frequency oscillations per oscillation.

In order to see whether it is possible to control the number of high

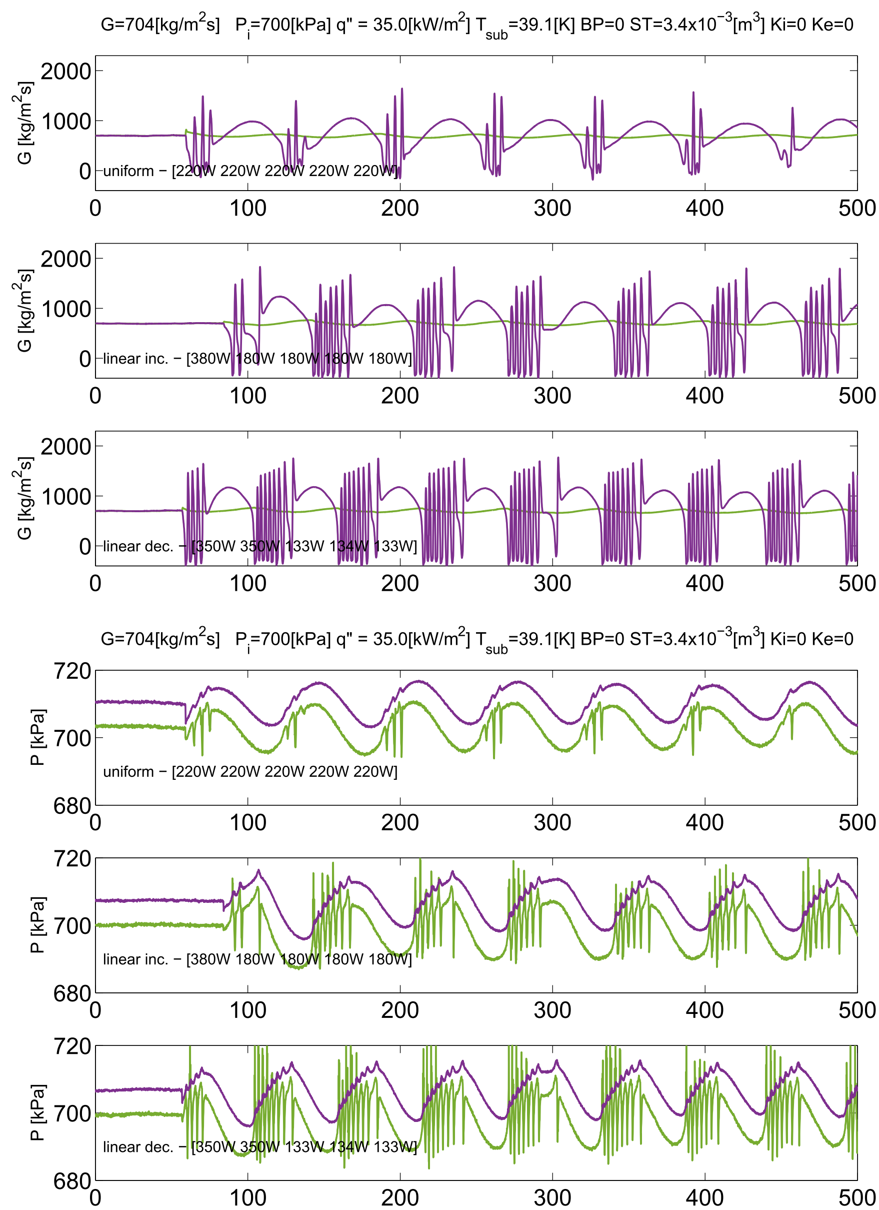

Fig. 11. Effect of the heating profile of the PDOs for cases A, D and E.

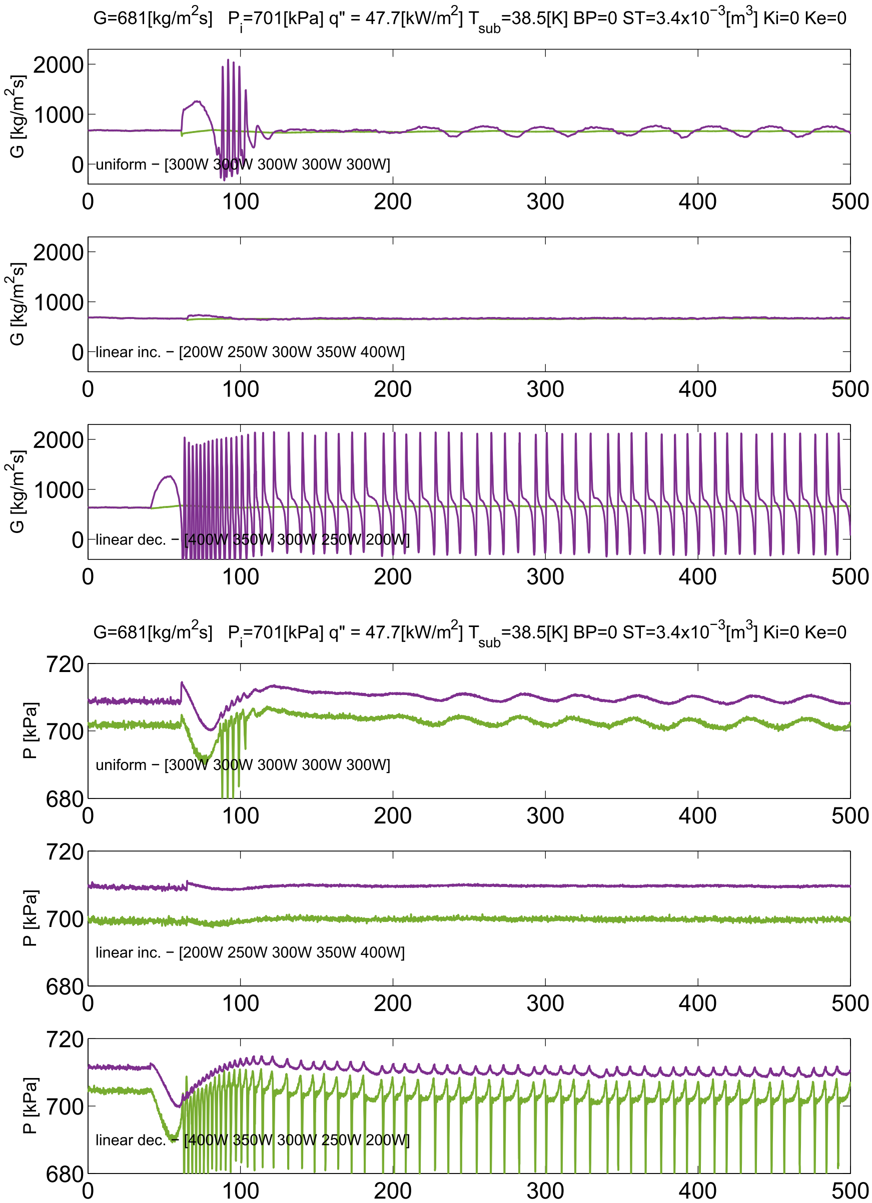

Fig. 12. Effect of the heating profile of the PDOs for cases F, G and H.

frequency oscillations, the total power was increased in the following case:

A. uniform [300 W 300 W 300 W 300 W 300 W]
B. linear increasing [200 W 250 W 3000 W 350 W 400 W]
C. linear decreasing [400 W 350 W 300 W 250 W 200 W]Fig. 12 shows that for the linear increasing profile, the PDOs vanish, while for the case of linearly decreasing heating, the oscillation contains only high frequency oscillations. A summary of the presented cases are shown (Fig. 13).

In summary, in the presented cases the PDOs present 3 types of wave forms:

i. Sinusoidal type-1: a kind of sinusoidal oscillation without high frequency components at low and high heat fluxes.
ii. Sinusoidal type-2: a kind of sinusoidal oscillation with high frequency components at intermediate heat fluxes.
iii. High frequency oscillations: at high heat fluxes and with decreasing power distribution.

In particular, the last case (iii) has not been found in the available literature. Further work is needed to identify the regions where the different PDO occurs and their effect on the heat transfer and pressure drop in the system.

3. Conclusions

In this work, the effect of the heating profile on the characteristics of pressure drop oscillations (PDO) is studied. It was observed that high frequency oscillations appear in a given range of heat fluxes, while for low and high heat fluxes with a uniform heating profile the high frequency oscillations vanish. In addition, a decreasing power distribution can increase the presence of high frequency oscillations, and at high heat fluxes only high frequency oscillations are observed.

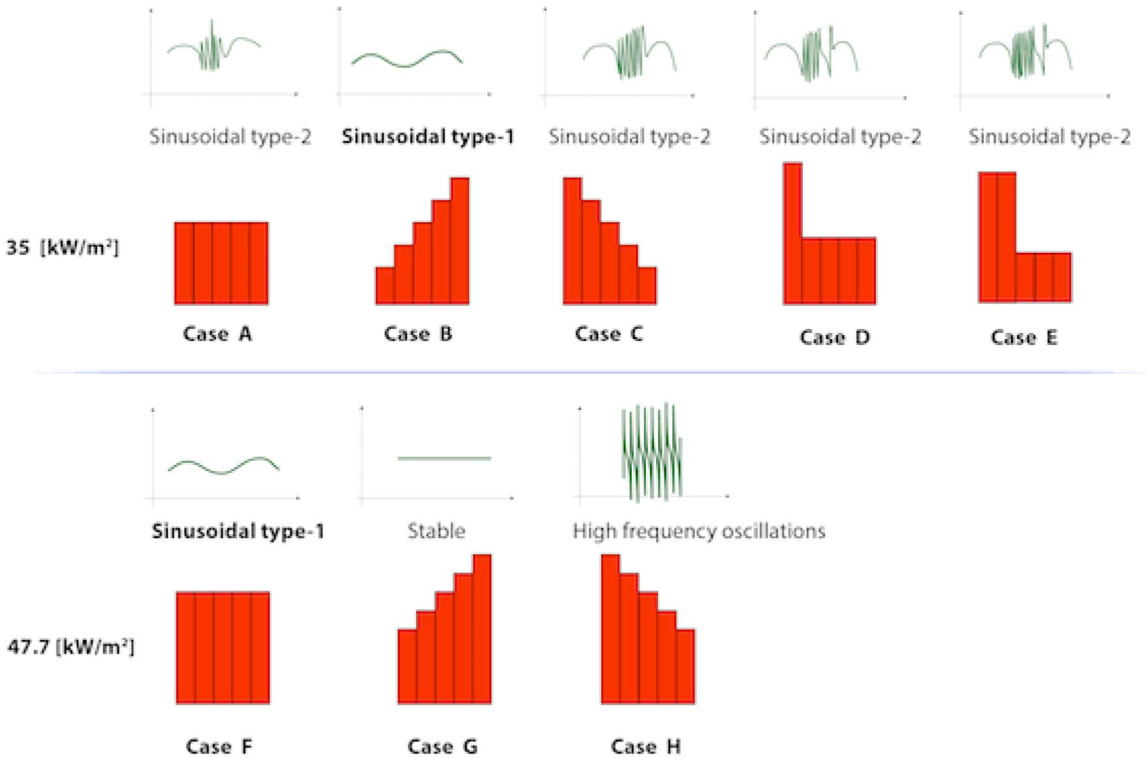

Fig. 13. Summary of the studied cases.

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