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Experimental study of pressure drop oscillations in parallel horizontal channels

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ABSTRACT

Two-phase flow instabilities are an undesirable phenomenon present in many fields and scales, ranging from large heat exchangers and boilers in industrial applications to micro-scale heat exchangers for high density power electronics. In the present study pressure drop oscillations in a two parallel horizontal channels system have been experimentally investigated, focusing in the individual behavior of each channel. The balanced (same characteristic pressure drop curve) and unbalanced cases have been analyzed finding different limit cycles than the typical single channel case. No pressure drop oscillations with both channels following the typical limit cycle were found. The oscillation mode detected consisted in one channel performing the usual limit cycle, while the other was always oscillating in the superheated vapor region.

1. Introduction

Two-phase flow boiling instabilities are an undesirable wide spread phenomenon present in many fields and scales, ranging from large heat exchangers and boilers in chemical and nuclear applications to micro-scale heat exchangers for high density power electronics in space applications. These types of instabilities can cause operational problems, affecting the efficiency and control of the processes, and in extreme situations, can lead to burnout and breakage of the equipment. Therefore the importance of having a clear understanding of its behavior. Two phase flow instabilities have been reviewed by several researchers (Boure et al., 1973; Kakaç and Bon, 2008; Tadrist, 2007). These instabilities are usually divided into two main groups: static and dynamic instabilities. Among the static instabilities, the most widely known is the Ledinegg type instability. For the case of dynamic instabilities, the most common ones and widely studied are density wave oscillations (DWOs) and pressure drop oscillations (PDOs). Pressure drop oscillations are actually compound instabilities, since they are dynamic instabilities triggered by a static instability. These kind of instabilities need in order to occur a compressible volume upstream the heated section (Cao et al., 2000; Doğan et al., 1983; Gürgenci et al., 1983; Kakaç et al., 1990, 1977; Mawasha and Gross, 2001; Mentes et al., 1983; Padki et al., 1991). The focus of this work is placed on PDO in parallel channels.

Very few studies have dealt with PDO in parallel channels (Manavela Chiapero et al., 2012). Most of the experimental, theoretical and numerical studies performed on two-phase flow instabilities in parallel channels have dealt with DWO (Aritomi et al., 1979; Clausse et al., 1989; Fukuda and Kobori, 1979; Guido et al., 1991; Guo et al., 2010; Hirayama et al., 2006; Lee and Pan, 1999; Podowski et al., 1990; Xiao et al., 1993; Yun et al., 2008; Zhang et al., 2009). Among these few studies dealing with PDO oscillations in parallel channels, Kakaç et al. (1977) performed an experimental study reporting oscillations in the inlet pressure of a setup of four parallel channels with cross connections. The stability limits were investigated but no information about the flow behavior in each channel was reported. It can be seen from their results that the behavior of the four channels together is too complex to understand the interaction between channels in the system. Experiments on two parallel channels could have brought a clearer idea of the behavior of the parallel boiling channels system. Ozawa et al. (1989) analyzed in great detail flow instabilities in an analogous air–water mixture system. The set up used was a twin parallel adiabatic system, with the possibility of adding compressible volumes in the gas and liquid feed lines in each channel. Even though this was an adiabatic system, the similarity of the flow oscillations with PDO in a boiling channel when adding a compressible volume to the air feed lines was remarkable (Ozawa et al., 1979). When the compressible volume was added only to the air feed lines the typical single channel pressure drop oscillations were found with both channels oscillating in phase with the same amplitude. However, when the compressible volume was added to the liquid feed lines

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two new modes of oscillation were found, named as "U-tube mode" (quasi-static out of phase oscillation) and "multi-channel mode". In the "U-tube mode" the oscillation was a quasi-static oscillation, with the gas flow and the liquid flow oscillating 180° out of phase in the two channels and the pressure drop approximately constant. The "multi-channel mode" was also a quasi-static oscillation, but with the gas flow in each channel oscillating independently, i.e. with different periods. Even though only two channels were used in this study, which made clear the behavior of the parallel system, the absence of heating and phase change makes the results hard to extrapolate to boiling parallel channels.

During the last ten years boiling in microchannels has gained the focus of many researchers due to the need of cooling of high-power density electronic devices and flow instabilities like PDO have been reported in several of such systems (Tadrist, 2007; Wu and Cheng, 2003; Zhang et al., 2010). Qu and Mudawar (2003) reported severe PDO in a two-phase microchannel heat sink, showing all channels oscillating in phase. Much effort has been made trying to stabilize these systems, for example by placing inlet restrictions (micro-orifices) (Szczukiewicz et al., 2013b,a). Again for the case of microchannels, the number of channels studied is too large to see any interaction between channels. Besides, this micro-systems usually have large common flow restrictions at the inlet and outlet of the parallel arrangement, making the channels move all together as a whole. Furthermore, the instrumentation is set in most of the cases in order to measure global variables and not the individual channels behavior.

Manavela Chiapero et al. (2011) analyzed numerically PDO oscillations in two parallel channels arrangements under balanced and unbalanced heat loads. The oscillation modes found in both cases were in phase. The unstable region was divided into two regions, "Region 1" where the oscillations take place, and "Region 2", dominated by stable maldistributed solutions. The oscillation mode with unbalanced heat loads found was with the most heated channel oscillating in the superheated vapor outlet region and the other channel following the typical PDO limit cycle. In a later study, Manavela Chiapero et al. (2013) considered the thermal capacity of the heated pipes in the model, finding the maldistributed oscillation mode also for the case with balanced parallel channels. These modes of oscillations are strongly connected to the global characteristic curve of the system. This global characteristic curve is the graphical representation of all the possible equilibrium points for the total pressure drop along the parallel channels arrangement as a function of the total mass flow rate. Akagawa et al. (1971) performed a broad theoretical and experimental analysis on the possible solutions and their stability in a three parallel boiling channels system. In this analysis the global behavior and flow distribution for equally heated channels and unbalanced heated channels was clearly shown and explained based on the characteristic curves of each channel. In the last decade many studies have also dealt with flow distribution and pressure drop vs. mass flux behavior for a parallel arrange of boiling channels (Minzer et al., 2006, 2004; Natan et al., 2003; Pustylnik et al., 2006; Taitel et al., 2008).

From the available literature it can be seen that there is very little information regarding the different modes of oscillation for PDO in parallel boiling channels and the physics behind the different behaviors. Furthermore, the experimental results reported are few and show contradictory effects. On the numerical side, few analysis have been made showing new results and limit cycles but there is still not detailed experimental data available to confirm these results.

In the present study, pressure drop oscillations are experimentally analyzed for two parallel horizontal heated channels. The aim of the study is to analyze two parallel boiling channels with the focus placed on the flow behavior at each channel in order to provide new basic knowledge about the different possible limit cycles in such configurations. In Section 2 the experimental facility is described together with the experimental procedure and the accuracy of the measurements. Section 3 shows the results obtained for the different cases analyzed. In Section 4 the main results and the limitations of the study are discussed. Finally, in Section 5 the main conclusions from the work are drawn.

2. Description of the facility

The experimental facility is a R134a loop consisting of a main tank, a pump, a pre-heater or conditioner, a surge tank or accumulator, an arrangement of five parallel heated channels and a condenser. The loop is schematically represented in Fig. 1. The fluid pressure is set by controlling the temperature in the main tank where the refrigerant is at saturation conditions. The fluid is driven by a magnetically coupled gear pump. The conditioner is a shell and tube heat exchanger with glycol in the shell side which is used for adjusting the R134a inlet temperature. Before entering the parallel heated channels the refrigerant flows through two Coriolis mass flow meters placed upstream and downstream of the accumulator. This accumulator has a compressible volume of approx. 8 l of nitrogen to allow for PDO occurrence. The heated stainless steel test sections are electrically heated by Joule effect with a rectified sine wave. Each heated section is 2 m long, with 5 mm and 8 mm internal and external diameter respectively. Ten thermocouples are distributed along the upper wall surface and three more are at the bottom of each heated section as sketched in Fig. 2. The ten upper thermocouples are equally distributed along the 2 m long heated section, with a separation of 60 mm and 50 mm from the beginning and end of the heated section respectively. The three thermocouples at the bottom are placed at the same position that the last three upper ones. The two parallel channels used in the present study are sketched in Fig. 2. The facility counts with three more parallel channels as previously mentioned. The inlet flow meter on every channel is a turbine flow meter. The number of channels used on a given experiment is selected with the control valves placed at the inlet and outlet of every channel. Inlet and outlet electric insulators are also used with the aim of assuring the current flow through the heated section and then avoiding electrical losses. Downstream of the outlet control valves, orifice plates are placed in order to provide an extra two-phase flow pressure drop at the channel outlet. The size of the orifice is

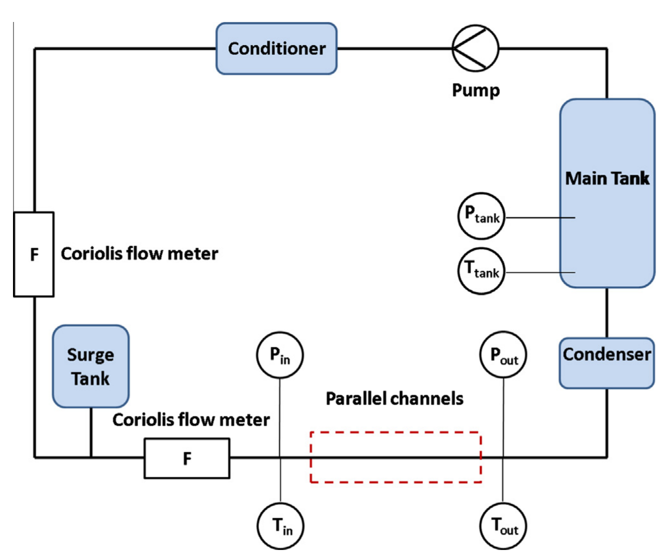

Fig. 1. Schematic representation of the experimental facility.

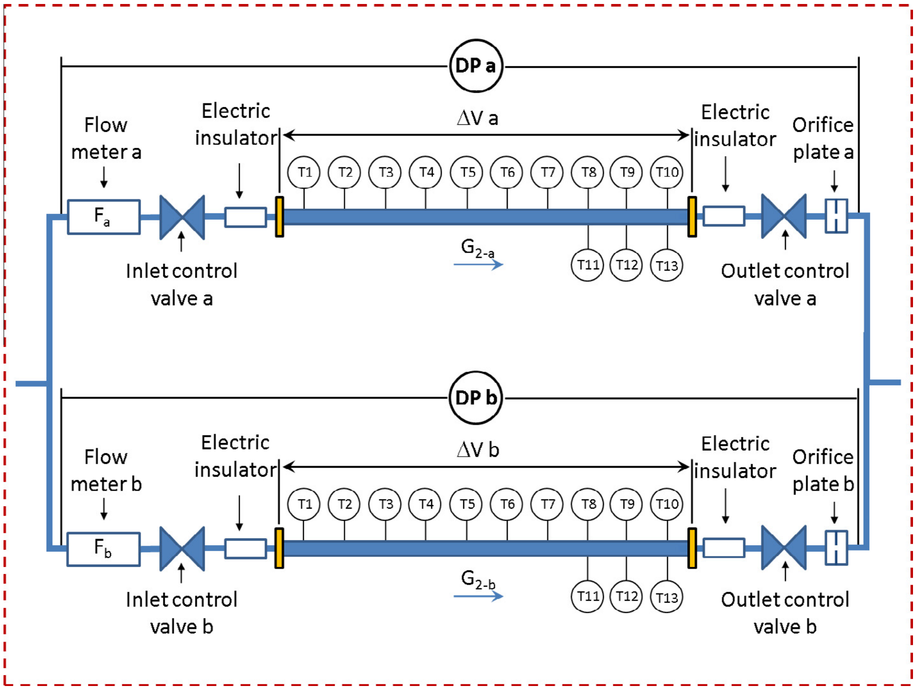

Fig. 2. Schematic drawing of the heated test section.

1.5 mm. The pressure drop along each channel (i.e. the sum of the pressure drops given by the heated test section, the turbine flow meter, the electric insulators, the control valves and the outlet restriction) is recorded with differential pressure transducers. In this study, only two of the five parallel channels were used.

2.1. Experimental procedure

The experimental procedure was divided into two parts; first the static characterization of all the components was performed, including the heated channels under different heating conditions, and then the dynamic characterization of the system under oscillatory behavior.

In order to register the pressure drop oscillations for the two parallel channels arrangement, the procedure was the following:

1. Set the system pressure, inlet fluid temperature and the thermal power applied to the channels according to the corresponding values registered in the static characterization of the heated channels.
2. Set the inlet mass flow rate at the saturated liquid outlet conditions (mass flow rate approx. value at which the fluid starts boiling at the outlet).
3. Decrease the flow rate until reaching the desired working point. Wait until stationary conditions are met.
4. Open the valve connecting the surge tank with the inlet of the parallel channels arrangement. The pressure in the surge tank must have been equalized with the system pressure previously.
5. Acquire the data if unstable behavior if present. If stable conditions are present, repeat the procedure from point 3.

2.2. Measurements and accuracy of measurements

The measurements have been performed with a computer equipped 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 2 Hz. For every steady-state experimental measurement reported 120 data points were acquired.

2.2.1. Pressure drop

The total pressure drop (Fig. 2) was recorded with a differential pressure transducer. A differential pressure accuracy of 0.075% full-scale was given by the supplier for the transducers (full-scale value of 10^5 Pa). This accuracy was checked by inhouse calibration.

2.2.2. Mass flow rate

The total mass flow rates before and after the surge tank were recorded with Coriolis flow meters. A mass flow rate accuracy of 0.2% of the reading was given by the supplier. The individual volumetric flows at each channel were measured with turbine flow meters. A volumetric flow rate accuracy of 1% of the reading was given by the supplier. Due to the fact that these flow meters need a minimum flow to be able to measure (flow > 0.003 kg/s), the flow rates reported for the channel with the lowest mass flow rate were obtained as the difference between the total flow entering the inlet distributor and the flow reading from the turbine flow meter in the channel with higher flow rate. Across the turbine flow meters the single phase pressure drop has a stabilizing effect on the system. In order to counteract this effect and make the system unstable, orifice plates are placed at the outlet of the heated channels as shown in Fig. 2.

2.2.3. Fluid temperature

The fluid temperature was registered at several points along the loop, including the inlet distributor and the outlet plenum of the parallel channels arrangement. For the temperature measurement, type T thermocouples 0.5 mm diameter have been used. The thermocouple accuracy after inhouse calibration was found to be 0.5 K. The absolute pressure at the inlet and outlet of the heated section was also recorded and was used for checking the saturation temperature T_{sat} of the fluid based on the equilibrium thermodynamical properties calculated with REFPROP (Lemmon et al., 2007). An absolute pressure accuracy of 0.04% full-scale was given by the supplier.

2.2.4. Heat flux

The heat flux was applied electrically by Joule effect to the fluid. A voltage potential was applied on each channel through 2 electrodes with a separation of 2 m along the channel. The power was given by low voltage and high current rectified sine waves. The amount of power was set by adjusting the duty of the signal. The thermal insulation around the piping and the heated section forces almost all the volumetric heat generated in the pipe wall to flow to the fluid.

For the heat flux, the error coming from the propagation is the error associated with the voltage and current measurements. Nevertheless, the thermal heat flowing to the fluid under stationary conditions was used for the calibration of the electrical value for different temperatures and conditions for single phase liquid considering the heat exchange with the surroundings. A final accuracy of 5% of the reported value was achieved.

3. Study cases

In the present study, pressure drop oscillations in a two parallel channel arrangement have been studied. The cases where the channels are balanced (same steady state characteristic curve) and unbalanced are treated separately. The outlet pressure in all the experiments was set at 6.5 x 10^5 Pa and the volume of nitrogen present in the surge tank in equilibrium conditions was 8 l.

3.1. Two balanced parallel heated channels

Due to the inherent physical differences in the channels, their steady-state behavior is not exactly the same. The main difference lies in the outlet restriction, where a small difference in its size has a large impact on the pressure drop behavior. Therefore, in order to have a steady state behavior as close as possible between each channel, slightly different heat fluxes were applied on each of them. Fig. 3 shows the steady state behavior for channel "a" and channel "b". The heat fluxes applied to channels "a" and "b" were 14,640 W/m^2 and 15,280 W/m^2 respectively. The difference might also be due to the uncertainty in the power applied given by the heating system.

Fig. 4 shows the total mass flow as a function of time during the oscillatory behavior for the parallel channels arrangement. The instant and the mean values are shown. The mean values are a smooth representation which allows us to get rid of the superimposed DWO and have a clearer picture of the main global behavior of the system. From now on all the experimental results presented for the mass flows will be smoothed for a clearer understanding. Nevertheless it should be kept in mind that the real instant behavior was like the one shown in Fig. 4.

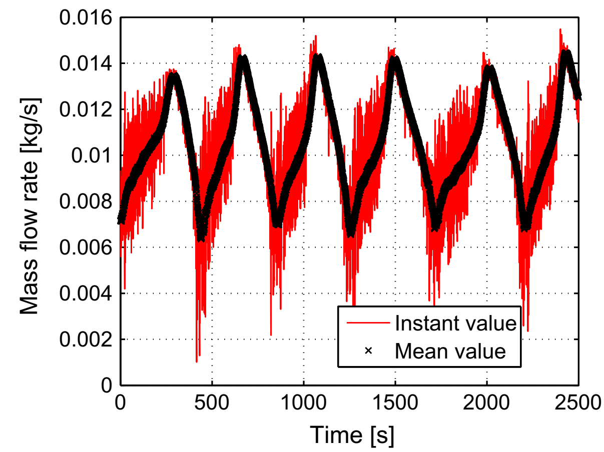

Fig. 4. Total mass flow rate leaving the accumulator during PDO. Balanced case.

The mean mass flow rates for each channel are shown in Fig. 5 while the pressure drop along each channel is shown in Fig. 6. The outlet channel wall temperature is shown in Fig. 7. This outlet temperature reported is the one recorded by the last upper thermocouple, 50 mm before the end of the heated section. While both channels exhibit PDO under unstable conditions when decoupled, this was not the case for the coupled system. As predicted by the model in Manavela Chiapero et al. (2013) both channels never undergo the typical PDO limit cycle together. It was always one channel performing the usual limit cycle, while the other was always oscillating in the superheated vapor region, dragged by the pressure constrain imposed by the other channel. This can be clearly observed in Fig. 8, where the limit cycles undergone by channels "a" and "b" (in blue and red respectively) and the total mass flow (plotted in green) are represented. The static behavior for each separate channel and both channels coupled (i.e. "global characteristic curve") is also sketched. Fig. 8 is important and should be observed in detail because except for the periods of the oscillations and the wall temperatures, all the information

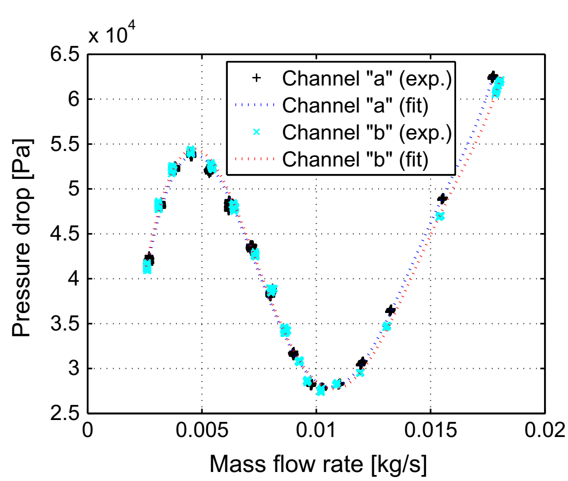

Fig. 3. Steady state characteristic curve for channel "a" (14,640 W/m^2) and channel "b" (15,280 W/m^2).

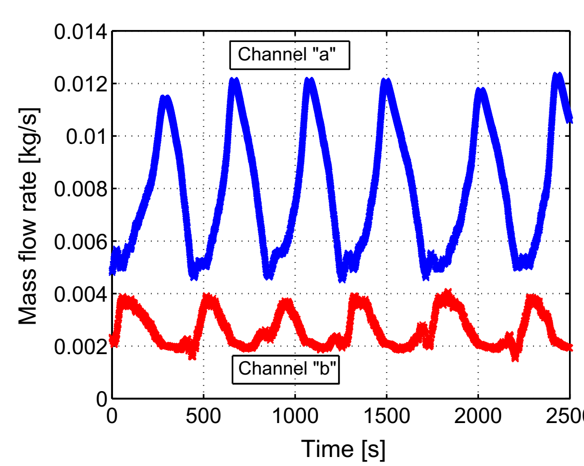

Fig. 5. Channels mass flow rate during PDO. Balanced case.

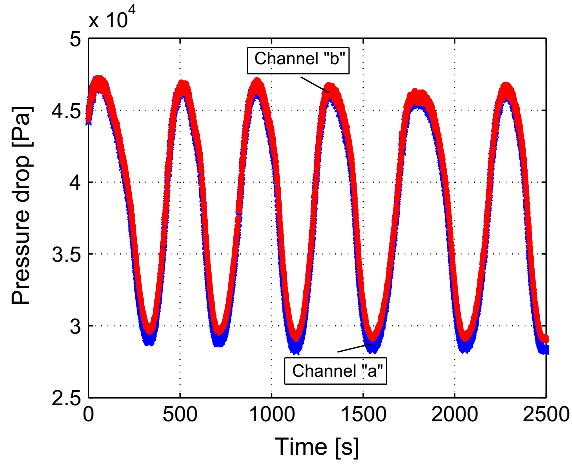

Fig. 6. Channels pressure drop during PDO. Balanced case.

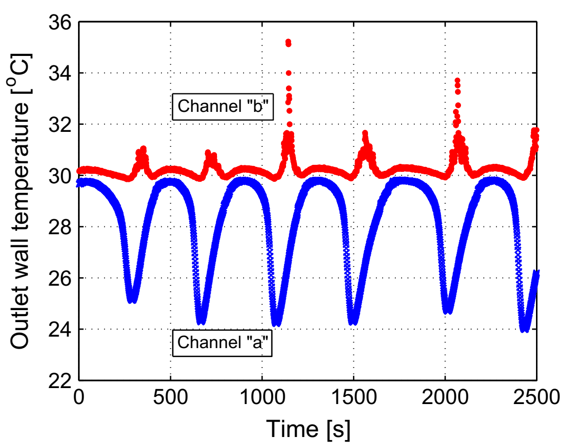

Fig. 7. Channels outlet wall temperature during PDO. Balanced case.

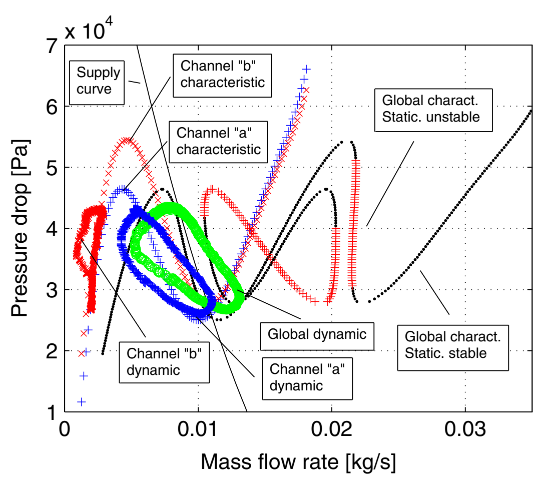

Fig. 8. Limit cycles for each channel and the total mass flow rate. Balanced case.

presented is summarized there. This figure presents the static and dynamic behavior of the pressure drop as a function of the mass flow rate for each channel and for the global arrangement of parallel channels. The steady-state supply curve is also sketched in order to visualize the possible equilibrium points. A detailed analysis on the static behavior of each channel and the global characteristic curve for coupled parallel heated channels can be found in Akagawa et al. (1971). Even though both channels have almost the same steady state behavior, it can be seen from Fig. 8 how channel "b" (in red[1]) oscillates around the superheated vapor outlet region of its steady state characteristic curve (also sketched in red in Fig. 8). On the other hand, channel "a" (in blue) follows the typical PDO limit cycle, closer to the region where the liquid leaves the channel as subcooled liquid in this case due to the reason that the initial unstable working point was closer to this region. The behavior of the total flow rate is represented in green in Fig. 8. It looks like a typical PDO limit cycle if it is plotted over the single channels steady state curves, but when plotted over the coupled-channels arrangement steady state curve, it can be seen that the oscillation takes place in the maldistributed zone. The importance in this limit cycle lies on the fact that one channel is always superheated at the outlet. Nevertheless, due to the presence of density wave oscillations, the channel with lower mass flow is most of the time wet, leading to small increases in the outlet wall temperature (see Fig. 7). The channel following the typical PDO limit cycle never reached dry-out conditions at the outlet, which agrees with the behavior observed when PDO were present in the de-coupled channels.

The different limit cycles followed by each channel might look counterintuitive when both channels have almost exactly the same steady state characteristic behavior. This oscillation mode can be understood considering the division of the system in regions 1 (oscillations region) and 2 (maldistributed stable solutions) as in Manavela Chiapero et al. (2011). For the present case, region 1 is narrow and it is not possible to intercept the global characteristic curve for the coupled channels in the negative slope region for both channels without intercepting other stable working point on region 2. This is clearly shown in Fig. 9 where the system supply curve for the experimental facility is plotted. In order to set the system in the operation point where both channels are working in its negative slope, a vertical supply curve as the one shown in Fig. 9 is necessary.

3.2. Two unbalanced parallel heated channels

In order to investigate the effect that an unbalanced channels configuration has on the oscillation modes, the heat applied to channel "a" was lowered. Fig. 10 shows the steady state behavior for channels "a" and "b", with 13,690 W/m^2 and 15,280 W/m^2 applied respectively. As predicted by the model in Manavela

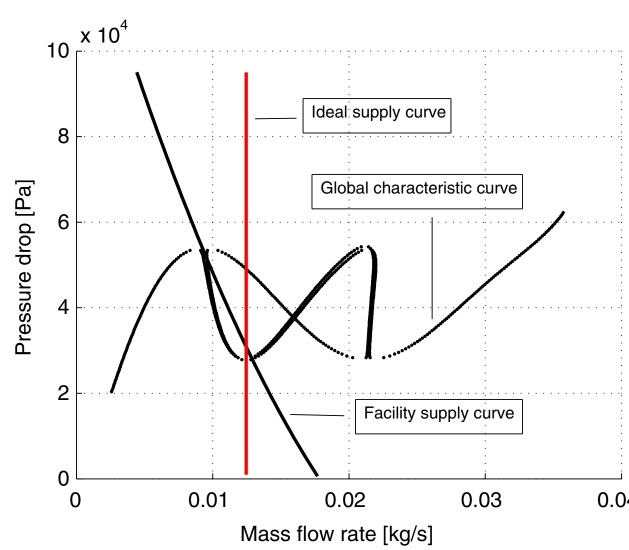

Fig. 9. Balanced coupled channels characteristic curve and supply curves.

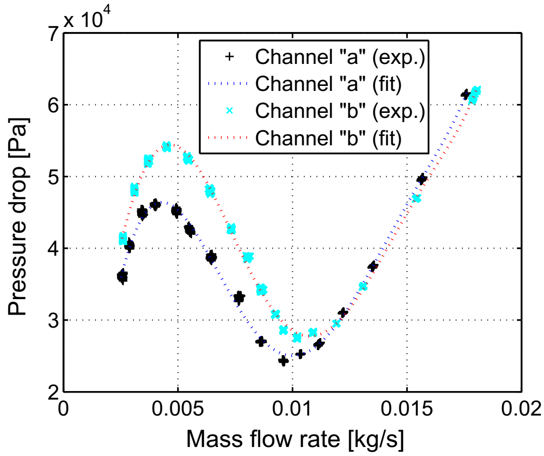

Fig. 10. Steady state characteristic curve for channel "a" (13,690 W/m^2) and channel "b" (15,280 W/m^2).

Chiapero et al. (2013) and Manavela Chiapero et al. (2011), the oscillation mode for this case was the same as the one shown before for the balanced channels case (Fig. 8), with the important remark that in the unbalanced case the channel being always in the region with superheated vapor at the outlet was the one receiving the larger heat load. This is actually in agreement with the stable steady state maldistributed solutions for this configuration, where the most heated channel always carries the lowest mass flow (Akagawa et al., 1971).

The total mass flow rate leaving the accumulator and the mass flow rate at each channel are shown in Fig. 11. If compared with Fig. 5, it can be seen that for this case, the difference between the minimum flow in channel "a" and the maximum flow in channel "b" is larger. The pressure drop at each channel is shown in Fig. 12. It is possible to see form Fig. 12 that the constrain of same pressure drop on each channel is satisfied during PDO. The wall temperature oscillations at the outlet of the channel with the larger heat load (channel "b") increase markedly when the system is unbalanced, as can be seen in Fig. 13. This phenomenon can be easily understood by looking at the global picture in Fig. 14. As can be seen, the lower limit for the oscillation in the pressure drop is given by the channel with the smaller heat load (channel "a"), which is the one performing the typical PDO limit cycle. Since the channel with the larger heat load is dragged to oscillate together with the less heated channel by the common pressure drop constrain, as the heat input in the channel with the smaller heat load decreases, the minimum pressure drop during

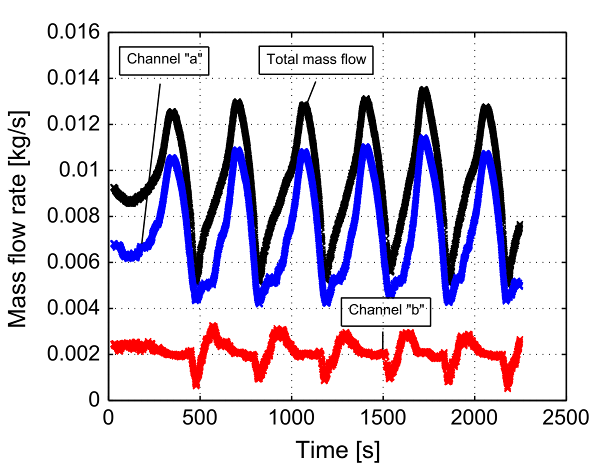

Fig. 11. Channels mass flow rate and total mass flow rate during PDO. Unbalanced case.

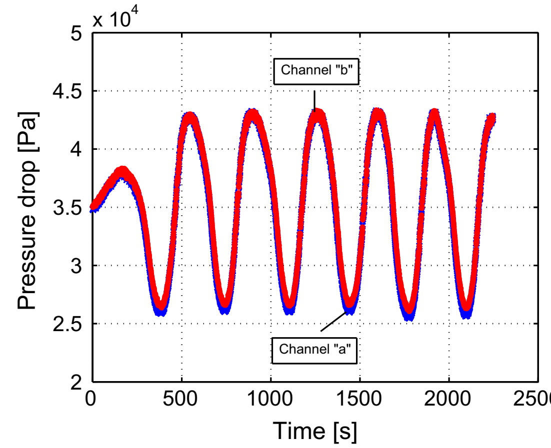

Fig. 12. Channels pressure drop during PDO. Unbalanced case.

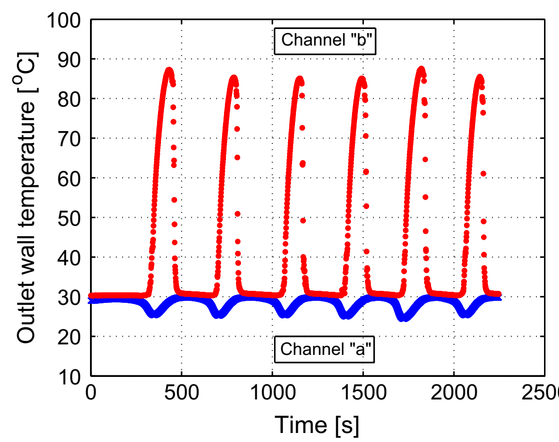

Fig. 13. Channels outlet wall temperature during PDO. Unbalanced case.

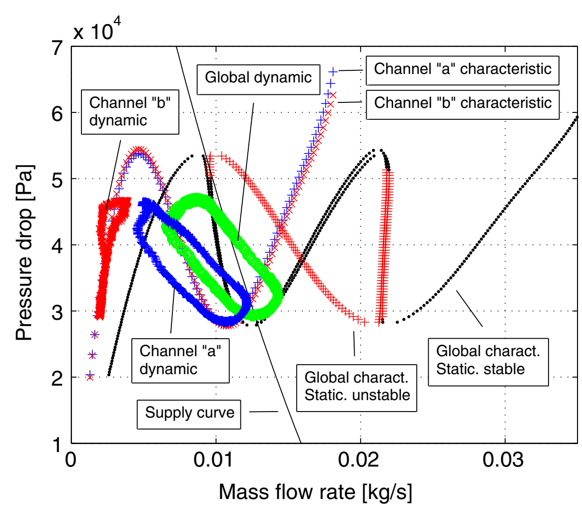

Fig. 14. Limit cycles for each channel and the total mass flow rate. Unbalanced case.

oscillations decreases as well, and so does the minimum mass flow in the more heated channel. This agrees with the results obtained for an intermediate case with channel "a" and channel "b" with 14,320 W/m^2 and 15,280 W/m^2 respectively. The results for the outlet wall temperature in the channel with the larger heat load

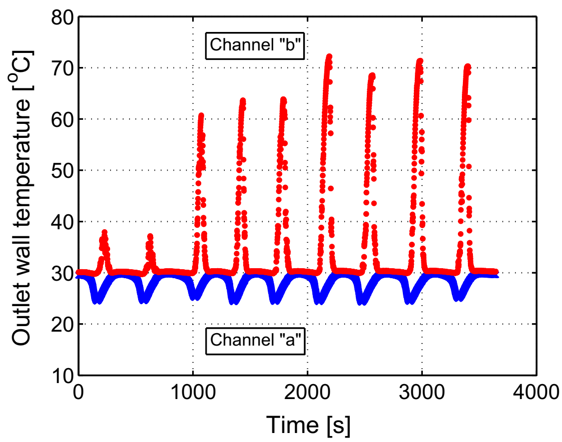

Fig. 15. Channels outlet wall temperature during PDO. Intermediate unbalanced case.

are shown in Fig. 15. The wall temperature oscillations lie in between the two previous cases as expected.

4. Discussion

The phenomena presented showed that for the conditions present in the experimental facility, PDO oscillations with both channels following almost the same path were not possible. Instead, the oscillation mode detected was with the less heated channel following the typical PDO limit cycle and the more heated channel forced to oscillate by the pressure drop constrain along the region with super heated vapor at the outlet. Even for the case where both channels have almost exactly the same characteristic static behavior, the same oscillation mode was found. These experimental results support the results obtained in the numerical analysis performed by Manavela Chiapero et al. (2013). In order to investigate if the oscillation mode with both channels showing the same behavior is possible, a steeper supply curve would be needed in the experimental facility. Fig. 9 shows the characteristic static curve for the balanced coupled channels together with the experimental facility supply curve and the ideal constant mass flow supply curve. It can be seen that in order to be able to intercept the demand curve in the region where both channels are in its negative slope without intercepting any stable maldistributed solution, an almost vertical supply curve is needed. This could be achieved with a higher power pump and a larger flow restriction upstream of the surge tank. One important consideration is that when we say that the channel with the larger heat load is the one with less flow during oscillations and maldistributed stable solutions, this applies for identical short channels. However, depending on the global characteristic curve, the oscillation mode with the more heated channel following the usual PDO limit cycle and the less heated channel oscillating in the region where the fluid leaves the channel as subcooled liquid should be possible as well. Also, for some particular shape of the global characteristic curve, the oscillation mode with the less heated channel performing the typical PDO cycle and the more heated one oscillating in the subcooled liquid outlet region might also be possible. This could be observed in long channels at low reduced pressure as in Akagawa et al. (1971), or either with different concentrated losses at the inlet and outlet of each heated channel.

5. Conclusions

Pressure drop oscillations in a two parallel horizontal channels system have been experimentally investigated in the present study. Special focus has been placed on the individual behavior of each channel, where experimental information is lacking in the literature. No pressure drop oscillations for both channels following the typical PDO limit cycle were found, not even for the case where both channels have almost the same pressure drop vs. mass flow steady state behavior. However, the present study cannot assure that this oscillation mode is not possible, due to the external system supply curve limitations in the experimental facility. Nevertheless, it can be stated that the oscillation modes presented here are more probable due to the fact that the constant inlet mass flow constrain and both channels having exactly the same behavior are conditions rarely met in real life applications. An interesting finding is that the outlet temperature at the channel with the larger heat load increases as the heat in the other channel is decreased, which might sound counter intuitive. The reason underlying behind this behavior is related to the fact that the less heated channel is the unstable channel in the PDO sense, and thus, the one that defines the pressure limits during the oscillations. Therefore, as the heat load in the unstable channel is decreased, the minimum pressure drop during oscillations is decreased as well, together with the minimum mass flow corresponding with that pressure drop in the channel with the larger heat load. The final consequence of the previous effects is the higher outlet temperature in one of the channels.

Acknowledgments

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