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Review on pressure drop oscillations in boiling systems

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ABSTRACT

Boiling flow instabilities are present in several heat exchanging systems. Pressure drop oscillations are low-frequency oscillations (periods larger than the residence time of a particle in the system) in pressure and mass flow rate. In addition to performance degradation and problems of system control, flow rate oscillations may induce oscillations in wall temperature which can lead to thermal fatigue and breakage of the equipment. The objective of this review is to summarize all the research done on pressure drop instabilities, what has been done and what still needs to be done. Several issues that still need to be addressed in the modeling and experimental fields are introduced and discussed.

Contents

1. Introduction

Two-phase flow boiling instabilities are undesirable phenomena because they can cause problems of system control, which is detrimental to the efficiency of the process and can lead to burn out and breakage of the equipment. These types of instabilities can be found in several applications such as cryogenic and refrigeration processes, nuclear reactors and many other systems involving forced convection boiling heat transfer. Therein lies the importance of understanding these phenomena and the measures that can be taken in order to avoid or minimize their occurrence. Several reviews on two-phase flow instabilities have been done in the last 50 years (Boure et al., 1973; Kakaç and Bon, 2008; Tadrist, 2007).

These instabilities can be divided in two main groups: static and dynamic instabilities. A steady flow is said to be stable if after small perturbations, its new operating conditions tend asymptotically toward the initial ones. If after a small change from its equilibrium point the system does not have any possible steady state solution in the vicinity of the original state, the flow is then subject to a static instability. On the other hand, dynamic instabilities are the ones where the inertia and feedback effects play a major role in the process. Among the static instabilities the most important and studied one is the Ledinegg type instability. For the case of dynamic instabilities, the most common ones are density wave oscillations (DWO), pressure drop oscillations (PDOs) and thermal oscillations (THOs). Pressure drop oscillations are actually compound instabilities, because they are dynamic instabilities triggered by a static instability. In this paper, the research done on pressure drop oscillations is reviewed. The structure of the article is given as follows. Section 2 reviews the first measurements on PDO and the most common approach to the modeling of these oscillations. Section 3 compiles the studies performed on the experimental, numerical and analytical field with PDO in single tube systems. Section

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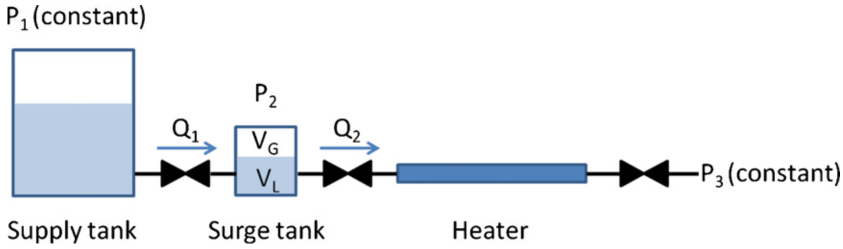

Fig. 1. Sketch of the system.

4 discusses the most relevant papers dealing with PDO in parallel channels and Section 5 reviews the studies done on PDO in microchannel systems. Finally, in Section 6 a discussion about the state of the art is done.

2. Modeling of PDOs

The first report showing the three main mechanisms of dynamic instabilities was done by Stenning and Veziroĝlu (1965). In this report, DWO, PDO and THO were presented, showing experimental results and the first associated models that describe the physics behind each phenomenon. In particular, the lumped parameter model presented for the explanation of PDO with a compressible volume upstream of the test section is still the one used nowadays due to its simplicity and the good agreement with the experimental data. However, this model was developed under certain hypothesis which must be taken into account. In order to use the lumped parameter model in the 1D space dimension we must verify that the period of the oscillations is much larger than the residence time of a fluid particle in the heated section. With this, it is possible to state that the system moves from one quasi-steady solution to another quasi-steady solution. This is not true during flow excursions, but the contribution on the period of the flow excursions is usually not significant when compared with the rest of the oscillation. A sketch of the typical system prone to develop PDO is shown in Fig. 1. The set of dynamic equations developed for the behavior of the system is then:

$$P_1 - P_2 = K_1 {Q_1}^2 + \rho_L \frac{L_1}{A_1} \frac{dQ_1}{dt}, \tag{1}$$

$$P_2 - P_3 = (P_2 - P_3)_s + \rho_L \frac{L_2}{A_2} \frac{dQ_2}{dt}, \tag{2}$$

$$P_1 - P_3 = constant, \tag{3}$$

$$Q_1 - Q_2 = -\left(1 - \frac{\rho_v}{\rho_L}\right) \frac{dV_G}{dt}, \tag{4}$$

where Q_1 and Q_2 are the volumetric flow rates in and out of the surge tank respectively, $(P_2 - P_3)_s$ is the pressure drop across the heater in steady state flow and is a function of Q_2; L_1 and L_2 are the tube lengths before and after the surge tank respectively, ρ_L is the liquid density, ρ_v is the density of saturated vapor and V_G is the volume of gas in the surge tank. If we neglect the loss of liquid volume due to evaporation, the term related with the densities in Eq. (4) vanishes.

A study on the stability of these equations shows that the system may be unstable when the slope of $(P_2 - P_3)_s$ is negative (Maulbetsch and Griffith, 1966). When the slope of the curve of P_2 as a function of Q_1 is more negative than the one corresponding to the heated section ($P_2(Q_2)$), the oscillatory behavior can take place. This can be clearly observed in Fig. 2. If the two curves (P_2 vs. Q_1 and P_2 vs. Q_2) are intercepted where the slope of the non-heated section is more negative than the slope of the heated section, a small increase in P_2 will cause Q_2 to decrease more than Q_1. This will make the level in the surge tank to rise and P_2 will increase further. Since the system is statically unstable and there are no stable points in the interception of the two curves, the system will follow the limit cycle delimited by ABCD shown in Fig. 2. In the study done by Stenning and Veziroĝlu (1965), the power applied to the fluid was considered constant, which appears to be justified by the small fluctuations in the tube wall temperature. In this report it was also pointed out that PDOs did not take place in all the points of the negative slope region. It was also observed that in tests performed with less heating power the PDOs were small in amplitude and stayed in the negative slope region instead of following the quasi-steady points.

In the following year Maulbetsch and Griffith (1966) analyzed flow excursions and PDOs, both analytically and experimentally. The model used was the lumped parameter model, where the energy storage mechanisms were the inertia of the flow in the boiling channel and the upstream system compressibility. The effect of a liquid compressible volume upstream the heated section on the critical heat flux at which the instability is triggered was analyzed. It was also found that for ratios of length to diameter greater than 150 for the heated section there can be sufficient compressibility to initiate this type of instability. This compressibility is inherent in the test section itself due to vapor generation and in this case, no amount of external throttling will be of any value. It should be remarked that the oscillations were not registered because the test section was always destroyed before finishing the first cycle. One year after, Maulbetsch and Griffith (1967) compared their predicted points of incipient instability with several published data. The effect of different compressible volumes (gas tank, gas trapped in the pipe and large amount of subcooled liquid) upstream the heated section for the critical heat flux was also analyzed by Daleas and Bergles (1965).

Stenning et al. (1967) performed a complete experimental and analytical study on the subject. In the modeling, the heat stored in the pipe walls was taken into account, considering the total actual heat applied to the fluid. Instead of taking into account the heat distribution along the pipe, a mean heat transfer coefficient as a function of the mass flow rate was used. Small amplitude

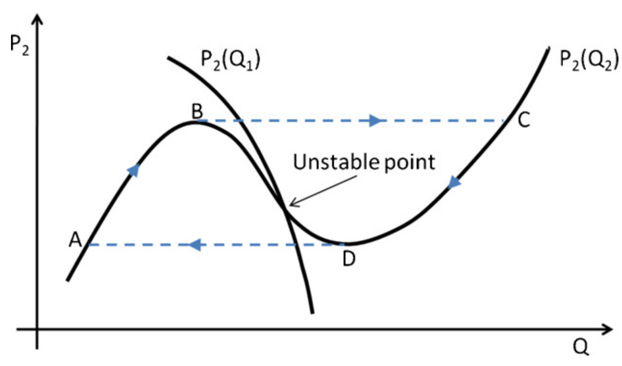

Fig. 2. Steady state curves for the system.

oscillations were found in the marginal stability regions and the thermal capacity of the wall was found to be a determinant factor in the amplitude of the oscillations. As the thermal capacity of the pipe was made smaller, the amplitude of the limit cycles increased, approaching the values given by the constant heat input assumption. Regarding the period of the oscillations, the analytical values obtained by the linearization of the system and neglecting the thermal capacity of the pipe were about one third of the experimental value, while with the non-linear analysis the periods found were ranging from 100% longer at onset to 40% longer at lower flow rates.

3. Experimental and numerical results on PDO

Pressure drop-type oscillations have been widely studied theoretically and experimentally. For the case of PDO, the large amplitudes on mass flow rate oscillations, changing from subcooled liquid to superheated vapor at the outlet, and the associated long periods, leads to oscillations in the tube wall temperature. These oscillations in the wall temperature are usually reported as thermal oscillations. Nevertheless, they are not pure thermal oscillations since the mechanism for the triggering and maintenance of oscillatory behavior is not thermal. However, these changes in the wall temperature and the effect of the thermal capacity of the pipe wall as an energy storage component definitely play an important role in some situations and should be taken into account, since the steady-state behavior of the heated pipe used for the lumped parameters model is a function of this amount of heat applied (especially in vertical systems) and the axial distribution of the heat load (Manavela Chiapero et al., 2011a). It may sound contradictory to take into account the heat stored in the heated channel wall when the strongest assumption on the modeling is that the system is moving from one quasi-steady state to the other. This is true during most of the oscillation except during flow excursions and it is in this part of the oscillations when the heat applied to the fluid can differ strongly (depending on the heat capacity of the tube material) from the constant heat applied to the pipe. Nevertheless, it should be clear that the quasi-static evolution hypothesis refers to the hydrodynamic behavior and not to the thermal one. Therefore, the period of the oscillations might be much larger than the residence time of a fluid particle in the system but not necessarily much larger than the thermal time constant of the tube wall.

In this section, experimental, numerical and theoretical studies dealing with PDO in a single boiling channel are summarized.

3.1. Experimental studies

Experimental work on PDO has been performed by several authors. Mentes et al. (1983) experimentally analyzed the effects of the internal surface of the heated pipe on the stability of a boiling system. The effect of the heat transfer coefficient was found to be determinant on the dynamics of the system. Although the steady-state behavior of pressure drop vs. mass flow rate does not change in a considerable way (for the case of fixed constant heat flux), the stability and the dynamics involved (amplitudes and periods of oscillations) do change in a considerable way. This is a very interesting experiment because it shows the importance of the heat interaction between the wall and the fluid during PDO. If we use the static values, assuming that the system moves from one quasi-steady-state to another, the N-shape plot should be the same, because the border condition is the heat applied, which was the same in all the experiments. Therefore, periods and amplitudes should have been the same for the different types of tubes used. However, the heat transfer coefficient has a direct influence in the tube wall temperature, and then in the thermal energy stored in the test section walls. Consequently, the effect of the thermal capacity of the wall was not negligible for the conditions in this experiments. Even though the authors related this influence of the different test sections on PDO behavior with the wave propagation lags and feedback effects in the system, the thermal capacity of the pipe seems to play a mayor role. The almost non-dependence on the difference setups for DWO observations also agrees with the thermal capacity effect, which plays a minor role during DWO.

Two phase flow instabilities in a horizontal single channel have been studied by Yüncü et al. (1991). The periods and amplitudes of PDO as a function of mass flux, heat flux and exit restriction diameter were analyzed and the effect of each parameter can be summarized as follows: (i) the period of the oscillations increases toward the stability boundaries with decreasing orifice diameter or increasing heat flux and (ii) the amplitude of the oscillations increases with smaller orifice diameters or higher heat fluxes. The effect on the period was supposed to be related to the compressibility in the surge tank. Then, as the orifice diameter is reduced or the heat flux is increased, the pressure inside the surge tank becomes higher, and so does the period. This statement might sound contradictory because the period is expected to decrease as the system gets stiffer. One reason why the periods increase as the orifice diameter decreases or the heat flux increases, could be the fact that the amplitude of the oscillations increases, increasing the time to complete the limit cycle. In the experiments it was also found, as expected, that the amplitude of the oscillations is related to the maximum and minimum pressure drop values of the static behavior of the system downstream of the surge tank.

Liu and Kakaç (1991) investigated experimentally two-phase flow instabilities in a single channel, forced convection, open loop, upflow system. The surge tank was pressurized with compressed air. A complete analysis of the effect of heat flux, subcooling temperature and surge tank volume on the periods and amplitudes of PDO, DWO and THO was performed (PDO were found to have always DWO superimposed and always accompanied by THO). The net effect on the pressure drop oscillations can be summarized as follows: (i) the periods and amplitudes of the oscillations increase with decreasing mass flow rate in the negative slope region of the steady state characteristics; (ii) the periods increase linearly with increasing heat input and the amplitude increases with increasing heat input; (iii) the amplitudes increase with decreasing inlet fluid temperature and the periods increase approximately linearly with decreasing inlet fluid temperature; (iv) and finally the periods were found to decrease with decreasing compressible volume in the surge tank. This is shown in Tables 1–3. The experimental procedure was systematic and clear, studying each parameter as isolated from the others as possible. However, it is interesting to note that the periods and amplitudes of oscillations increase monotonically as the mass flow rate is decreased, while it is expected that when reaching the flow rate corresponding to the local maximum in the static pressure plot, both amplitudes and periods start decreasing (for PDO) as the system gets more stable. Information regarding the output quality would have been useful in order to know in which region the tests have been performed.

Ding et al. (1995) also analyzed two-phase flow instabilities in horizontal heated channels with R-11 as working fluid. They found three unique phenomena which do not take place in vertical upflow systems. One of them is that the inlet pressure comes to a stop approximately halfway along its rising course (at this point the bottom wall temperature starts to increase at a higher rate) and then works its way up again until it reaches a peak. The other two unique features are that the rising process is less stable than the falling process of inlet pressure and that DWO are superimposed on the falling portion of the pressure curve, instead of being in the rising portion as observed in vertical upflow systems. Another important feature is the fact that the PDO takes place when the operating point is still in the positive slope region (the oscillation region is

Table 1
Effects of mass flow rate on oscillations (Liu and Kakaç, 1991).

Mass flow rate (g/s)	Thermal oscillation		Pressure oscillations			
	Amplitude (°C)	Period (s)	Amplitudes		Periods	
			P.D. (bar)	D.W. (bar)	P.D. (s)	D.W. (s)
20.92	18.5	15	0.60	0.62	15	2.2
16.28	28.8	21	0.75	0.61	21	2.5
11.89	65.5	28	0.89	0.57	28	2.6
9.06	100.2	40	0.94	0.50	40	2.7
7.31	119.8	49	0.96	0.42	49	3.0

Table 2
Effects of heat inputs on oscillations (Liu and Kakaç, 1991).

Heat input (W)	Thermal oscillation		Pressure oscillations			
	Amplitude (°C)	Period (s)	Amplitudes		Periods	
			P.D. (bar)	D.W. (bar)	P.D. (s)	D.W. (s)
400	4.8	13	0.21	0.10	13	1.5
600	10.4	18	0.52	0.22	18	1.5
800	48.3	30	0.76	0.32	30	1.2
1000	113.0	37	0.92	0.39	37	1.2

shifted to the right on the characteristic curve as compared to an upflow system). It seems that pressure drop oscillations never occur alone in horizontal systems; they are always superimposed with other higher order oscillations. They also remarked that the oscillations involved macroscopic fluctuations of every system parameter, repeating itself between the vapor line and the liquid line, but not necessarily bridging the two lines. The results for PDO observations show that a reduction in the mass flux produces a decrease in the amplitudes and periods of the oscillations (same trend was observed with an increase of the inlet temperature). The periods of the oscillations also increase as heat input decreases. The effect of the mass flux on the amplitudes and periods of the oscillations can be related with the fact that the unstable region is shifted to the right on the characteristic curve for horizontal channels. Hence, decreasing the flow rate will lead to the stable region sooner than in the vertical setup. Clearly PDO oscillations have different features in horizontal systems, compare with upflow systems. A projection of the limit cycle in the inlet pressure–mass flux plane would have been useful for the understanding of the behavior of the system. One explanation for the strange behavior of the inlet pressure might be the amplitude of the oscillations in flow rate during the superimposed DWO. The amplitude of the oscillations in the flow rate because of DWO is much higher than the one associated with the PDO, crossing the flow rate value of the supply curve several times, and then changing the sign on the surge tank pressure variation.

A very interesting experimental analysis has been performed by Guo et al. (2001). The experimental setup was a closed forced convection loop with water as the working fluid in a helically coiled heated section. The effects of evaporator inclination, position of surge tank and axial distribution of heat flux on PDO stability limits and dynamical behavior were analyzed. The inclination of the heated section was not found to be a relevant parameter, but the position of the compressible volume was found to be an important parameter. In this work, two different positions for the surge tank were studied, namely straight after the pump and at the inlet of the evaporator (as is usually placed for PDO experiments), as it can be seen in Fig. 3. Two different types of PDO were reported for each position of the surge tank. These two types of oscillations, 1st PDO and 2nd PDO, correspond to the surge tank after the pump far from the test section and just before the test section, respectively. The time evolution of the mass flow rate, pressure drop, absolute pressure at the inlet and outlet and the fluid and wall temperatures are shown in Fig. 4 for both types of oscillations. For the 2nd PDO (most common PDO) the compressible volume needed in the surge tank for the triggering of the instability was less than for the 1st PDO under the same conditions. Therefore, when it is not possible to remove a compressible volume before an evaporator in a given application, one option is to move it upstream the test section as far as possible from the inlet. For the study of axial heat distribution, the heated region was divided into two regions with two different heat loads. It was found that non-uniform heat flux distribution decreases the initial boundaries of PDO, especially of those occupying higher heat flux values at higher mass quality regions. With the same experimental rig Guo et al. (2002) studied the effect of oscillatory phenomena in the heat transfer coefficient. The data of oscillatory single phase heat transfer coefficients were found to be higher than those of steady flow with corresponding conditions and strongly connected with the frequency and amplitude of the oscillations. It was reported that the oscillation in low frequency is more beneficial for heat transfer enhancement than that in high frequency and that the larger amplitudes of oscillations enhance the heat transfer. For the case of oscillatory two-phase flow heat

Table 3
Effects of inlet subcoolings on oscillations (Liu and Kakaç, 1991).

Inlet liquid temperature (°C)	Thermal oscillation		Pressure oscillations			
	Amplitude (°C)	Period (s)	Amplitudes		Periods	
			P.D. (bar)	D.W. (bar)	P.D. (s)	D.W. (s)
−10	162.0	68	1.19	0.51	68	3.0
0	132.1	62	1.06	0.36	62	3.2
10	124.8	50	0.98	0.43	50	3.2
23	119.9	47	0.96	0.42	47	3.0

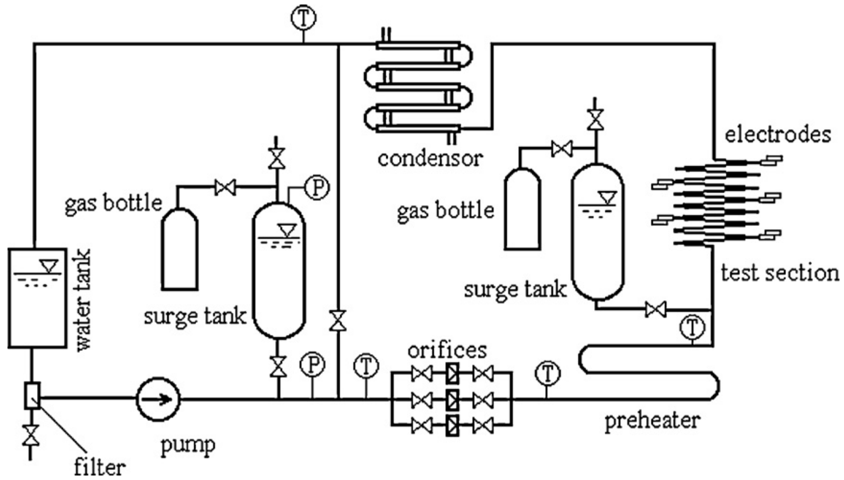

Fig. 3. Schematic diagram of the experimental facility (Guo et al., 2001).

transfer, the time averaged heat transfer coefficient under PDO is much lower than that of stable conditions.

Çomakli et al. (2002) performed an experimental study on PDO, DWO and THO. The system is a horizontal electrically heated channel with R-11 as working fluid. The PDOs registered were always together with superimposed DWO and the unstable region was found to be placed in a narrower region than other experimental studies with horizontal pipes (if they are compared with vertical upflow systems the unstable region is always narrower in horizontal heated pipes). Among the experimental results they found that the stability boundaries move to lower mass flow rates with decreasing inlet temperature and that the periods and amplitudes of the pressure drop oscillations increase with decreasing inlet temperature and decrease with decreasing mass flow rate. The same trend of shifting the stable region to the right of the stability curve observed in horizontal channels by Ding et al. (1995) was also observed in this paper. However the threshold for the instabilities in the higher flow rates does not move, which actually implies a narrower region for PDO occurrence. The oscillations in flow rate have the same features than the ones reported by Ding et al. (1995), but the amplitudes related with the superimposed DWO are less strong (superimposed DWO amplitudes and frequencies are still higher than the ones showed for pure DWO). In these measurements it was not found any plateau in the pressure oscillations, but the shape of the limit cycle still seems very different from the one for vertical channel because of the mass flow rate behavior.

Table 4 shows discrepancies between different authors about the influence of mass flow rate and heat flux on the amplitudes and periods of pressure drop oscillations in horizontal channels. Thus, it seems that the effect of different variables on flow stability depends on the particular experimental situation and generalizations are not appropriate. It can also be seen from Table 5 that the influence of the heat flux and mass flow rate in vertical channels differs from the one in horizontal channels. The effect of the gravitational component of the pressure drop in vertical boiling systems is an important factor which changes the influence of the heat applied on the pressure drop vs. mass flow rate behavior. Besides, it should also be taken into account that the effect of the mass flow rate depends on which region of this plot (Fig. 2) the system is operating in. Even though it is not possible yet with the knowledge available on PDO, to state the global influence of every given variable, there are some trends that are present in every publication. For example, in all the experiments performed with different compressible volumes in the surge tank it was found that an increase in the compressible volume leads to an increase of the period of the oscillations. As a summary, it can be said that the amplitudes of the oscillations are more related with the steady-state behavior of the system and that the periods are closely related with the energy storage elements, like the compressible volume, the flow inertia and the thermal capacity of the pipe. Higher heat fluxes will always increase the amplitude of the negative slope region and then the oscillation amplitudes, whereas larger compressible volumes will lead to larger periods and a behavior closer to the quasi-static evolution assumption. For the case of larger hydraulic inertias or thermal capacities of the pipe, the periods will also increase as the former two increase, but the limit cycle will separate from the static characteristic curve.

Even though pressure drop oscillations have been widely studied in the experimental field, more experimental research still needs to be carried out in the subject. The behavior of PDO in horizontal channels is not fully understood yet. Experiments with the aim of decoupling DWO from PDO in horizontal channels would be very helpful in order to have a clearer idea of the phenomenon. It has been reported in several papers that the mean two phase heat transfer coefficient under oscillatory flow is different than the one for steady-state conditions. There is still need for two phase-flow heat transfer correlations under oscillatory conditions. These data will allow the numerical models to take into account the actual heat flux applied to the fluid in a more representative approach. For the measurement of such coefficients, it is important to be able to have an accurate and trustable estimation of the heat stored in the pipe during the oscillations, in order to know the real heat applied to the fluid.

3.2. Numerical studies

The modeling of PDO did not change much since its beginning in the 1960s and the same lumped parameter model is still used. Nevertheless, the way of solving the steady state equations for a boiling fluid in a pipe has changed and different models have been used considering effects like subcooled boiling and thermal non-equilibrium. Besides, the thermal capacity of the pipe wall and the actual heat applied to the fluid at every time step have also been taken into account by several authors. Gürgenci et al. (1983) modeled pressure drop oscillations and density waves oscillations. For the case of PDO, a very simple model was developed, neglecting the inertia effects of the flow and the heat capacity of the wall. The results for the pressure drop oscillations are in good agreement with the experimental data regarding the amplitude of the oscillations, but a discrepancy with the periods length was found,

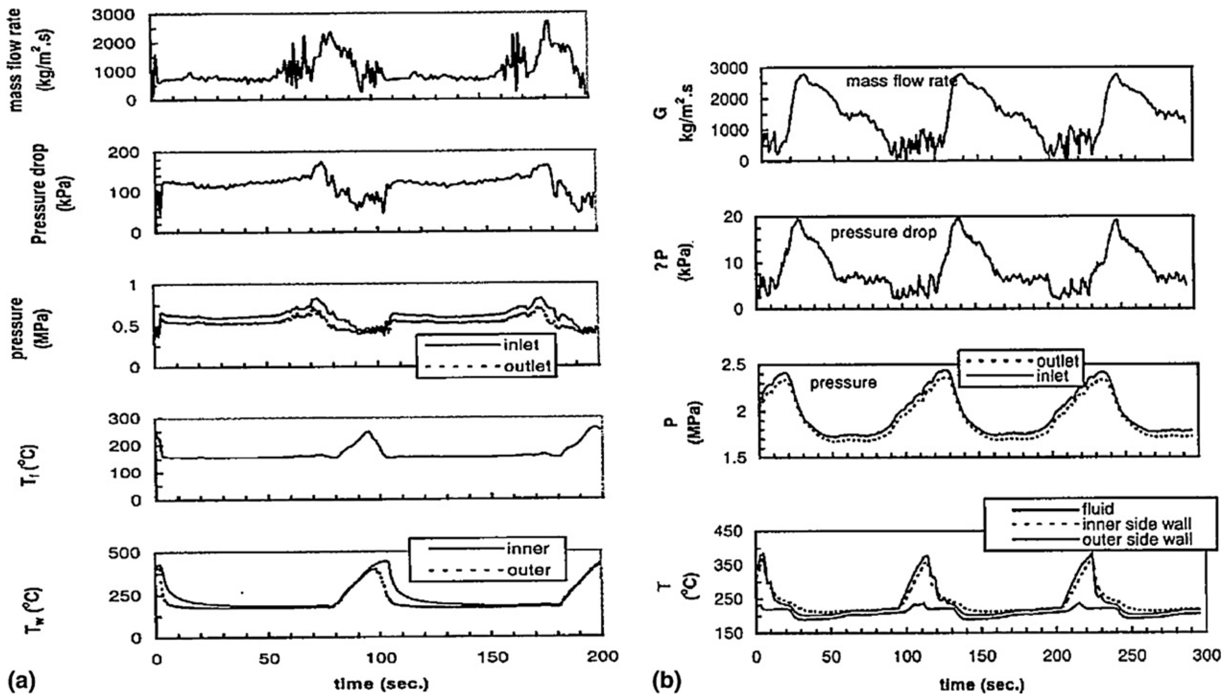

Fig. 4. Typical oscillation curves when the system compressible gas volume is oriented (a) in front of a pre-heater and (b) at the inlet of test section (Guo et al., 2002).

Table 4
Summary of the effects of each parameter on the periods and amplitudes of PDO (experimental results in horizontal channels).

Parameter	Effect on the period	Effect on the amplitude
Mass flow rate (increase)	Yüncü et al. (1991) – decrease	Yüncü et al. (1991) – no effect
	Çomakli et al. (2002) – increase	Çomakli et al. (2002) – increase
	Ding et al. (1995) – increase	Ding et al. (1995) – increase
Heat flux (increase)	Yüncü et al. (1991) – increase	Yüncü et al. (1991) – increase
	Ding et al. (1995) – decrease	Ding et al. (1995) – increase
Inlet temp. (increase)	Çomakli et al. (2002) – decrease	Çomakli et al. (2002) – decrease
	Ding et al. (1995) – decrease	Ding et al. (1995) – decrease

presumably due to the role that the inertia of the flow plays during the flow excursions. The model used was the simplest possible showing an acceptable performance in predicting the amplitudes.

Doğan et al. (1983) performed both experimental and numerical work on the analysis of pressure drop and density wave oscillations. The modeling of the pressure drop oscillations is a lumped capacitance method, dividing the loop in several segments. The velocity of the boiling boundary was taken into account and updated in order to prevent it from being higher than the velocity of a fluid particle. Regarding the PDO simulations, several important factors have been taken into account in the modeling, such as the subcooled boiling region for the heat transfer and the thermal capacity of the walls of the pipe with the utilization of the actual heat flux to the fluid for every time step. They found that the variation in the heat input plays an important role in generating and sustaining the pressure drop oscillations. In this extensive work the model seems to take into account every important effect within the limits of the lumped parameters approximation. The periods obtained with the model fit well with the experimental data while the amplitudes of the oscillations are underpredicted. The oscillations shown for PDO seem to be still under transient behavior. A clearer picture of the oscillation already developed might show a better agreement closer to the 10% of deviation stated in the conclusions.

Both experimental and modeling work has also been done by Kakaç et al. (1990). Pressure drop and thermal oscillations were observed and predicted by the model. The model used is a quasi steady-state model for the behavior of the pressure drop and heat transfer along the loop, with a lumped method for solving the

Table 5
Summary of the effects of each parameter on the periods and amplitudes of PDO (experimental results in vertical channels).

Parameter	Effect on the period	Effect on the amplitude
Mass flow rate (increase)	Liu and Kakaç (1991) – decrease	Liu and Kakaç (1991) – decrease
	Kakaç et al. (1990) – decrease	Kakaç et al. (1990) – decrease
	Padki et al. (1991) – decrease	Padki et al. (1991) – decrease
Heat flux (increase)	Liu and Kakaç (1991) – increase	Liu and Kakaç (1991) – increase
	Kakaç et al. (1990) – increase	Kakaç et al. (1990) – increase
	Padki et al. (1991) – increase	Padki et al. (1991) – increase
Inlet temp. (increase)	Liu and Kakaç (1991) – decrease	Liu and Kakaç (1991) – decrease
	Kakaç et al. (1990) – decrease	Kakaç et al. (1990) – decrease
	Padki et al. (1991) – decrease	Padki et al. (1991) – decrease

dynamics involved. This quasi steady-state approach is justified, as explained in Section 2, because the periods of the oscillations are much larger than the residence time of any fluid particle in the flow. Therefore, these oscillations can be "assumed to take place as a succession of quasi-steady-state operating points of the system". The model uses for the steady state heat transfer coefficient in the two-phase flow region, a correlation developed by the authors from their experimental measurements of heat transfer. The model takes into account the change in the actual heat transferred to the fluid due to the thermal capacity of the walls of the heater at every time step during the simulation. The results from simulations are in good agreement with the experimental data. The model neglects the inertia of the mass flow, which does not seem to have an important effect in the periods of the oscillations. This suggests that for the conditions studied, the thermal capacity has a larger influence on the dynamics of the system than the hydraulic inertia. It is important to say, however, that the implementation of the hydraulic inertia in a lumped way is not fully justified, in the sense that it has its larger influence in the period of the oscillations during the flow excursions, where the flow is under the larger pressure driving forces, and at the same time, where the quasi-steady-state evolution does not hold.

Padki et al. (1991) simulated pressure drop and thermal oscillations and the results were validated against experimental data obtained for upwards boiling flow of Freon-11. Regarding the modeling of the oscillations, the drift flux model was used for the steady state solution of the pressure drop in the boiling channel and the instantaneous value of heat applied to the fluid was taken into account for the pressure drop vs. mass flow rate characteristics. The inertia of the flow was neglected, though. The model implemented is essentially the same used by Kakaç et al. (1990), with the implementation of drift flux model for the solving of the steady-state equations. A very interesting idea for the experimental tests was the use of two different test sections, with same dimensions and material, but one bare and the other coated with Linde High-Flux coating. The relevance lies in the fact that in the experiments the thermal capacity plays a significant role during oscillations, so a strong dependence on the heat transfer coefficient is expected. Unfortunately, the results shown for the different test sections correspond to different conditions. Hence it is hard to infer the influence of the heat transfer coefficient on the behavior of the system.

Cao et al. (2000) have taken into account the effects of thermal non-equilibrium for the steady state representation of the pressure drop vs. mass flow rate. The net effect is that the pressure drop for the regions with low outlet quality increases due to the two-phase flow in the subcooled boiling regime. This effect is also reflected in the periods of the oscillations, obtaining smaller periods (closer to experimental data) than with the thermal equilibrium model. One year later Cao et al. (2001) modeled PDO using the typical lumped parameter model, neglecting the thermal capacity of the pipe wall, and using the drift flux model for the steady state solution of the upflow boiling pipe. The oscillation amplitudes and periods were reasonably predicted by the theoretical model. A very simple and useful model for the pressure drop at the exit restriction was presented and validated with experimental data. It was found that this pressure drop is a function of not only the quality of the fluid, but also of the heat applied to the fluid upstream. The importance in the accuracy of the modeling of the outlet restriction lies in the fact that the pressure drop in this component can be much larger than the one in the heated section. Further research on characterizing two-phase flow pressure drop across a restriction is still necessary since although many correlations are available in open literature (Friedel, 1988; Morris, 1991; Fossa and Guglielmini, 2002), the uncertainties associated for a given set-up can be very large.

The thermohydraulic dynamics of a horizontal boiling channel with a surge tank was also modeled by Mawasha and Gross (2001) with an integral method in the spatial dimension. For the steady-state behavior of the pressure drop vs. the mass flow rate, a cubic nullcline obtained from empirical data (Yüncü et al., 1991) was used. The time evolution of the wall temperature was calculated, taking into account the thermal inertia of the pipe, although the heat applied to the fluid was supposed to be constant because the N-shape curve was fitted from experimental data. The periods and amplitudes obtained from the simulations for the pressure oscillations have a good fitting with the experimental data, which means that in the case analyzed, the thermal capacity of the pipe did not play a significant role. This is contrary to the previous mentioned studies, indicating that there might be a critical value for when the pipe heat capacity is important or not.

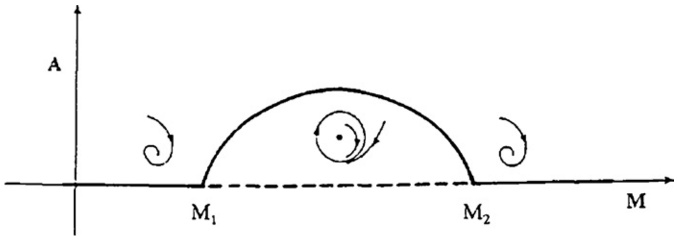

Fig. 5. Schematic bifurcation diagram of the planar system: *A*, the radius of the periodic orbit, which is asymptotically stable, as a function of parameter *M* (mass flow).

Some recent papers dealing with the modeling of PDO are those from Kakaç and Cao (2009) and Kakaç et al. (2009). Table 6 presents a summary of the different approaches mentioned in this section.

Recently, Zhang et al. (2011) applied active control schemes to suppress pressure drop oscillations in a modeling study. The control devices used were the inlet valve and the supply pump. Regarding the modeling of the PDO, the inlet flow was assumed to be constant (positive displacement pump) and the inertia of the flow and the thermal capacity of the pipe wall were taken into account in the lumped parameter model. For solving for the pressure drop in the pipe and the wall temperature, simplified steady-state lumped-channel flow heat transfer and friction correlations were used. The effect of the thermal capacity of the pipe was found to be an important parameter, with the period of the oscillations being proportional to it. A very interesting result was that above a given value of thermal capacity, the oscillations were suppressed. This is a major proof for the need of finding a criterion in order to be able to determine for each particular case if the heat capacity should be taken into account in the modeling.

3.3. Bifurcation studies

Some research has been carried out in the field of non-linear dynamics and bifurcation theory for PDO. Padki et al. (1992) modeled PDO applying an integral method with the aim of reducing the dimensionality of the problem. A bifurcation analysis was done using the total heat applied to the flow as the bifurcation parameter. It was found that pressure drop limit cycles are generated after a super-critical Hopf bifurcation and the static Ledinegg instability is caused by a saddle-node bifurcation. The stability criteria for both types of instabilities were derived in terms of the magnitude of the negative slope of the steady-state pressure drop vs. mass flow rate behavior (independent of the two-phase flow model used). Later, Liu et al. (1995) formulated a planar system for the modeling of PDO using a lumped parameter model assuming constant inlet mass flux to the surge tank. They found that the limit cycles are generated after a super-critical Hopf bifurcation using the surge tank inlet mass flow rate as the bifurcation parameter (Fig. 5). It was also found that these limit cycles converge to an asymptotically stable equilibrium point after a reverse supercritical Hopf bifurcation.

Table 6
Summary of the different relevant studies dealing with PDO in a single channel.

Researcher	Steady-state model	Thermal non-eq.	Flow inertia	Thermal capacity	Actual heat to the fluid
Gürgenci et al. (1983)	Homogeneous flow	No	No	No	No
Doĝan et al. (1983)	Homogeneous flow	No	Yes	Yes	Yes
Kakaç et al. (1990)	Homogeneous flow	No	No	Yes	Yes
Padki et al. (1991)	Drift flux	No	No	Yes	Yes
Cao et al. (2000)	Drift flux	Yes	Yes	No	No
Cao et al. (2001)	Drift flux	No	Yes	No	No
Mawasha and Gross (2001)	Experimental data fitting	Is included in exp. data	Yes	Yes	No
Kakaç and Cao (2009)	Drift flux	No	Yes	Yes	No
Kakaç et al. (2009)	Drift flux – homogeneous (comparison)	No	No	Yes	Yes

Srinivas and Pushpavanam (2000) performed a parametric analysis on PDO. The different regions in the parameters plane of inlet subcooling and inlet valve (between the surge tank and the boiling channel) coefficient where PDO are prone to take place were identified. The different regions characterized by the operating point lying in the different parts of the system characteristic and the channel characteristic were isolated using the D-partition method. The bifurcation parameter used for the system pressure drop characteristic was the total pressure drop, which is a control parameter that can be varied experimentally. The channel pressure drop cannot be viewed as an independent parameter because this is determined by the pressure in the surge tank. A superposition of the results from the singularity theory along with the Ledinegg and marginal stability boundaries allowed to locate the regions in the parameters plane where PDO are possible.

As a summary of this section it can be said that the lumped parameter model predicts with good accuracy the amplitudes and periods of the oscillations. The errors in the periods are usually larger and related to the hypothesis of the quasi steady-state evolution, which is not valid during the flow excursions, and the disregarding of the thermal capacity of the pipe wall. Nevertheless, as the compressible volume increases, the periods increase and the system behavior follows the steady-state plot closer and the percentage of the flow excursions on the total period of the oscillations becomes less significant. In the pioneer studies conducted by Maulbetsch and Griffith (1966, 1967), the frequency of the oscillations was found to be, after a linearization of the lumped parameters equations, mainly proportional to the volume of the surge tank and the inertia of the flow. The correlation obtained is the following,

$$w^2 = \frac{1}{2I_1I_2^2}\left[2I_1I_2\left(\frac{dp}{dv}\right)_0 - \left(\frac{\partial p_{in}}{\partial Q}\right)^2(I_1+I_2) - \left(\frac{\partial p_{in}}{\partial Q}\right)\sqrt{\left(\frac{\partial p_{in}}{\partial Q}\right)^2(I_1+I_2)^2 + 4{I_1}^2I_2\left(\frac{dp}{dv}\right)_0}\right] \quad (5)$$

where Q is the volume flow rate out of the surge tank, p_{in} is the inlet pressure, I_1 and I_2 are the inertias of the flow into the surge tank and into the heated section respectively and $(dp/dv)_0$ is a measure of the compressibility of the system.

Stenning et al. (1967) also linearized the equations considering the thermal effect of the pipe wall as an energy storage element, besides the compressible volume and the inertia of the flow. The relation obtained for the frequency of the oscillations is much more complex than Eq. (5), but it allows to analyze the effect of the thermal capacity of the wall in PDO. In addition to the compressible volume, the thermal capacity of the wall and the heat transfer coefficient were found to have a key role in the period of the oscillations. The period (T) is actually proportional to the square root of the product of the compressible volume (V_G), the thermal capacity (Mc_m) and the heat transfer coefficient (h_o),

$$T\alpha\sqrt{V_G \cdot Mc_m \cdot h_o} \quad (6)$$

Furthermore, as the thermal capacity was decreased the amplitude of the limit cycles increased, approaching the values given by the model which assumes constant heat flux to the fluid.

Pressure drop type oscillations (and thermal oscillations induced by PDO) can be, in most of the cases, avoided by increasing the inlet pressure drop, which leads to a considerable waste of energy. Therefore, sometimes it is a better option to operate some systems under unstable conditions when the oscillations amplitudes and frequencies are known and bounded. Therefore the importance in knowing the periods and amplitudes of the oscillations with a considerable accuracy.

To sum up, it can be stated that the predictions made with the lumped parameter model for PDO are in good agreement with experimental results for the cases where the oscillation periods are much larger than the residence time of a particle in the heated channel, while the model cannot be applied for stiffer systems with periods of the same order of the residence time of a fluid particle. It is known that when the thermal constant of the wall is much larger than the residence time of the fluid particle in the system, the thermal capacity of the wall and the actual heat applied to the fluid play an important role, but there is still lacking a clear condition for when the thermal effect should be taken into account for the analysis.

4. PDO in parallel channels

Regarding PDO in parallel channels there is limited information available. No out-of-phase oscillations have been registered so far to our knowledge. When modeling or measuring PDO in a single channel, the steady state behavior of the boiling pipe is a fundamental feature of the system in order to understand and analyze the oscillatory behavior. For the case of parallel boiling channels with common inlet and outlet headers, the situation gets more complex. If we assume that the pressure drop is the same in each channel (i.e. distributed pressure losses in the headers are negligible) the typical N-shape curve for pressure drop vs. mass flux has a different shape for the boiling channels arrangement as a whole (Fig. 6). Akagawa et al. (1971) made a broad theoretical and experimental analysis on the possible solutions and their stability in a three parallel boiling channels system. 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. A stability criteria for the working points regarding flow excursion instabilities was developed.

The possible solutions and flow excursions in a parallel channel arrangement with a surge tank upstream the inlet plenum have been numerically analyzed by Manavela Chiapero et al. (2011b). It was found that Ledinegg-type flow excursions are present with a

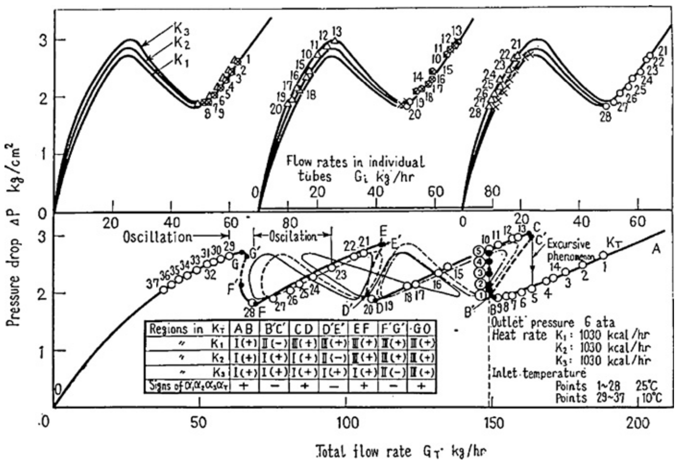

Fig. 6. Experimental results for three parallel tube system (Akagawa et al., 1971).

surge tank upstream the heated section and the operation of one channel in the negative slope region of the pressure drop curve will induce a flow excursion until all the channels are in the positive slope region of their characteristic pressure drop vs. flow rate curve. Other studies related with flow distribution and pressure drop vs. mass flux behavior for a parallel arrange of boiling channels are Natan et al. (2003), Minzer et al. (2004), Minzer et al. (2006), Taitel et al. (2008), and Pustylnik et al. (2006). In a more recent study, Taitel and Barnea (2011) made a dynamic analysis on the stability of the possible solutions in a two parallel channels arrangement. The effect of the rate of change of the heat applied or the inlet mass flow rate on the evolution of the transient was also analyzed. Although the heat flux was changed externally as a control parameter during the transient analyses, it is possible to notice how the dynamics on the heat flux variations influence the behavior of the system, even leading to different final results in the parallel channels configuration.

Kakaç et al. (1977) reported pressure drop oscillations in an experimental setup of four parallel channels with cross connections. The pressure oscillations in individual channels were reported and found to be the same. Nevertheless, no information was given about the flow rate per channel during PDO. The cross-connected four parallel-channel system is more stable than the four parallel-channel system without cross-connections, i.e. the minimum heat input at which this system can operate without any transient PDO is higher in the cross-connected system than that of the system without cross-connections. It is also shown that when the heating is unbalanced (2 channels heated and 2 unheated channels) the system gets more unstable. However, if instead of taking into account the total heat applied, the heat load per channel is used, the unbalanced case is still less stable but the difference is very small. Also differences in the periods of transient PDO were observed, finding larger periods in equal heating experiments than those observed in unequal heating experiments.

Ozawa et al. (1989) analyzed flow instabilities in a twin parallel adiabatic channel system with air–water mixtures. In a previous experimental and analytical study Ozawa et al. (1979a) found an analogous behavior of the pressure drop vs. mass flux for a boiling channel for an air–water mixture with fixed water mass flux and variable air mass flux. In this previous analysis it was also found that with the presence of a compressible volume in the gas feed line pressure drop-type oscillations like the ones corresponding to a boiling channel system (Ozawa et al., 1979b) were present when the working point was situated in the negative slope region. In the parallel channel analysis, both analytical and experimental analysis were made but this time with compressible volumes in both the liquid and the gas feed lines for each channel (Fig. 7). First, the maldistribution phenomenon with all the possible solutions and their stability was analyzed. Then, with the presence of the compressible volumes the oscillatory phenomenon was studied. Very interesting observations were reported. It was found that without the presence of the surge tanks in the liquid feed lines the typical single channel pressure drop oscillations were present in the system with both channels oscillating in phase with the same amplitude and shape. Interesting results were found when the compressible volume in the liquid feed lines was added. Two other modes of oscillation were found, namely “U-tube mode” and “multi-channel mode”, both quasi-static oscillations. The compressible volume in the liquid lines leaves the liquid flow rate free to oscillate and then the oscillations gain one extra dimension (pressure, gas flow rate and liquid flow rate) as shown in Fig. 8. In the multi-channel mode, the gas flow rate oscillations are smaller in amplitude but with different periods in each channel. However, no such a behavior was found in a parallel boiling channel system.

Manavela Chiapero et al. (2011c) analyzed pressure drop oscillations in parallel channels. The behavior of individual channels in a two parallel boiling channels arrangement was modeled for the cases of balanced and unbalanced heat loads. The unstable region was divided in two different regions. The oscillation modes found were in phase with different limit cycles per channel depending on the region of operation and the heating mode. The region at lower vapor quality was found to be always stable with maldistributed solutions for the case of unbalanced heat load.

5. PDO in microchannels

Boiling microchannel systems have gained the focus of many researchers due to the need of cooling of high-power density electronic devices. Flow instabilities like PDO have been reported

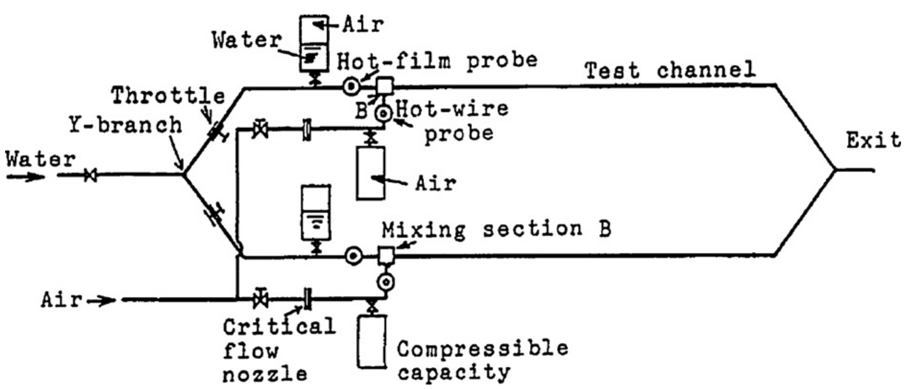

Fig. 7. Experimental setup from Ozawa et al. (1989).

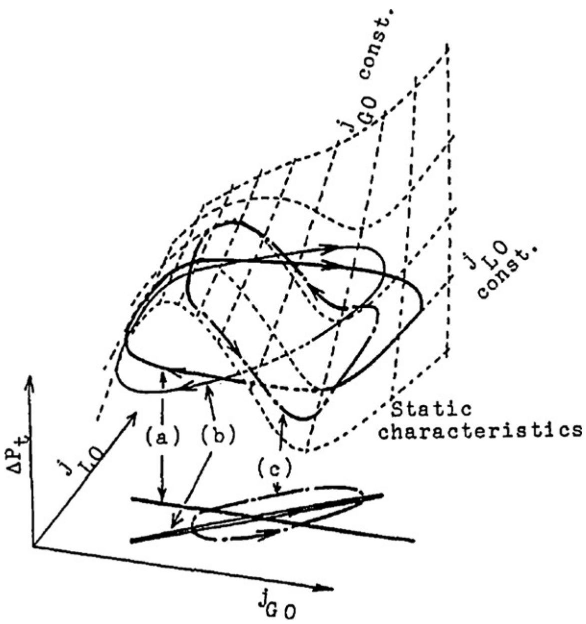

Fig. 8. Different modes of oscillation from Ozawa et al. (1989).

in several of such systems. Tadrist (2007) made a review on two phase-flow instabilities in microchannels. Static and dynamic instabilities take place in boiling microchannels showing similar behavior than in regular channels (hydraulic diameter greater than 10 mm). Consolini and Thome (2009) analyzed boiling heat transfer for R-134a, R-236fa, and R-245fa in micro-channels. Flow boiling oscillatory instabilities were found during the experiments, which if neglected, would lead to a substantial deviation from the corresponding values for stable flow. Two-phase flow affected by oscillatory instabilities was exposed to oscillations in pressure (and therefore in temperature) and in heat transfer, leading to the corresponding temperature oscillations in the heated wall. The stability of the flow during the experiments was guaranteed by the presence of an inlet valve at the entrance of the heated section, which isolates the boiling flow in the evaporator from any upstream compressibility. It was found that mean heat transfer coefficient for R-245fa and R-236fa exhibited smaller values during instability, increasing the difference as the vapor quality increases. It should be remarked that for the case of R-134a, no such difference was found between stable and unstable behavior, which added to the fact that this fluid requires much more heat flux for the instabilities to propagate, makes R-134a a good working fluid for electronics cooling.

Several experimental and numerical studies have dealt with PDO in single and parallel boiling microchannel systems. Wu and Cheng (2003) performed measurements on flow boiling of water in parallel silicon microchannels. The large amplitude, long period oscillations on fluid pressure, mass flux and wall temperature were reported for the first time (Fig. 9). Although the periods and shape of the oscillations resemble pressure drop-type oscillations, these oscillations were reported as a different type of oscillations because of the absence of a compressible volume upstream of the heated section. In a following investigation by Wu and Cheng (2004), two other boiling modes were observed besides the previous reported liquid/two-phase alternating flow. Continuous two-phase flow and liquid/two-phase/vapor alternating flow were measured and visualized.

Qu and Mudawar (2003) reported severe pressure drop oscillations in a two-phase microchannel heat sink. Although there was no surge tank upstream of the test section in the experimental setup, periodic, large-amplitude flow oscillations were registered as a

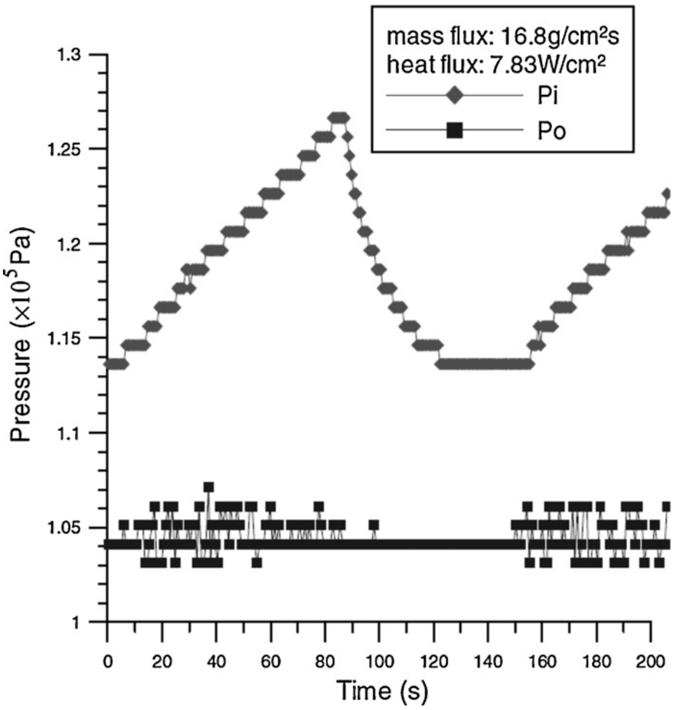

Fig. 9. Pressure fluctuations in microchannels registered by Wu and Cheng (2003).

result of the interaction between vapor generation in the channels and a compressible volume in the flow loop upstream of the heated sink. During these oscillations all channels oscillated in phase.

Huh et al. (2007) studied experimentally flow boiling in a single microchannel. The oscillations measured were identified as flow pattern oscillations (Fig. 10). Nevertheless, this type of oscillations can be the cause or the consequence of other type of oscillations, such as PDO. Other studies that found oscillations similar to the pressure drop-type are Qi et al. (2007) and Wang et al. (2007).

Wang et al. (2007) performed experiments on unstable and stable flow in single and parallel microchannels. Water was used as the working fluid and two different kinds of instabilities regimes were found, defined as short-period oscillation and long-period oscillation, for both single and parallel microchannels. One order of difference in the value of the heat-to-mass flux ratio needed for the triggering of the different regimes was found between the single microchannel and the parallel channels configurations,

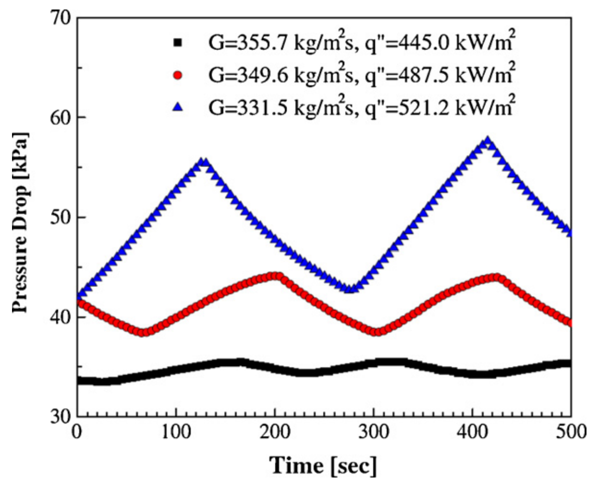

Fig. 10. Pressure fluctuations in microchannels registered by Huh et al. (2007).

with the parallel arrangement being more stable. It was also found that the oscillation period of temperature depends on the heat-to-mass flux ratio for the long-period oscillation regime. Moreover, the periods in the single channel configuration were one order of magnitude higher than the ones in parallel channels for the same hydraulic diameter and at the same heat flux condition. Even though the mechanism explained for the oscillations is related to the periodic bubble expansion in both upstream and downstream directions, typical on the confined spaces of microchannels, the short-period and the long-period oscillations resemble the DWO and PDO, respectively, present in the macroscopic channel systems.

Zhang et al. (2010a) modeled and measured PDO in a microchannel system. An active control of pressure drop oscillations in microchannels systems was implemented and it was theoretically proved that a simple feedback control system based on mass flow acceleration can regulate the oscillation amplitudes in a satisfactory manner. In further studies the effect of the wall thermal capacity and an external heat flux depending on time (closer to the real case on electronics cooling application) was analyzed together with active control implementation (Zhang et al., 2010b,c,d). It was suggested that a length/diameter ratio greater than 150 is easily achieved in microchannels and thus, this is one reason why so many researchers have observed boiling flow oscillations in these systems (Stenning and Veziroĝlu, 1965). It was also pointed out by the authors that although poor nucleation is an issue with silicon microchannels and this can cause some differences with respect to conventional size channels made of metals, the basic principles of instabilities will not change greatly assuming the same nucleation characteristics (i.e. the fundamental equations associated with the pressure drop-flow rate characteristics curves, instability criteria and so on, are the same).

Boiling flow in microchannels is a hot topic nowadays, and lot of effort is conducted in that direction in order to have a better understanding of the phenomena involved (heat transfer, pressure drop, flow patterns, etc.). Two-phase flow boiling instabilities can take place in microchannel systems as well, and even though the macroscopic behavior seems similar, the mechanisms behind are not fully understood yet. Among the most widely known instabilities (Ledinegg, DWO and PDO), PDO are the ones most reported during experiments in microchannels. Bergles et al. (2003) also pointed out that the effect of very long channels ($L/D > 150$) may be easily achieved in microchannels, making these systems particularly prone to develop PDO.

6. Discussion

Pressure drop oscillations are present in different scales, ranging from large scale industrial equipment to microscale cooling devices. These undesirable phenomena decrease the performance of two-phase flow heat exchanger equipment and can even destroy them due to burnout or thermal fatigue. Therefore, the characterization and understanding of this type of oscillations are a necessity. The mechanisms of PDO are well understood and have been widely analyzed theoretically and empirically. The lumped parameter model has not changed markedly from its first approach during the 1960s, except for the addition of the thermal dynamics of the pipe wall. Nevertheless, there are still several issues that have not been clarified so far. The most important one is the occurrence of PDO found by Maulbetsch and Griffith (1966) for pipes with ratios of length to diameter greater than 150 without a compressible volume upstream of the heated section. It is said that for these cases the amount of vapor in the channel is enough to provide the necessary compressible volume. However, this compressible volume is located downstream of the heated section and is more similar to the case of having the surge tank after the test section. Although this might seem plausible since the negative slope can still be achieved in the outlet valve after the surge tank, there are no reports of any test performed with a surge tank at the outlet of the heated channel to our knowledge, so it is still an open question. This compressible volume, is also not present in the oscillation during the subcooled liquid part of the limit cycle. Regarding the modeling is also difficult with the lumped parameters model to find a critical compressible volume for triggering the oscillations because as the amount of gas decreases, the system becomes more stable but, at the same time, the frequency rises, reaching the limit of applicability of the model. With respect to parallel channel arrangements, the experimental data are limited and there is almost no theoretical work dealing with the phenomena of PDO, for instance showing whether it is possible to have out-of-phase oscillations. Many recent studies have found two-phase flow oscillations in microchannels, showing a similar macroscopic behavior, even though the physics in microchannels have different characteristics. It was shown that PDO can take place in microchannels and it is possible to predict them, but with the same limitations that in regular channels. Many other types of instabilities have also been found in microchannels, which seems to have a similar behavior than the PDOs or the THOs produced by them.

Further studies could be carried out with the aim of clarifying the assumptions that a sufficient volume in the heated section has a similar effect than the compressible gas in the surge tank. The behavior of PDO in horizontal channels seems to differ from the typical behavior in upflow systems. It will be interesting if it is possible to experimentally decouple superimposed DWO from PDO in horizontal boiling systems in order to have a better picture of the limit cycles and the time evolution of the flow rates. Furthermore there is no clear criteria for knowing in which cases the thermal capacity of the wall could be neglected. The thermal coupling between parallel channels has not been analyzed either, and it is known that the dynamics in the heat flux changes can affect the flow configuration after a transient (Taitel and Barnea, 2011). For the case of plate-fin heat exchangers, this is a very important effect which should be taken into account.

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