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MAL-DISTRIBUTION PHENOMENA INDUCED BY MULTIPLE SOLUTIONS IN PARALLEL CHANNELS HEAT EXCHANGERS

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Abstract

In this work a parallel boiling channel arrangement with an upstream compressible volume is modeled and analyzed. First, flow excursions in a single boiling channel are presented in order to understand the flow excursions in the parallel channels system. Stable and unstable solutions are identified and discussed with the help of the plot of pressure drop versus mass flux, first for two parallel identical channels equally heated, and then extended to a more general case.

Introduction

In the design of multi-stream heat exchangers it is usually presumed that the inlet flow and temperature distribution across the heat exchanger channels are uniform and steady. But in reality multi-stream heat exchangers can suffer from flow instabilities and mal-distribution problems, which can lead to several problems of system control, mechanical damage and, in some extreme cases, the breakage of the equipment because of thermal fatigue.

Instabilities can be classified as static (e.g. Ledinegg) or dynamic (e.g. pressure drop oscillations). Both Ledinnegg instability and pressure drop oscillations (PDO) can occur when the pressure drop versus mass flow rate curve of the system shows a negative slope (usually refer to as an "N-shape" curve) with the system working in that region. The intersection between the "N-shape" curve and the external characteristic curve (e.g.: pump characteristic curve) defines the possible working points of the system. In particular, PDOs need in order to occur, a compressible volume within, or upstream, of the heated section [1-8].

In a system of parallel channels connected to common inlet and outlet headers, the two-phase flow can be distributed in different configurations among the channels for a given pressure drop condition between the two headers. This results in a complex problem as each parallel tube can operate in a different flow condition affecting the overall performance of the heat exchanger. The thermodynamic quality of the fluid at the outlet of the heat exchanger will also be modified because of the mal-distribution phenomena (different total mass flow rate across the heat exchanger). When several channels are coupled in a parallel arrangement, the system "N-shape" curve is not an "N-shape" curve anymore, but rather a complicated combination of possible operating points for the system as a whole.

Several experimental, theoretical and numerical studies have been conducted in the area of two-phase flow instabilities in parallel channels. Kakac and Bon [9] have made a broad review on two-phase flow instabilities in general, compiling also several studies dealing with instabilities in parallel channels. Aritomi et. al [10] analysed the effects of three different kinds of thermo-hydraulic conditions between two parallel upflow boiling channels on the stability of the system. No surge tank was used in these experiments and judging from the periods of the oscillations with respect to the resident time of a fluid particle in the heated section, the parallel channels instabilities seem to have the behaviour of DWO. Most of the studies regarding two phase flow instabilities in parallel channels have focused on DWO [11-16] and few experimental studies dealing with PDO can be found [2, 14]. Lately, due to the need of cooling of high-power density electronic devices, two-phase flow instabilities like PDO have been analysed in boiling microchannel systems. Zhang et. al [17] applied the same model used for PDOs in a single macrochannel system treating parallel microchannels as a single representative channel. Zhang et. al [18] also analysed the Ledineeg stability for microchannels but again representing the heated parallel channels arrangement as a single boiling representative channel. Several oscillations reported for parallel arrangements in microchannels look like PDOs but are still not well understood [19-22]. To our knowledge, no numerical models for PDO have been extended to parallel channels. The treating of all the possible steady-state solutions for parallel channels systems is an important factor for understanding the behavior of parallel channels coupled by the same pressure boundary condition and has been widely studied in the last ten years [23-26], although without taking into account PDO behaviour. A wide and detailed analysis on the stability of the different solutions for two-parallel channels was done before by Akagawa et al. [27], but without taking into account the compressible gas volume used to simulate the effect of very long boiling pipes.

In this work, the typical model for PDOs is extended to parallel channels coupled by the condition of same inlet and outlet pressure. It is first showed how flow excursions from unstable solutions to stable ones can take place for a single channel with a surge tank upstream of the heated section. This concept is extended afterwards in order to show how flow excursions can take place in an individual channel of a parallel channel system leading to highly maldistributed solutions in some cases.

1. Problem description

The common approach to simulate a heat exchanger is a one channel approach. If we are interested in the instability behavior of the equipment, a useful plot is the total pressure drop versus total mass flow rate. For the case of a single boiling channel we can have a negative slope in this plot, which means that for increasing flow rates, the pressure drop will decrease. This region is usually prone to Ledinegg type instabilities (flow excursion). The occurrence of flow excursion instabilities in this region depends on the external circuit thermohydraulic characteristic behavior. As it has been said before, it is possible to have three different solutions for a given fixed pressure drop. In this situation, the working point in the negative slope zone is unstable and the system will experiment an excursion to one of the other two possible solutions. Interesting results appear if we want to model PDOs in a boiling channel. For these oscillations to take place it is necessary that the negative slope of the boiling pipe (demand curve) be less steep than the slope of the external system (supply curve). It is also necessary for regular boiling channels (length/diameter < 150) to have a compressible volume placed upstream of the heated section [28]. When the working point is still in the negative slope region but the absolute value of the slope is larger than the absolute value of the slope of the supply curve in the operation point, a situation similar to the Ledinegg instability takes place. There is actually a sudden flow excursion to the overheated vapor or the subcooled liquid region, followed by a slow evolution close to the steady-state behavior of the heated pipe. This is actually a PDO which after being triggered reaches a stable operating point (where the slope of the demand curve is positive).When several channels are arranged in a parallel array more equilibrium solutions are possible for the global behavior of the system. If we use a one-channel model in order to detect the unstable region mass fluxes for a multichannel heat exchanger, the model is enough. The main problem with the one-channel approach is that it does not give any information about the mal-distribution phenomena that the heat exchanger can suffer. The flow mal-distribution and the instabilities are closely related and usually one is triggered by the other, resulting in a feedback process. If we use the one-channel model we can check that we are working outside the unstable region, but we have no information about the mass flux distribution in the channels, and thus, the system can be operating below the design specifications.

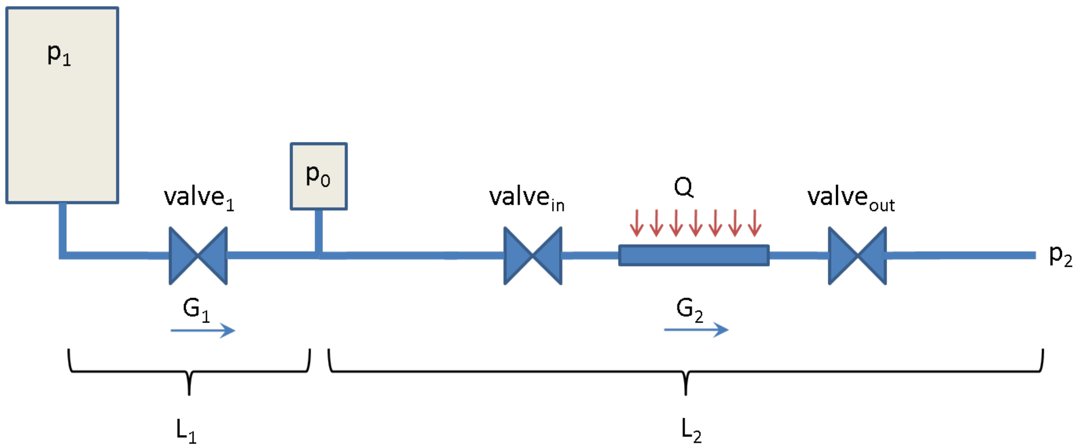


Figure 1 Sketch of the modeled system.

The system modelled is shown in Fig. 1. It consists of an inlet tank at a fixed pressure p_1 connected to a surge tank through a valve $valve_1$. The surge tank is filled with a certain amount of compressible gas, which allows the flow before and after the surge tank to be different. Downstream the surge tank there is an electrically heated section with an inlet valve ($valve_{in}$) and an outlet valve ($valve_{out}$). Finally, after the outlet valve the pressure is fixed at p_2. For this system, the three variables are p_0, G_1 and G_2, which are the surge tank pressure and the mass fluxes before and after the surge tank respectively. Assuming the gas in the surge tank as an ideal gas, we can arrive at Eq. 1,

$$\frac{dp_0}{dt} = \frac{p_0^2}{nRT_{sat}}(G_1 - G_2)\frac{A}{\rho_l} \tag{1}$$

where p_0 [Pa] is the pressure at the surge tank , G_1 [kg/m^{2}s] and G_2 [kg/m^{2}s] the mass fluxes before and after the surge tank respectively, n the number of moles of gas in the surge tank, R [J/(mol.K)] the universal gas constant, T_{st} the temperature in the surge tank, A [m^2] the cross section area of the pipes in the system and ρ_l [kg/m^3] the density of the liquid phase of the fluid.

From the momentum equation for the fluid before and after the surge tank, we get

$$\frac{dG_1}{dt} = \left[p_1 - p_0 - \Delta p_{valve}(G_1)\right]\frac{1}{L_1} \tag{2}$$

$$\frac{dG_2}{dt} = \left[p_0 - p_2 - \Delta p_{HS}(G_2)\right]\frac{1}{L_2} \tag{3}$$

where L_1 [m] and L_2 [m] are the lengths of pipe before and after the surge tank respectively (Fig. 1), p_1 [Pa] and p_2 [Pa] the pressure at the inlet tank and at the outlet of the system respectively, Δp_{valve} [Pa] the pressure drop across valve $valve_1$ and Δp_{HS} [Pa] the pressure drop along the test section plus the pressure drop across valves $valve_{in}$ and $valve_{out}$.

In order to obtain the pressure drop for the region between the surge tank and the outlet of the system Δp_{HS}, we solve the steady-state balance equations for the boiling pipe.

The model solves, for each channel, the conservation of mass, momentum and energy equations for the subcooled liquid at the inlet and the superheated vapor (if any) at the outlet (Eqs. 4 to 6), and the conservation of mass and momentum for the two-phase flow along the pipe, (Eqs. 7 to 9):

$$\frac{\partial}{\partial z}\left(\rho_j v_j\right) = 0 \tag{4}$$

$$\rho_j v_j \frac{\partial v_j}{\partial z} = -\frac{\partial p}{\partial z} - \frac{4}{D_i}\tau_w \tag{5}$$

$$\rho_j v_j \frac{\partial e_j}{\partial z} = \frac{4}{D_i} q_w^{"} \tag{6}$$

$$\frac{\partial}{\partial z}\left(\left(1-\alpha\right)\rho_l v_l\right) = -\frac{4}{D_i}\frac{q_w^{"}}{h_{lv}} \tag{7}$$

$$\frac{\partial}{\partial z}\left(\alpha \rho_v v_v\right) = \frac{4}{D_i}\frac{q_w^{"}}{h_{lv}} \tag{8}$$

$$\frac{\partial}{\partial z}\left(\left(1-\alpha\right)\rho_l v_l^2\right) + \frac{\partial}{\partial z}\left(\alpha \rho_v v_v^2\right) = -\frac{\partial p}{\partial z} - \frac{4}{D_i}\tau_w \tag{9}$$

The boundary conditions for the problem are the inlet pressure, inlet temperature and mass flux.

Because heat is applied to the fluid, the liquid can start boiling in some part of the pipe and, in some other part, can also evaporate completely and become superheated vapor. For this reason the pipe is splitted into several parts. At the beginning we always have single phase fluid, as long as the fluid has a positive subcooling temperature. After that, if the heat load is large enough, or the mass flux small enough, the fluid will start boiling, leading to a two-phase zone. If the fluid boils completely before it reaches the end of the pipe, then the superheated vapor regions begins leading to a new single phase region.

The boundary conditions for the solution of the two-phase region are the mass flux, pressure and thermodynamic quality at the inlet (taken from the solution at the end of the liquid region). For the vapor single phase region, the boundary conditions are the mass flux, pressure and temperature at the inlet (taken from the solution at the end of the two-phase region).

For the calculation of the pressure drop in the restriction after the heated section, the model proposed by Kakac et al. [29] is used.

The equations needed for the closure of the system are the following. For the frictional pressure drop, the single phase friction factor is given by the Haaland correlation [30].

$$\frac{1}{\sqrt{f_{Dc}}} = -1.8\log\left[\frac{6.9}{\mathrm{Re}} + \left(\frac{\varepsilon/D_i}{3.7}\right)^{1.11}\right] \tag{10}$$

where f_{Dc} is the Darcy friction factor, Re is the Reynolds number and ε/D_i is the relative roughness.

For the two-phase frictional pressure drop, the shear stress is obtained as:

$$\tau_w = f_{l0}\frac{G^2}{2\rho_l}\phi_{l0}^2 \tag{11}$$

where ϕ_{l0}^2 is the Friedel two-phase multiplier [31]:

$$\phi_{l0}^2 = E + \frac{3.24MH}{Fr^{0.045}We^{0.035}} \tag{12}$$

where

$$M = x^{0.78}\left(1-x\right)^{0.224} \tag{13}$$

$$E = \left(1-x\right)^2 + x^2\frac{\rho_l f_{v0}}{\rho_v f_{l0}} \tag{14}$$

$$We = \frac{G^2 D_i}{\rho_h \sigma} \tag{15}$$

$$Fr = \frac{G^2}{gD_i\rho_h^2} \tag{16}$$

$$H = \left(\frac{\rho_l}{\rho_v}\right)^{0.91}\left(\frac{\mu_v}{\mu_l}\right)^{0.19}\left(1-\frac{\mu_v}{\mu_l}\right)^{0.7} \tag{17}$$

$$\rho_h = \frac{\rho_l\rho_v}{\rho_l x + \left(1-x\right)\rho_v} \tag{18}$$

Fr is the Froude number, *We* is the Weber number, σ [N/m] is the surface tension and μ_l [Pa.s] and μ_v [Pa.s] are the dynamic viscosities of the liquid and the vapor phases respectively. The friction factors f_{v0} and f_{l0} are for the total mass flow as all vapor and all liquid, respectively. These friction factors are calculated from:

$$f = f_{DC}/4 \tag{19}$$

The model for the two-phase flow region is a simplification of the two-phase separated flow model presented by Sripattrapan and Wongwises [32].

2. PDO in a single boiling channel

As it has been described in Sec. 1, when the working point of the system is in the negative slope region of the demand curve, and the absolute value of the slope is smaller than the absolute value of the slope of the demand curve, PDOs are triggered. A typical example is shown in Fig. 2.

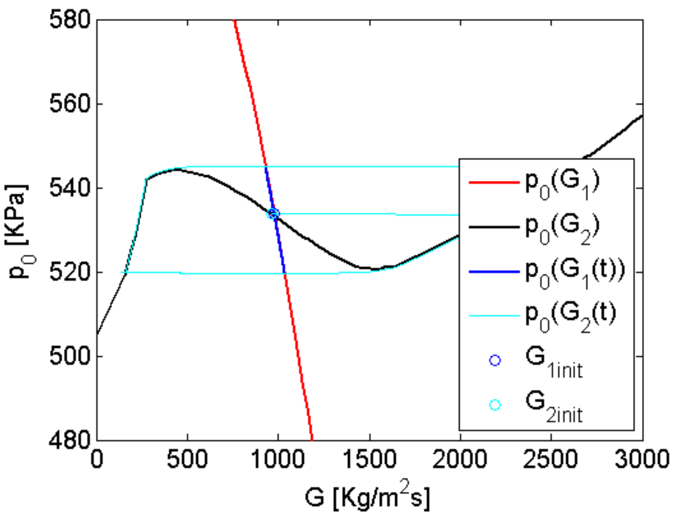
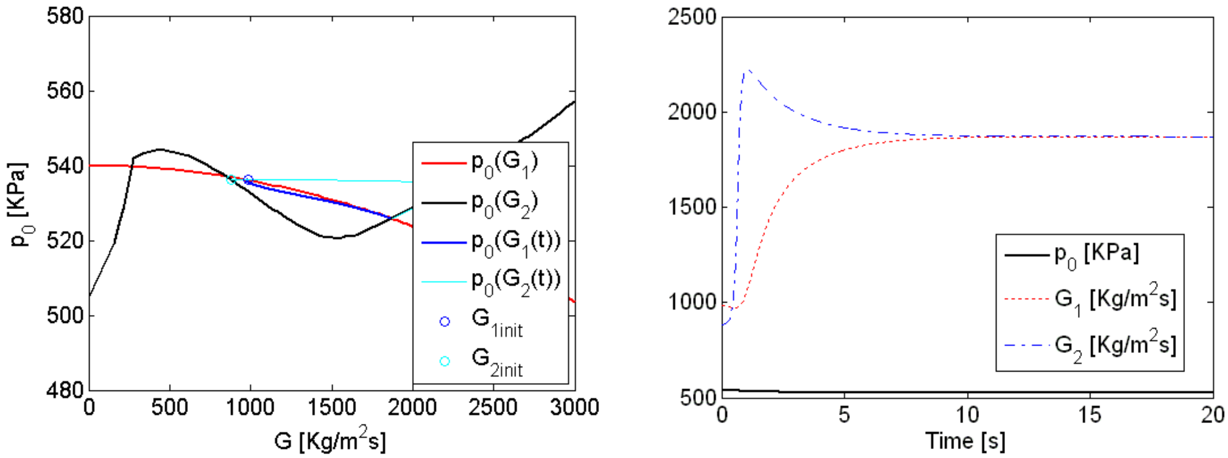


Figure 2. PDO in a single boiling channel.

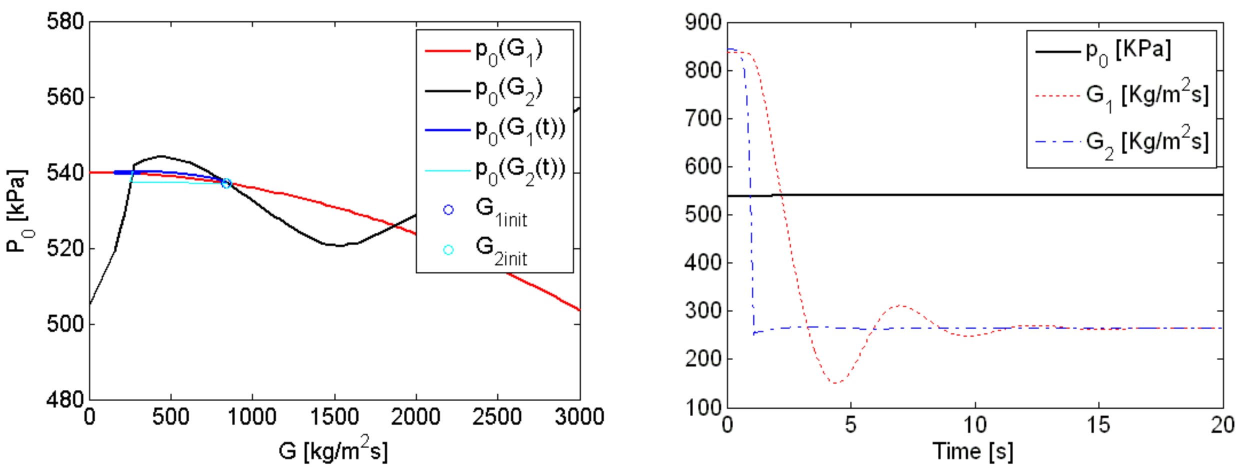
2.1 Flow excursions with surge tank

Based on Fig. 3(a), if the working point is still in the negative slope region of the demand curve, but the absolute value of the slope is now larger than the absolute value of the slope of the supply curve, then the situation is different. If we only consider the equation for the dynamics of the pressure in the surge tank (Eq. 1), the operation point should be a stable equilibrium point. It can be seen that a slight decrease in the pressure will lead to a larger flow rate before the surge tank than the one after the surge tank (Fig. 3 (a)) leading to an increase in the surge tank pressure. On the other hand, if the perturbation sets the pressure above the equilibrium value, the mass flow rate before the surge tank will be smaller than the flow rate after the tank (Fig. 4 (a)), leading to a decrease in the surge tank pressure. However, if for example the pressure in the surge tank decreases a little, when the pressure starts to rise, the value of p_0 is above the steady-state value for both flow rates (Fig. 3 (a)). If we take a look at the equations which consider the dynamics and the inertia of the mass flow rates before and after the surge tank (Eqs. 2 and 3), it is possible to see that this will make G_1 decrease while G_2 will increase. Furthermore, the increase in the flow rate after the surge tank will be larger because the pressure difference is much larger. This will end up with a flow excursion to the subcooled liquid region, followed by a slow change in the surge tank pressure and in both flow rates along their equilibrium curves to the subcooled region equilibrium point (Fig. 3 (b)). The opposite situation takes place if the pressure increases slightly, leading to a flow excursion to the superheated vapor region (Fig. 4 (b)).



(a) (b)

Figure 3. PDO flow excursion type to the subcooled liquid region: (a) pressure drop vs. mass flux plot, (b) time evolution.



(a) (b)

Figure 4. PDO flow excursion type to the superheated vapor region: (a) pressure drop vs. mass flux plot, (b) time evolution.

3. Flow excursions with surge tank in two parallel boiling channels

For two parallel channels with inlet and outlet valves in each channel, the set of Eqs. (1)-(3) becomes:

$$\frac{dp_0}{dt} = \frac{p_0^2}{nRT_{sat}\rho_l}\left(A_1 G_1 - A_2\left(G_{2a} + G_{2b}\right)\right) \tag{20}$$

$$\frac{dG_1}{dt}=\frac{1}{L_1}\left[p_1-p_0-\Delta p_{valve}\left(G_1\right)\right] \tag{21}$$

$$\frac{dG_{2a}}{dt}=\frac{1}{L_2}\left[p_0-p_2-\Delta p_{HSa}\left(G_{2a}\right)\right] \tag{22}$$

$$\frac{dG_{2b}}{dt}=\frac{1}{L_2}\left[p_0-p_2-\Delta p_{HSb}\left(G_{2b}\right)\right] \tag{23}$$

where the subscripts *a* and *b* go for each channel.

If two boiling channels are arranged in a parallel configuration, with the constrain of having the same inlet and outlet pressure, the possible equilibrium solutions are more than in the case with one boiling channel. The pressure drop versus mass flux is not a function anymore. The case for two identical parallel channels equally heated is shown in Fig. 5. One interesting situation for this case is when the external curve intercepts the single channel curve in the subcooled liquid region. For the case shown in Fig. 5, it is possible to see that if we consider the behavior of a single channel, there is only one possible solution, which is also stable. However, when we consider all the possible solutions for the parallel arrangement, we can see that there are two more possible solutions (actually there are four more, but two of them are overlapped). At first sight this case looks like the one described in the previous section. For this case, the solution in the middle is composed by one channel working in the negative slope two-phase flow region and the other working in the positive slope subcooled liquid region. This situation is unstable, and after a perturbation in the surge tank pressure, the unstable channel will undergo a sudden flow excursion, followed by a slow displacement close to the steady-state supply and the two demand curves. Depending on the sign of the perturbation the system will move to one (Fig. 6) or the other stable point (Fig. 7), in the same way as for the single heated channel. The stable solution with smaller mass flux is with one channel working in the superheated vapour region and the other in the subcooled liquid, both with a positive slope.

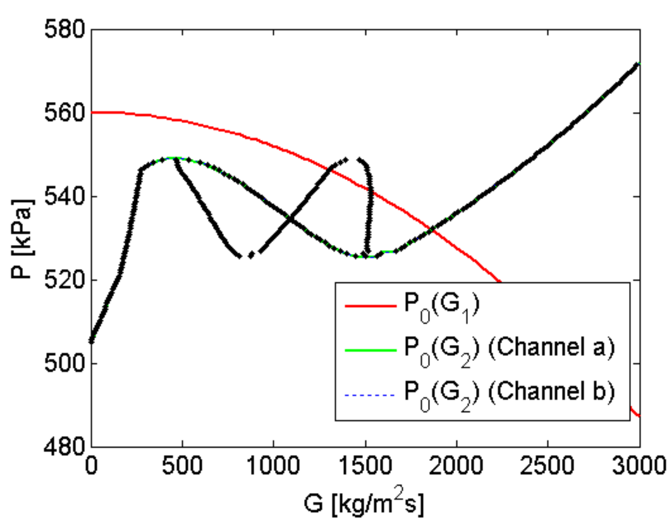
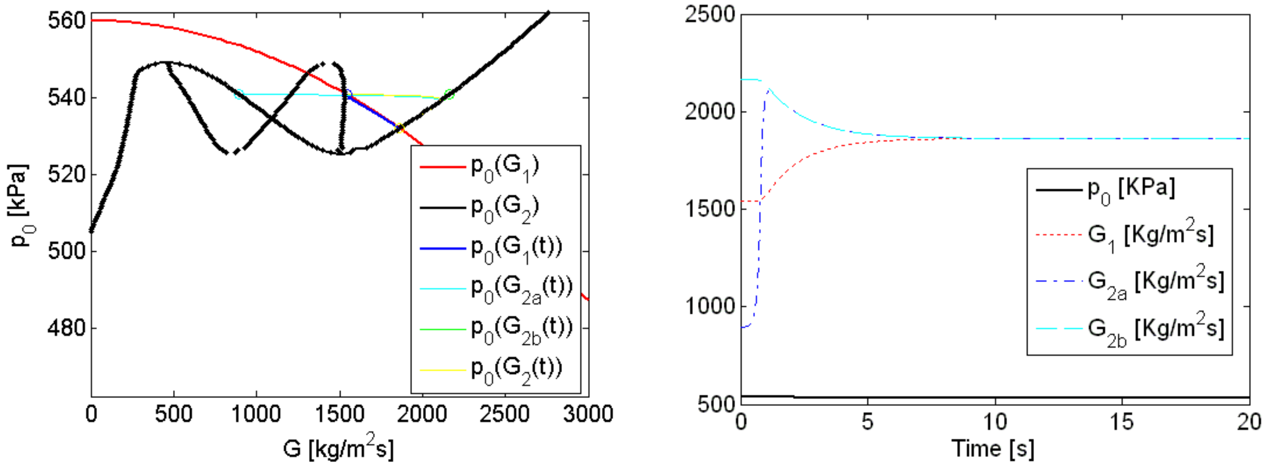
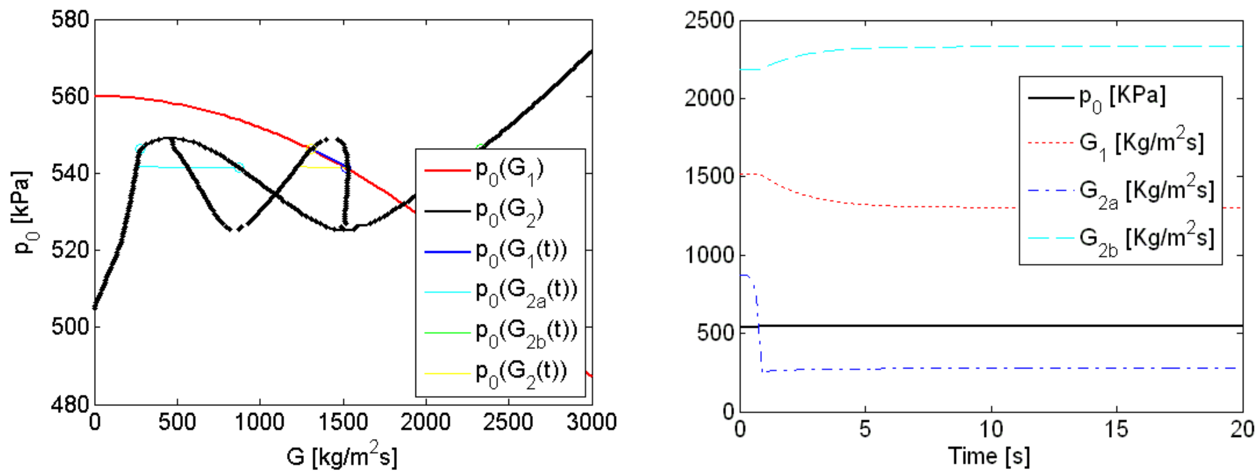


Figure 5. Possible global unstable working point for two identical parallel channels equally heated.



(a) (b)

Figure 6. PDO flow excursion type of one unstable channel to the subcooled liquid region for two identical parallel channels equally heated: (a) pressure drop vs. mass flux plot, (b) time evolution.



(a) (b)

Figure 7. PDO flow excursion type of one unstable channel to the superheated vapor region for two identical parallel channels equally heated: (a) pressure drop vs. mass flux plot, (b) time evolution.

4. Multiple parallel boiling channels

The behavior shown in the last section can be extended to more complex cases. If we consider, for instance, three parallel boiling channels coupled by the restriction of same pressure in the inlet and outlet, with different heat loads, the possible solutions will be like the ones shown in Fig. 8. Global behaviour similar to the one shown in Fig. 8 can be obtained with same heat load per channel but different inlet subcooling or absolute inlet pressure in each channel. This means non-uniform distribution along the plenum. The effect of parameters such as inlet subcooling and inlet pressure in the static behavior of a boiling channel is more extensively described in [33].

The solutions lying in the so-called “stable branches” (Fig. 8) are all the possible solutions with the three channels working in one of the positive slope regions (superheated vapor or subcooled liquid). Therefore, all the other solutions have at least one channel working in the negative slope region, and thus, are unstable equilibrium solutions. Furthermore, we can see that all the solutions that include at least one unstable solution will experiment a flow excursion until they settle in one of these stable solutions. It should be noted that all the stable solutions which are not lying over the three of the single channel solutions, are maldistributed solutions. These solutions which are stable but highly mal distributed cannot be seen in a one channel stability approach.

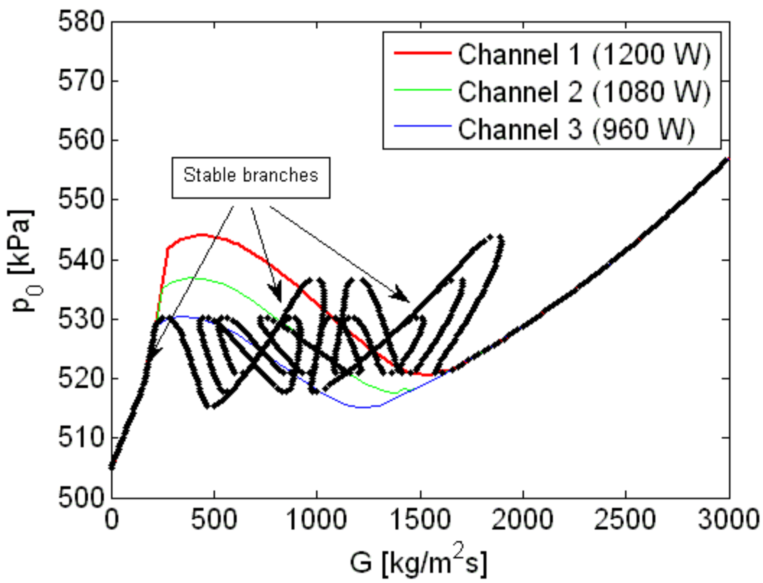


Figure 8. Possible solutions for three identical parallel channels with different heating loads.

5. Conclusions

In this work, a parallel boiling channel system with fixed constant uniform heat flux applied to the channels and a compressible volume upstream the channels arrange has been investigated numerically. The model applied is the single PDO lumped parameters model, solving for the time and the space averaged values for the flow rates before and after the surge tank. The model has been extended to multiple channels, obtaining flow maldistributed stable solutions. The overall static solutions plot has been found useful for the understanding of the possible solutions and their stability. In particular, the single channel approach for parallel boiling channels is not enough to visualize the solutions and understand the behaviour of the heat exchanger.

6. References

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