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# A VERIFICATION PROBLEM FOR THERMAL-HYDRAULICS SYSTEMS CODES DEALING WITH TWIN-PARALLEL-BOILING CHANNELS

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**Abstract**. In the analysis of the nuclear safety of complex nuclear systems, almost one-dimensional system thermal-hydraulics codes are to be used perhaps for a couple of decades from now. Computational Fluid Dynamics (CFD) tools are accepted at present to be a support of such analyses and they are used coupled to systems codes or as separate analysis tools for isolated components with boundary conditions obtained from systems codes. The restricted acceptance of "pure" CFD codes is due to many reasons but two of them are relevant, namely a) the apparent lack of CFD grade experimental data and b) the need for a complete verification and validation (V&V) and the uncertainty quantification for the codes currently available. There is plenty of experimental data related to integral test facilities (ITFs) that constitute macroscopic systems behavior information and a consolidated data base for such purposes. Despite of this, additional verification cases may be added to the above mentioned consolidated data. The results presented in this paper, show how a validation case lead to find a not still reported (in the Authors knowledge) verification case. The problem is related to twin-parallel-boiling channels, connected through common plena. This is, of course, a problem that deserved many tens of papers in the last four decades. Flow splitting without reversal was computationally found and to explain this behavior a theoretical model limited in scope was developed that was a posteriori verified using a particular systems code (RELAP5/MOD3.3) commonly applied to perform safety analyses of nuclear power plants. The rationale followed, the analysis performed and the confirmatory computational results found are summarized in this paper.

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# 1. INTRODUCTION

This paper shows the path followed to discern the cause of some unexpected behavior in the prediction of the flow distribution in parallel boiling channels with common inlet and outlet plena. This configuration is common in the core of boiling water reactors in pressurized water reactors of nuclear power plants and in other installations that typically consist of a set of parallel, vertical tubes with the above mentioned physical configuration and a common downcomer. As it may be expected, there is plenty of consolidated literature on the subject since four decades ago but, despite this, the present analysis will be also of restricted scope, showing the way followed to perform the verification and validation (V&V) in the particular field of natural circulation (NC).

The results of the analysis to be presented have been found following a somewhat peculiar way, namely: a) a validation study considering an integral test facility (ITF) was under way, b) the usual one pipe nodalization for a steam generator was refined to consider two tubes because of the real, more realistic geometry of the ITF, c) for the sake of symmetry verification equal (average) heights for the pipes were imposed, d) an unexpected, asymmetrical, steady flow splitting was found using a systems thermal-hydraulics (TH) code named RELAP5/MOD 3.3, e) sensitivity studies were performed that avoided this splitting but lead the results outside the uncertainty band of the experiment, then, f) an approximate theoretical analysis was performed and the conditions for unsymmetrical flow splitting have been predicted and g) finally, the code prediction for this TH problem was found to be in concordance with the theoretical results. The previous sequence showed that a validation study could lead to a verification problem that should be adequately predicted by a TH systems code.

Results obtained on the flow along two identical parallel, vertically oriented channels with common input and output plena will be reported in this paper. Results have been obtained using a systems code (RELAP5/MOD3.3) and an approximate theoretical analysis performed to explain non symmetrical flow splitting. The theoretical results implied considering constant input flow rate to the plena but this condition is not a limitation because the simulated stepwise reduction scenario implies quasi-constant flow rate during the step.

Criteria for the application of these results in practical V&V studies have been drawn also for the original, more general, SG problem that will be reported elsewhere.

# 2. ANALYSIS

## 2.1. A summary of previous validation analyses, including appearance of SG unsymmetrical splitting

Experiment SEMISCALE NC02-A (S-NC02-A) in its single loop geometry has been documented three decades ago, as a part of a series of reports on natural circulation experiments in this ITF and a final report may be found in e.g. Loomis and Soda (1982). This experiment consists of a controlled, natural circulation, stepwise mass inventory reduction transient. The proposed assessment nodalization, as reported in the manuals of the code used (RELAP5/MOD3.3gl and MOD3.3iy Patch4), as provided by the United States Nuclear Regulatory Commission (1995), was considered. This one SG tube representation corresponds to the intact loop of the installation. Figure 1 shows the natural circulation flow map (NCFM) as defined by D'Auria and Frogheri (2002) resulting from the simulations of experiment S-NC02-A using the above mentioned nodalization for the particular case of 60 kW power. RM% stands for the percentage of mass remaining in the system and diminishes in a stepwise manner due to the experiment design. When a very small break loss of coolant accident (SBLOCA) is considered, RM% diminishes in continuous way. This figure deserves some consideration because a special sensitivity analysis was considered. This sensitivity analysis

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has been detailed by Lazarte and Ferreri (2012), giving consideration to the modifications to the code that allowed multiplying, by a factor chosen randomly, five heat transfer correlations and the wall friction factor. It seemed natural to the authors to seek the effect of random variations of multipliers (ranging from 0.5 to 1.5 with a uniform distribution) affecting several closure correlations because of the balance between buoyancy and friction in quasi-steady states. Five heat transfer correlations were chosen based on a reference run that detailed the ones used in the thermo-siphon oscillations regime during the transient. The bulk friction factor correlation was also magnified by a factor. The same was considered for the gravity acceleration that could also be modified by a factor (this may seem strange but its interest will be shown later in this paper). Setting all multipliers equal to unity implies that results must be the same than the ones obtained from the original executable RELAP5. This was appropriately verified comparing the outputs from runs associated to the S-NC02-A experiment.

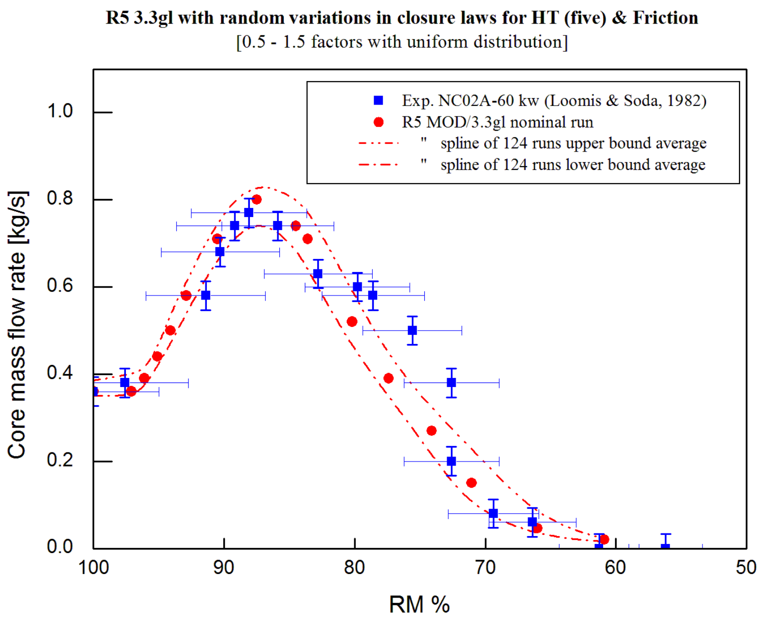


Figure 1 NCFM for S-NC02-A including bands for parameters variation and experimental data.

The main conclusion that may be drawn from Figure 1 is that the stepwise scenario is satisfactorily represented, with predicted behavior included in the experimental uncertainty band, even considering the aforementioned variation of parameters. This lack of sensitivity led the authors to pursue in a further, more detailed geometrical representation of the SEMISCALE-ITF for this experiment.

The broken SG is constructed with two tubes of different height. The nodalization as proposed in the RELAP5 assessment manual represents the intact SG loop, constructed with six tubes of three different heights, whose average is the height in the nodalization. In passing, it must be noted that this lumping from the real geometry to the one tube configuration in said manual, implies that the flow and heat transfer areas considered correspond to the intact loop, *i.e.* six SG tubes. The obvious way to proceed would be representing the tubes with their specified geometries. However, instead of firstly following this way and for the sake of symmetry verification, it was decided to represent the SG by two equal tubes of average height, *i.e.* splitting the original SG (the one in the original nodalization) tube in two identical tubes, as specified in the S-NC02-A experiment with half flow area. Heat slabs have been appropriately

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redefined. The effects of distributed friction should not influence too much the results when compared with concentrated pressure losses.

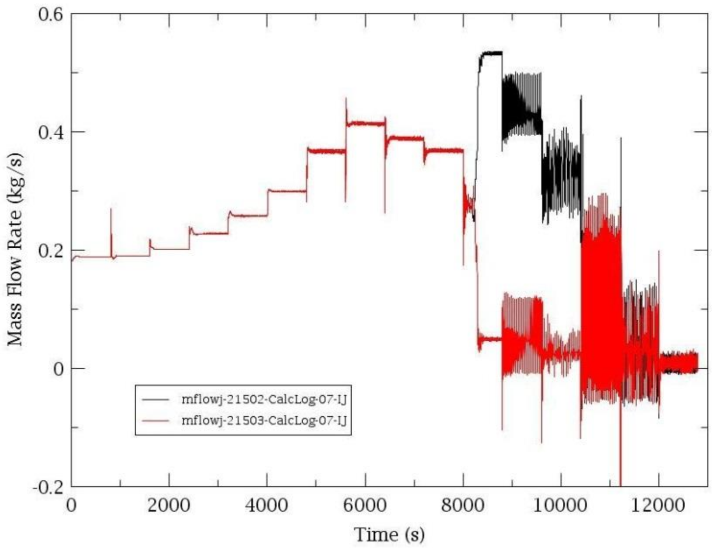


Figure 2 Mass flow rates in the tubes of the SG for stepwise reduction of mass inventory. Concentrated pressure losses as in the assessment example.

Figure 2 shows the flow rate in the tubes of the SG as a function of time for a stepwise mass inventory reduction. For the particular values of the relevant concentrated pressure losses, coincident with the one SG tube nodalization, the oscillations are in phase. The nomenclature in what follows for these losses is: Ki and Ke represent the concentrated pressure loss factors at the inlet and outlet of the SG tubes while KI and KE represent the corresponding values at the SG plena. Code (RELAP5/MOD3.3) calculated abrupt area changes loss coefficients are denoted by “a=1”. In a consistent way with the analysis of Bang et al. (1998), it was decided to impose concentrated pressure losses as given by the “abrupt area change” in the SG tubes.

It is evident from Figure 2 that the flow splits non-symmetrically in the tubes. Its sum is constant and equal to the loop flow rate. It must be also considered that in one SG tube simulations, these oscillations are usually considered as thermo-siphon oscillations and this interpretation is kept here too.

Additionally, it is usually accepted that a very SBLOCA (with an approximate linearly decreasing mass inventory) can be representative of a stepwise varying mass inventory. This has been established three decades ago, see e.g. Loomis and Soda (1982) and Duffey and Sursock (1987) and also shown as a verification example by Lazarte and Ferreri (2012) in relation to the experiment under analysis. Then, the simulations to be considered from hereon will also show results obtained for a 1 mm diameter break size, as in the stepwise experiment considered. The geometrical details of the break have also been checked with the ones reported by Bang et al. (1998).

All concentrated loss coefficients in the SG were removed, except those calculated by the code for computing the “abrupt area change”. Figure 3 shows the mass flow rate for both channels as function of inventory in the primary system. Once again, there is a flow splitting and out-of-phase oscillations, which remain for inventories lower than 75 %. For a mass inventory about 79 % the flow is still oscillating but the splitting disappears.

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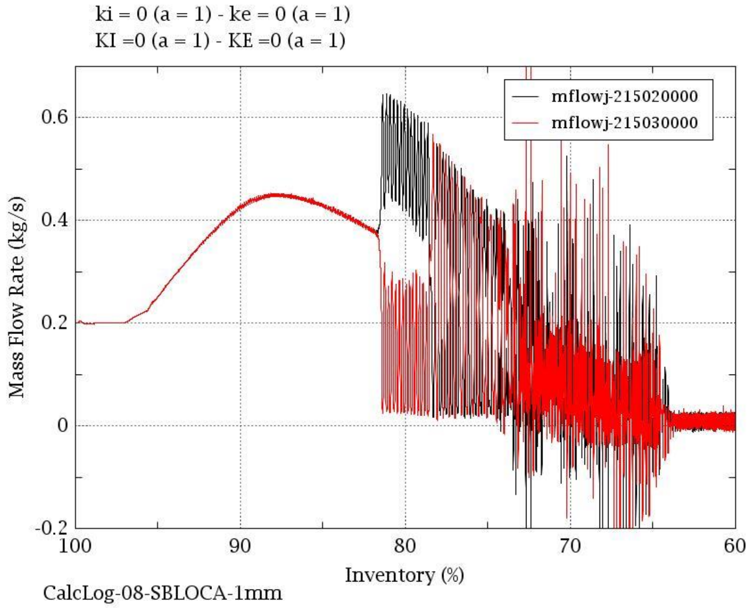


Figure 3 Mass flow rate in the SG tubes, showing a period of "flow split" for a SBLOCA.

It is important to record the mass inventory at which the flow splits because this value will be considered as boundary condition for an analytical treatment of the problem. In the case shown the flow splits when the inventory is about 83%. At this condition, the SG inlet is a mixture of two phase flow with a quality close to 0.08, and the fluid comes out subcooled. The pressure oscillates between 6.2 and 7.0 MPa, approximately. The following simplified analysis will be based on these conditions. Out-of-phase flow oscillations after splitting may be noted in Figure 3b.

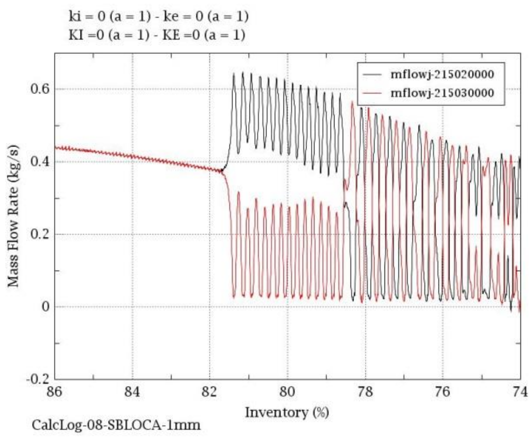


Figure 3b Mass flow rate in the SG tubes, showing out-phase oscillations. Zoom from Figure 3.

The observed behavior can be avoided, for instance, increasing the inlet concentrated loss coefficients. This reduces the relevance of gravity term in pressure drop, as it will be shown in the following section. However, notwithstanding this rather artificial way of performing, it was verified, but the observed results increased the lack of coincidence with the experiments

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outside the uncertainty band of the experiments and the most important question, i.e. can this flow splitting be explained by an appropriate theory?, remains unanswered.

### 2.2. An approximate analysis of unsymmetrical flow splitting in twin, parallel boiling channels with common input and output plena.

Given the flow peculiarities for the considered geometry, which is depicted in Figure 4, an approximate model was set up. In order to proceed, oscillations in two parallel boiling pipes were firstly considered. This subject has received plenty of attention since more than three decades ago, given the behavior of said systems. This interest has persisted up to recently and an interesting example may be found, e.g. in the analysis by Colombo et al. (2012) Since the starting point in this work were the results obtained by Ambrosini and Ferreri (2006), the present authors decided to extend said results to two parallel pipes. The results confirmed the ones shown by Colombo et al. (2012), showing in-phase and counter-phase density waves oscillations as a function of the values of the concentrated pressure losses.

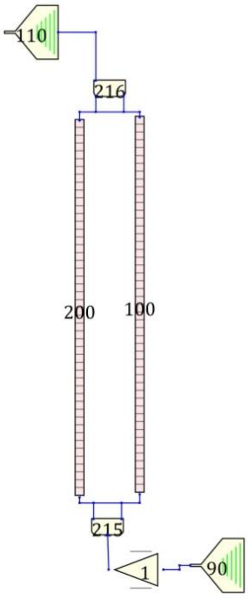


Figure 4 Sketch of the nodalization used in RELAP5 for simulating two boiling channels.

These simulations, through suitable modifications of governing parameters, did not show the flow splitting behavior, so the simplified analysis to be considered and the verification using RELAP5 that follows, may give a way to the understanding of this situation.

Let us first consider a single boiling pipe and homogeneous, equilibrium fluid model (HEM). As it is well-known, the pressure drop along a boiling channel can be written as:

$$\Delta P = g\, Z_B\, \rho_f + g\,(L - Z_B)\,\rho_m + \frac{k_i\, \dot{m}^2}{2A^2\rho_f} + \frac{f\left(\frac{Z_B}{\rho_f} + \frac{L - Z_B}{\rho_m}\right)\dot{m}^2}{2A^2 D} + \frac{ke\, \dot{m}^2 \phi_{2\phi}^2}{2A^2\rho_f} \qquad (1)$$

where $Z_B$ is the non-boiling length, $\dot{m}$, is the mass flow rate, $A$ is the channel area, $g$ the gravity acceleration, L the channel length, $f$ the friction factor (assumed constant in this analysis), $\rho_f$ is the liquid density at saturation and $\rho_m$ a mean density in the two phase region calculated at half outlet quality. Parameters $k_i$ and $k_e$ are the concentrated friction values at the inlet and outlet of

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the individual channels, respectively. $\phi^2_{2\phi}$ is the two phase friction factor defined by $(v_f + v_{fg} x)^{-1}$ that acts as mixture density, and it is equal to the unity when the fluid is saturated with $x = 0$.

Some useful (and commonly used) definitions are:

$$N_p = \frac{Q\, v_{fg}}{h_{fg} v_f\, \dot{m}}, \quad N_S = \frac{\Delta h_{in}\, v_{fg}}{h_{fg} v_f}, \quad N_{fr} = \frac{fL}{2D} \tag{2}$$

where $N_p$, $N_S$ and $N_{fr}$ are the phase change, subcooling and friction dimensionless numbers; $v_{fg}$, is the difference between the gas and liquid specific volumes and $h_f$ and $h_{lg}$ are the saturation and latent heat, respectively.

Suppose now two parallel (twin channels) as shown in Figure 4. The pressure drop through them should be equal; i.e. $\Delta P_1 = \Delta P_2$. Following the idea used by Popov et al. (2000), let us try to find if there are solutions that allow the twin (identical) channels to have different mass flow rates and equal pressure drop (for a given inlet mass flow rate) during boiling. This is a static analysis.

In most cases, the pressure drop along of the channel is assigned and kept constant as a boundary condition. However, in this case, we will fix the inlet mass flow rate and outlet pressure. From mass conservation: $\dot{m}_1 + \dot{m}_2 = \dot{m}_T$ = constant.

Defining: $N_{pM} = \frac{Q\, v_{fg}}{h_{fg} v_f\, \dot{m}_T}$ and $N_{pi} = \frac{Q\, v_{fg}}{h_{fg} v_f\, \dot{m}_i}$ and setting:

$$\phi = \frac{\dot{m}_1}{\dot{m}_T} \qquad 1 - \phi = \frac{\dot{m}_2}{\dot{m}_T}$$

then

$$N_{p1} = \frac{N_{pM}}{\phi}, \quad N_{p2} = \frac{N_{pM}}{1-\phi}$$

The boiling channel length $Z_{B1}$ and $Z_{B2}$ are defined as the position at which the fluid becomes saturated, that is

$$Z_{B1} = \frac{N_s\, L}{N_{p1}} = \frac{L\, N_s\, \phi}{N_{pM}} \qquad Z_{B2} = \frac{N_s\, L}{N_{p2}} = \frac{L\, N_s (1-\phi)}{N_{pM}} \tag{3}$$

The different $\Delta P$ terms for channel 1 will be evaluated in what follows. Recall that $\Delta P$ for channel 2 is the same as for channel 1 but exchanging $\phi$ by $1-\phi$. The friction term in (1), using the definition of the dimensionless numbers, reads

$$\Delta P_{1f} = f \frac{\dot{m}_T{}^2 \phi^2}{2A^2 D\, \rho_f} L \left( N_{sub} \frac{\phi}{N_{pM}} + \left(1 - \frac{N_{sub}\phi}{N_{pM}}\right)\left(1 - N_{sub} + \frac{N_{pM}}{\phi}\right)\right) \tag{4}$$

Following a similar procedure, the pressure drop for channel 1 due to form losses is

$$\Delta P_{1fL} = \frac{k_i\, \dot{m}_T{}^2 \phi^2}{2A^2 \rho_f} + \frac{k_e \dot{m}_T{}^2 \phi^2 (1 - N_{sub} + \frac{N_{pM}}{\phi})}{2A^2 \rho_f} \tag{5}$$

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where $\phi_{2\phi}^2$ was replaced by $1 - N_s + N_{pM}\phi$.

The gravity contribution, although it is disregarded in this work, results,

$$\Delta P_{1g} = g\ Z_{B1}\ \rho_f + g\,(L - Z_{B1})\,\rho_{m1} = g\,N_{sub}\,\rho_f \frac{\phi}{N_{pM}} + \frac{g\,L\left(1 - N_{sub}\frac{\phi}{N_{pM}}\right)\rho_f}{\left(1 - N_{sub} + \frac{N_{pM}}{\phi}\right)} \tag{6}$$

Once again, the value $\rho_{m1}$ may be calculated at the half exit quality. Adding (5) to (7), the total pressure drop along channel 1 become

$$\Delta P_1 = \frac{k_i\,\dot{m}_T{}^2\phi^2}{2A^2\rho_f} + \frac{ke\,\dot{m}_T{}^2\phi^2\left(1 - N_{sub} + \frac{N_{pM}}{\phi}\right)}{2A^2\rho_f} + f\frac{\dot{m}_T{}^2\phi^2}{2A^2D\rho_f}L\left(N_{sub}\frac{\phi}{N_{pM}} + \left(1 - N_{sub}\frac{\phi}{N_{pM}}\right)\left(1 - N_{sub} + \frac{N_{pM}}{\phi}\right)\right) \tag{7}$$

Pressure loss $\Delta P_2$ has the same expression as (6), (7) and (8) changing $\phi$ by $1-\phi$.

Since $\Delta P_1 = \Delta P_2$ then

$$G(1-\phi) = \Delta P_1 \frac{A^2\rho_f}{N_{fr}\ \dot{m}_T{}^2} = \Delta P_2 \frac{A^2\rho_f}{N_{fr}\ \dot{m}_T{}^2} = G(\phi) \tag{8}$$

$$G(\phi) = k_{im}\phi^2 + k_{em}\phi^2\left(1 - N_S + \frac{N_{pM}}{\phi}\right) + 2\phi^2\left(\frac{N_S\,\phi}{N_{pM}} + \left(1 - N_{sub}\frac{\phi}{N_{pM}}\right)\left(1 - N_{sub} + \frac{N_{pM}}{\phi}\right)\right) \tag{9}$$

For simplicity $k_{em}$ and $k_{im}$ denote $k_e$ and $k_i$ divided by $N_{fr}$. The main objective is to find the roots of the equation $G(\phi) - G(1-\phi) = 0$. The equation may have at most three possible solutions. One obvious solution is $\phi$ = ½ which means equal flow rate for both tubes. The other two solutions may be obtained solving the quadratic polynomial:

$$\phi \to \frac{1}{2} \mp \frac{N_S\sqrt{\left(-2N_{pM}\left(2 + k_{em} + k_{im} + (2 + k_{em})N_{pM}\right) + 2(4 + k_{em})N_{pM}N_S - 3N_S{}^2\right)}}{2N_S{}^2} \tag{10}$$

Real solutions exist if the discriminant is greater than zero, i.e.:

$$-2N_{pM}\left(2 + k_{em} + k_{im} + (2 + k_{em})N_{pM}\right) + 2(4 + k_{em})N_{pM}N_S - 3N_S{}^2 > 0 \tag{11}$$

In order to check the results, following the values for the different parameters are defined by Ambrosini and Ferreri (2006), we set: $k_i$ = 23; $k_e$ = 5; $h_{fg}$ = 1.5039x$10^6$ J/kg; $h_f$ = 1.267 x$10^6$ J/kg; $f$=0.01; L = 3.66 m; $D_0$= 1.24 cm. Hence $N_{fr}$ = 1.476; $k_{em}$ = 3.39 and $k_{im}$ = 15.58. For these values, the solutions of the above inequality are shown in Figure 5. Inside the colored zone are the possible real solutions for $\phi$ and the boundary corresponds to zero discriminant.

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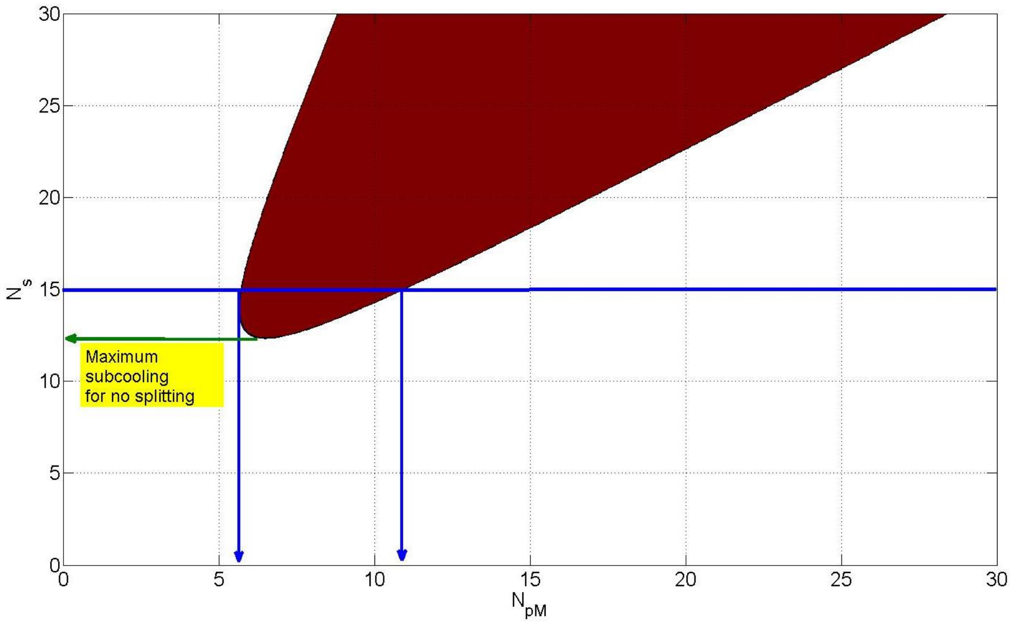


Figure 5 Contour plot of inequality (12).

For instance, let us select $N_S$ close to 15 (fixing liquid temperature), two values $N_{pM}$ are obtained, namely: 5.7 and 11. These values correspond to the intersections of the horizontal line and the boundary. So, for $N_{pM}$ ranged between 5.7 and 11, the system will have more than one solution for each channel. Besides, fixing the inlet mass flow rate to 0.2 kg/s and the total power to 150 kW (delivered to the fluid in 2500 sec), $N_{pM}$ is close to 10. Figure 6 shows the results using RELAP5, with the HEM option.

As it can be seen in said figures there is no flow split (other than symmetrical). No agreement with the model exists because RELAP5 considers gravity. We recalculated using a modified RELAP5 version with variable gravity acceleration to keep simulations independent from changes in flow regimes that may arise using horizontal pipes. For this case we selected $g=10^{-9}$, *i.e.* disregarding the effects of the gravity term. Now, the simulations using RELAP5 may be observed in Figure 7.

The flow splits in a symmetric way. Please note that the splitting appears close to 2000 s. The power when splitting is about 120 kW, giving $N_{pM}$ = 8 (close to one of the boundary). Recall that the $N_{fr}$ number was selected arbitrarily and should be adjusted to a mean value.

Previously, it was considered two fluids using HEM model. When simulating applying the two-fluid model in RELAP5, the results are shown in Figure 8.

With the two-fluid model (now considering gravity) flow split was obtained at about 1500 sec (here the total power was delivered to fluid in 1500 sec instead of 2500 sec as in the HEM model). The most important observation is that the mass flow in both channels start oscillating about 1400 sec ($N_{pM}$ = 8) and splits close to $N_{pM}$ = 10. These values are similar to the theoretical ones.

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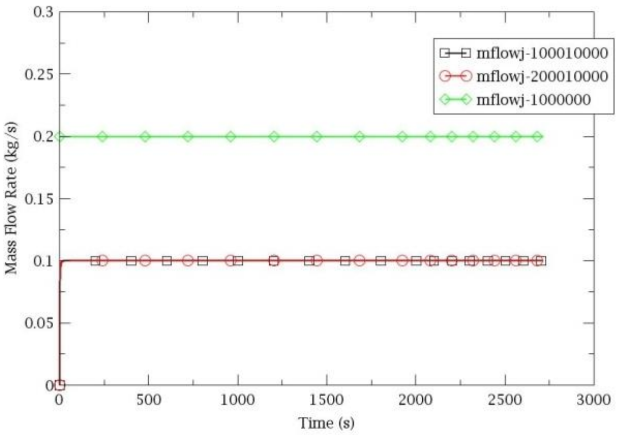


Figure 6 Mass flow rate through channels (named 100 and 200) using HEM model (gravity contribution is considered) using RELAP5. There is no flow splitting.

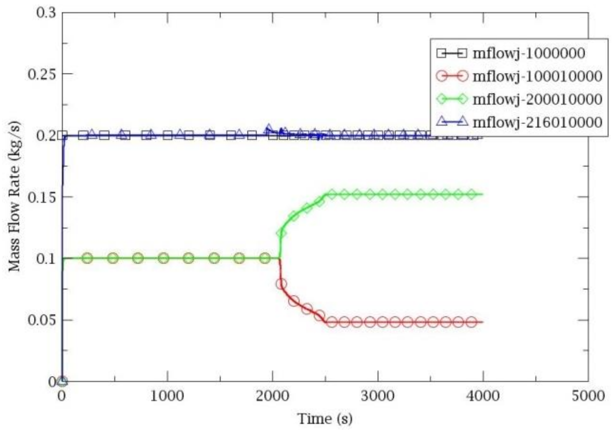


Figure 7 Mass flow rate through channels (named 100 and 200) using RELAP5. There is a stable flow splitting close to 2000 sec. (Vanishing gravity contribution).

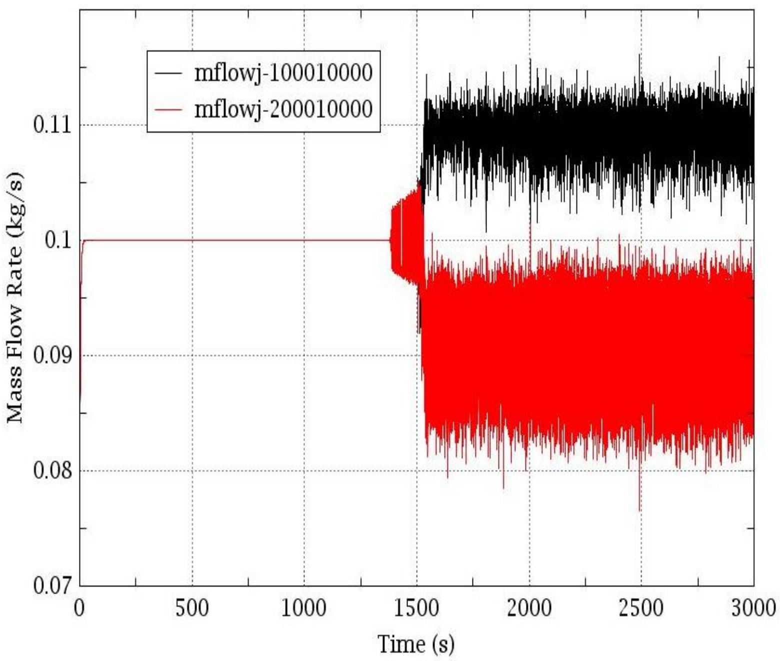


Figure 8 Mass flow rate through channels (named 100 and 200) using two-fluid model in RELAP5.
There is a stable flow splitting close to 1500 sec.

Based on figure 5, there exists a maximum subcooling number, about 12, for getting splitting. Recalling that when subcooling number increases it means a decrease of fluid temperature or enthalpy this maximum $N_s$ corresponds to the maximum temperature at which flow splitting may be expected.

The maximum subcooling number may be calculated from (11), obtaining:

$$N_s^{max} = \frac{8 + 4k_{im} + \sqrt{6}\sqrt{(2 + k_{em})(2 + k_{em} + k_{im})^2 + k_{em}(6 + k_{em} + k_{im})}}{4 + k_{em}(2 + k_{em})} = 12.3$$

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The mass flow rate for the two fluid model with inlet temperature set as 355 K (Ns ~ 12), keeping all other conditions the same as in figure 8, is depicted in figure 9. It may be seen that no flow splitting or other stable states come up.

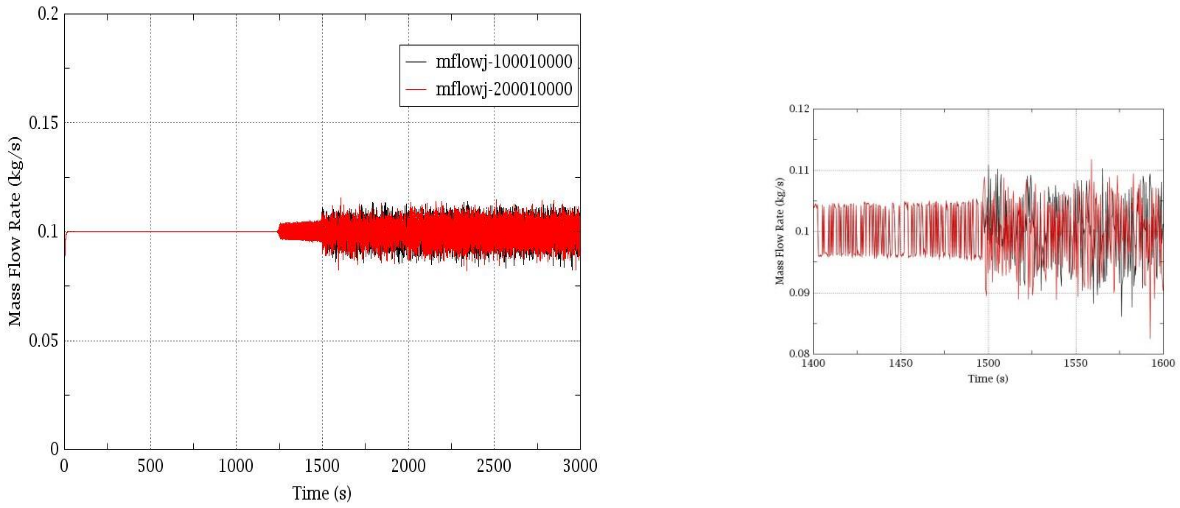


Figure 9 Mass flow rate through channels (named 100 and 200) using two-fluid model in RELAP5 There is no flow splitting close to 1500 s for Ns=12.

## 3. DISCUSSION

Static instabilities exist depending on the intersection between the system characteristic curve and the driven force curve. This means that the system becomes unstable if

$$\partial \Delta P / \partial \dot{m} < 0 \qquad (12)$$

It can be proven that depending on the system parameters (pressure, temperature, inlet and outlet concentrated loss coefficients) the acceleration and gravity terms may be neglected in the pressure drop equation. So, the maximum contributions to be considered are the distributed friction and the concentrated irreversible pressure drop terms. This hypothesis may be appropriate for vertically heated channels as it was shown in the analysis above.

In the analysis for twin heated channels, the existence of multiple steady states for a fixed total mass flow rate was shown. It should be noted that flow splitting follows the instability threshold given by the mass flow rate that vanishes expression (12). It is well-known that the threshold is close to the onset of boiling, that fall by the local minimum of the characteristic pressure drop curve against mass flow rate.

As it is shown in figures 7 and 8, the instability develops and then the flow splitting takes place when appropriate conditions are met. The instability starts at a lower $N_p$ (for each channel) than splitting. No flow splitting has been seen previous to the instability development at least for cases studied here. Hence, the static or zero order instability is a necessary condition for triggering flow splitting but does not seems to be sufficient.

When dealing with two U tubes, as in steam generators or boilers, gravity increases its relevance in pressure drop calculations as well as in the heat transfer to secondary side. Despite of this, the flow splitting may come from multiple steady states in the U-tubes as in the parallel boiling channels. This may justify why flow splitting in the Semiscale NC-02A experiment simulation was found. At present a simplified map is being developed, aimed at determining the regions that U-tubes have other multiple steady states.

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## 4. CONCLUSIONS

Results obtained on the flow along two identical parallel, vertically oriented channels with common input and output plena have been reported in this paper. Computational results have been obtained using a systems code (RELAP5/MOD3.3) and an approximate theoretical analysis performed to explain non symmetrical flow splitting. Results have been obtained imposing constant input flow rate but this condition is not a limitation because given the simulated stepwise reduction scenario implies quasi-constant flow rate during the step. The analytical model has been applied to set a couple of cases with parameters similar to the experiment and the calculations performed with the systems code closely verified the splitting conditions.

Criteria for the application of these results in practical V&V studies have also been obtained for the original, more general, SG problem that will be reported elsewhere.

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