Use of RELAP50MOD3.3 Code to Get Fluid Dynamic Stability Maps

Use of RELAP5/MOD3.3 Code to Get Fluid Dynamic Stability Maps

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INTRODUCTION

The study of fluid dynamic instabilities is important to avoid their occurrence in components like steam generators in nuclear and conventional power plants. Fluid dynamic instabilities usually arise in the heated channels characterized by boiling conditions either with a vertical layout or in case of inclined or helically coiled pipes. In case of parallel channels, like in the steam generators, oscillations determine different flow rate in different channels, even if the total flow rate is constant. Instabilities must be avoided because they may lead to mechanical vibrations, to thermal crisis and heat transfer deterioration as well as to problems in system control and regulation.

Several authors have studied fluid dynamic instabilities in the past: Kakac [1] classified them in terms of static and dynamic instabilities or also in terms of pure or composed ones: a system is subject to static instabilities if, when disturbed, it reaches a new operating condition in a succession of static working points, whereas the same system is subject to dynamic instabilities when there are feedback effects of various parameters which lead to oscillating transient condition.

Density wave oscillations (DWO) were studied for the first time by Stenning [2]; they are dynamic instabilities caused by a variation of pressure drop in two-phase flow and, at the same time, by the delay of this effect on the whole system: this means that other parameters are affected by feedback effects in the time scale leading to flow rate oscillations in the system. As suggested by Fukuda [3], parallel channel instabilities seem to be similar to DWO in a single heated channel, that are always due to a variation of flow parameters like pressure drop. Moreover flow pattern instabilities are generally considered static ones and they usually arise during the transition from slug to annular flow pattern; in this case, after the transition, pressure drops are reduced, the flow rate increases and in turn, with a larger flow rate, flow pattern becomes again slug flow; very often the processes which occur in industrial components are a combination of different kind of instability.

Stability maps are a powerful tool to predict the onset of instabilities in fluid dynamics systems and many authors have developed stability maps, either in a theoretical way or by experiments or by numerical way. G.Yun et al. [4] proposed both a theoretical and an experimental study, whereas Papini [5] performed a comparison of the stability maps obtained experimentally with the RELAP5/MOD3.3 [7] code prediction. Further work is needed to increase the fluid dynamic instability knowledge and, in particular, the prediction of the phenomenon by means of fluid-dynamics codes.

DESCRIPTION OF THE ACTUAL WORK

In the present paper, the main goal is to study the possibility to predict the density wave oscillations, flow pattern oscillations and parallel channel oscillations by RELAP5/MOD3.3 in some simple cases like a single vertical heated channel and in parallel channels both in vertical and inclined layout. The present work concerns the RELAP5/MOD3.3 code ability to predict instabilities and to get instability maps for such simple cases; in particular the stability of the helical steam generators designed for nuclear reactors is investigated.

Helically coiled pipes heat exchangers are interesting components in many fields, in nuclear and conventional power plants, due to better performances regarding heat transfer and mechanical stresses induced by the thermal expansion. In order to investigate the fluid dynamic instabilities by means of RELAP5/MOD3.3 code, the helically coiled pipes are described as inclined pipes with an inclination equal to the angle of the helical pipe. This approximation allows to take into account the gravitational effect and the difference between the various helically coiled pipes, but cannot take into account secondary flows. The analysis concerns a multichannel system with three inclined pipes with different angles. In order to describe a helical pipe with an inclined pipe, by considering the angle of the helical pipe as the angle of straight pipe inclination, the adopted length and the height of the pipe are the same as those of the helical ones.

Stability Maps

The stability maps, that were adopted the first time by Ishii and Zuber [6], are a powerful instrument to understand the physical limits of the devices you are dealing with. All the main parameters affecting the system are well represented by means of two non-dimensional numbers as introduced by Zuber, that is the "*Subcooling number*" and the "*Phase Change number*", that are defined as follows:

$$N_{sub} = \frac{\Delta h_{in}}{h_{fg}} \frac{v_{fg}}{v_f} \tag{1}$$

$$N_{pch} = \frac{\phi}{W h_{fg}} \frac{v_{fg}}{v_f} \tag{2}$$

As an example, for a single heated channel, the two parameters can be represented in a x-y diagram, showing the stability map with the classical "L- shape", where all the points on the right of the limit line correspond to the arise of instabilities as shown in Fig.1.

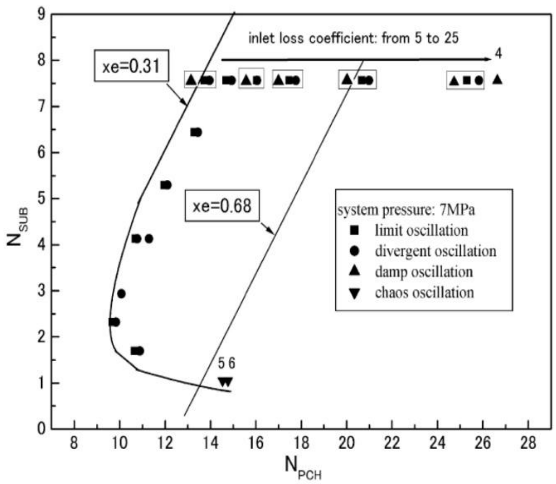

Fig. 1. Ishii- Zuber stability maps for a single heated channel [6]

RELAP5/MOD3.3 Facility Modelling

The simulation of a real plant by means of the one-D semi-implicit RELAP5/MOD3.3 system code, based on a fluid volume model, is performed splitting up the facility into small volumes separated by junctions. The model chosen to investigate the instability phenomenon depends on the number of the facility channels: two time dependent volumes and a pipe divided in 50 volumes are used in the case of a single channel, whereas two branches at the inlet and at the outlet are added in the other cases. Two single junctions connect the time dependent volumes to the pipe; so a constant pressure difference is imposed between the inlet and the outlet of the system. Heat structures in parallel provide heat to produce the two-phase flow inside the pipe. The single channel simulation is presented in Fig. 2 whereas the characteristic of the pipe are reported in Table I.

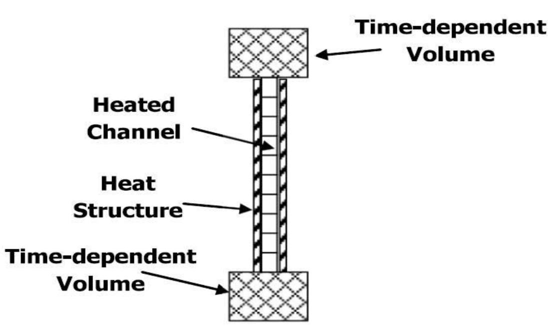

Fig. 2. Single channel simulation

TABLE I. Single channel geometrical data

Parameters	Values
Total Length [m]	5
Diameter [cm]	1.2
Roughness [m]	$2.5 \cdot 10^{-5}$
k_{loc} $inlet$	0
k_{loc} $outlet$	0
Layout	Vertical

In the case of multichannel system, the simulation has been performed with a three channel system in parallel, firstly with a vertical layout and secondly with three inclined pipes with different angles to simulate a real steam generator with helically coiled pipes (Fig. 3).

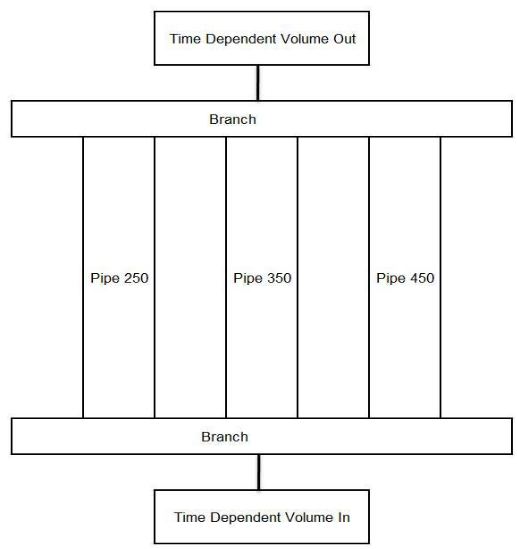

Fig. 3. Scheme for multichannel systems

The main variable associated with the tests is the pressure of the system: the steps needed to build the stability maps are the following:

i. For each reference pressure value, the ratio between v_{fg} and v_f is provided.
ii. Several sample sub-cooling values are chosen to evaluate the *Subcooling numbers*. Subcooling values are defined as follows:

$$x_{sub} = \frac{h_{l,sat} - h_{in}}{h_{fg}} = \frac{\Delta h_{in}}{h_{fg}} \quad (3)$$

where Δh_{in} is the inlet subcooling.
iii. Holding a "*Subcooling number*" constant, thermal power is increased in a linear way until reaching the first flow rate oscillation (Fig. 4). Instabilities are considered fully developed when the amplitude of the

oscillations reaches the 50% of the average flow rate.

iv. Evaluating the time of the first oscillation, the value of the thermal power corresponding to the characteristic time is computed.

v. Evaluating the flow rate as the average of the oscillations, the "*Phase-change number*" is found.

vi. Plotting the *Subcooling number* and the *Phase-change number*, a system stability boundary is identified.

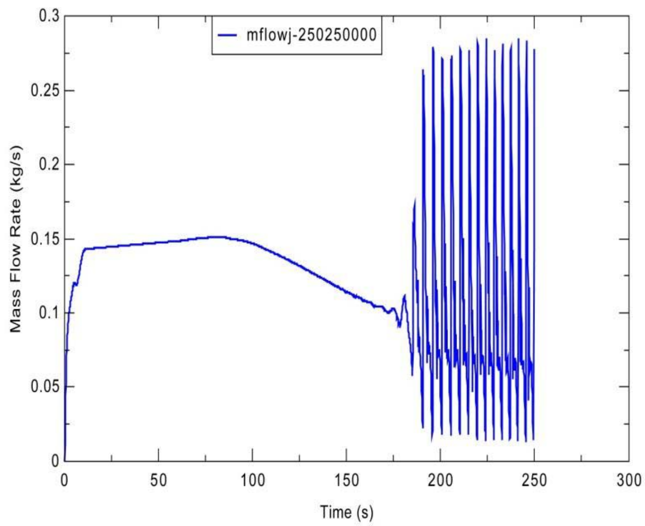

Fig. 4. Arising of flow oscillations

RESULTS

Single channel

The stability map, at three values of the pressure, is reported in Fig. 5. The "L-shape" can be seen and the region where the system is stable is on the left of the curves, whereas instability conditions are the ones on the right. The Subcooling number in correspondence of the slope inversion (Fig. 5) can be considered constant at different pressure (it is about 0.98).

The onset of instabilities does not correspond to a flow regime transition, which however can be foreseen by the code by means of different relationships according to the flow regime condition, but it is provided by dynamic feedback effects of system parameters in the solution of conservation equations.

From the definition of the two numbers represented in the stability map a new relationship between *Subcooling number* and *Phase-change number* can be obtained:

$$N_{SUB} = N_{PCH} - x_{out}\frac{v_{fg}}{v_f} \qquad (4)$$

So in correspondence of the slope inversion the steam quality at the outlet as a function of the pressure can be evaluated from eq. (4) and it is shown in Fig. 6.

The pressure of the system is an important parameter to evaluate the instability and the results show that the pressure increase leads to a more stable system because the densities of the two-phase become closer. Such results agree with literature data, considering that pressure increase leads to a higher steam quality at the outlet without the arising of instabilities.

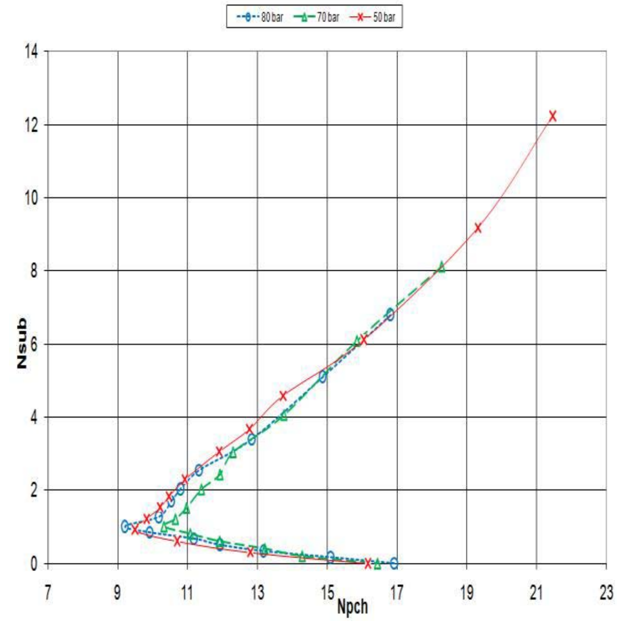

Fig. 5. Stability Map for a single channel

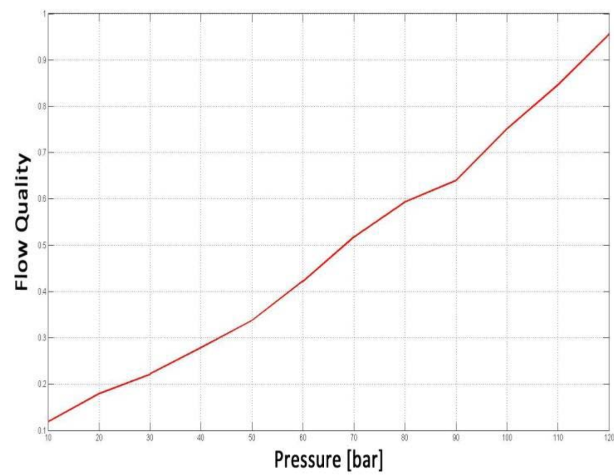

Fig. 6. Effects of the pressure on the steam quality at the outlet

The results obtained for a single channel with vertical layout are consistent with the ones shown by Papini [5] analysis with RELAP5/MOD3.3 code in the framework of instability analysis at SIET Company laboratory; as shown in Fig. 7, for a single channel, with two pressure losses located at the inlet and the outlet of the pipe and for similar Sub-cooling numbers, the maximum error of the *Phase-change number* is about 20%.

Multichannel systems

The use of the RELAP5/MOD3.3 code to get the stability maps is extended to multichannel systems. The

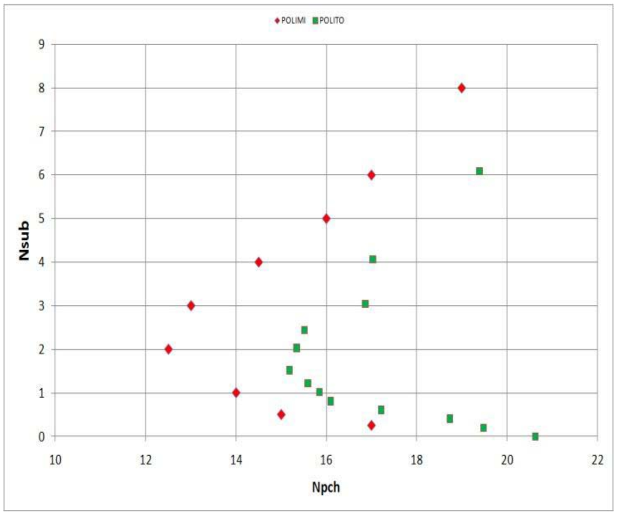

Fig. 7. Comparison between the present work (POLITO) and Ref. [5] (POLIMI) results

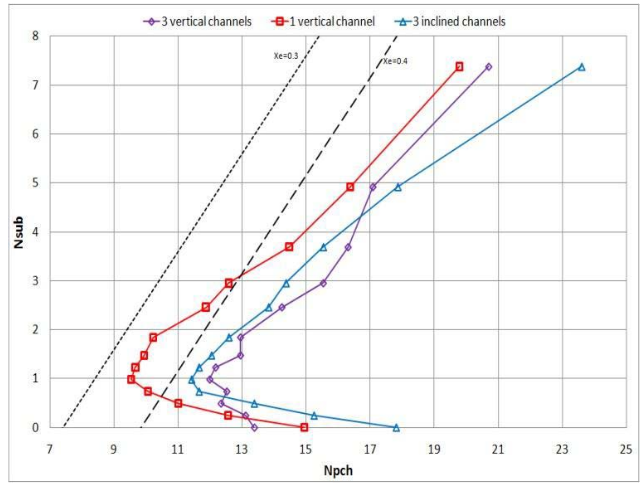

Fig. 8. Stability Maps for multichannel system

pressure chosen for the analysis is 58 bar, that is the design pressure for the innovative nuclear reactor IRIS steam generator; the procedure is the same as the previous one, by assuming different subcoolings and by increasing the thermal power in a linear way. The adopted scheme has been reported in Fig. 3.

The stability map obtained by means of the RELAP5/MOD3.3 code is reported in Fig. 8, where there is a comparison between the single vertical channel, three vertical channels in parallel and three inclined channel at a pressure of 58 bar. The results confirm the classical "L-shape" for the boundary curve between the stable zone and the unstable one; the results show also that a multichannel system is more stable than a single one, as regards the density wave oscillations and in agreement with the literature data. In fact, the outlet steam quality at the instability onset for a single channel is about 30%, whereas it is about 40% for the multichannel system.

CONCLUSION

The analysis that has been carried out in the present paper shows the possibility to predict the onset of density wave oscillations by means of RELAP5/MOD3.3 code for simple geometry systems, whereas the difference between 1D and 3D approximations is not relevant for the purpose of the analysis; the shape of the boundary line in the stability maps is in agreement with the other authors prediction. The approximation used for helically coiled pipes in the multichannel systems seems not to affect the instability onset and the classical shape of the instability maps, that seem a powerful tool for the fluid dynamic instability prediction.

NOMENCLATURE

h_{in}: inlet enthalpy
$h_{l,sat}$: liquid saturation enthalpy
h_{fg}: vaporization enthalpy
k : localized pressure loss coefficient
Npch: Phase change number
Nsub: Sub-cooling number
v_{fg}: difference between vapour and liquid specific volume
v_f : liquid specific volume
W: mass flow rate
x_{out}: outlet quality
ϕ: thermal power

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