RESULTS OF THE IAEA BENCHMARK EXERCISE ON FLOW STABILITY IN HEATED CHANNELS WITH SUPERCRITICAL FLUIDS

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Abstract

The paper reports on a benchmarking activity carried on within the frame of the IAEA CRP on "Heat Transfer Behaviour and Thermo-hydraulics Codes Testing for SCWRs", aimed at comparing the results of linear and non-linear codes and models in the application to a simple reference geometrical condition. The simplicity of the proposed problem was conceived to allow for the application of one-dimensional models. The results of the analyses were reported in dimensionless form, adopting recently proposed definitions in order to check their suitability to represent stability thresholds. Both dynamic and static instabilities were addressed. The paper presents the results of this benchmark exercise as well as the preliminary conclusions.

1. Introduction

Flow stability is a relevant issue to be addressed in the design of Supercritical Water Reactors (SCWRs) (see e.g., [1-3]). However, the relevance of instability phenomena for supercritical nuclear reactor applications needs to be carefully assessed, in view of some basic considerations.

On one hand, a basic understanding of the physical mechanisms involved suggests that an unstable behaviour similar to the one occurring in Boiling Water Reactors is in principle possible in SCWRs [4-7]. In particular, the modelling techniques that resulted useful for predicting BWR stability behaviour can be adapted to the analysis of supercritical fluid systems with relatively minor changes [8-10]. In different instances, it was shown that available one-dimensional and CFD codes do predict the occurrence of instabilities in supercritical fluid systems when appropriate operating conditions are reached. Therefore, and assuming that future experiments, that are still lacking, will not show any grossly unexpected behaviour presently disregarded in modelling, unstable behaviour is expected to possibly occur in supercritical pressure systems and nuclear reactors, with the potential of perturbing operation in similarity to what observed for in boiling water reactors. It must be anyway considered that design details of proposed SCWR systems may have a considerable role in defining how relevant the different instability mechanisms may be for safety and operation. As a consequence, since an experimental confirmation of the occurrence of instabilities in conditions of practical interest for reactor systems was not yet provided, it would be necessary that any future relevant experiments would be performed to provide the necessary basis for discussing plant phenomena.

While waiting to clarify the situation experimentally, it seems appropriate to gain insight into the characteristics of the addressed phenomena by using code and model applications. A great incentive to pursue this line of research is the mentioned experience in simulating BWR stability conditions, which finds an almost immediate application in this new field. A code benchmarking activity in relation to the stability of heated channels with fluids at supercritical pressure was decided at the 1st Research Coordination Meeting of the IAEA Coordinated Research Project on Heat Transfer Behaviour and Thermo-hydraulics Codes Testing for SCWRs (Vienna, 22-25 July, 2008). This action was assigned for coordination to AECL and the University of Pisa.

The reference data generated to propose the problem have been published separately [11], by making use of the highlighted phenomena to discuss the capabilities of the dimensionless numbers proposed for identifying instability conditions. The problem proposed for this benchmark exercise [12] involves two main sections:

1. a basic set of analyses for operating conditions concerning a vertical pipe with supercritical pressure water and different degrees of outlet throttling;
2. an additional set of analyses for vertical and horizontal pipes related to fluid-to-fluid comparison, with strong inlet and outlet throttling.

It must be noted that the proposed problem has some aspects that make it somehow ideal in view of the operating conditions envisaged for a nuclear reactor, like the neglect of heater capacity and heat conduction. In this respect, the performed activity must be considered simply as an exercise designed to assess codes to be applied to more complex reactor core configurations and in envisaging experiments with operating fluids other than water.

Eight different organisations involved in the IAEA CRP, in addition to the University of Pisa that coordinated the effort and proposed the reference data, took part in the exercise (see the Appendix). The obtained results were documented in a quick look report [13], proposing first comments and preliminary conclusions. Further comments were received later on by participants, preparing for the final discussion to be included in project reports.

The paper describes the main characteristics of the proposed problem and the results obtained by the participants, trying to highlight the main lesson learned from the activity.

2. Benchmark problem specifications and reference data

2.1 Problem specifications

The benchmark exercise was proposed with reference to the conditions represented in Figure 1. In particular, a circular rough pipe with uniform cross section is assumed to join two plena, mainly included to assign inlet and outlet conditions. Uniform imposed heat flux is assumed along the pipe and variable inlet and outlet throttling is assumed.

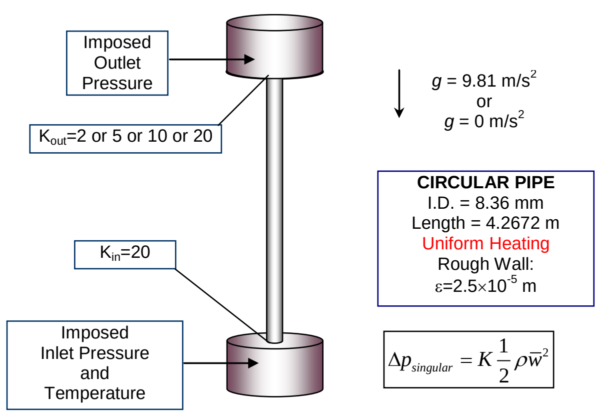

Figure 1. Geometrical and physical boundary conditions proposed for the Benchmark Exercise.

In the first part of the exercise, only water at a pressure of 25 MPa is specified with vertical channel orientation, while in the second part three additional fluids were considered, being CO_2, R23 and NH_3 at working pressures of 8.0, 5.7 and 15.0 MPa, addressing both vertical and horizontal channel conditions. For those participants who did not have the possibility to address the fluid-to-fluid part of the exercise, having available only tools applicable to water, it was suggested to make use of water at 30 and 40 MPa in order to address the effect of different fluid properties on the stability boundaries obtained in dimensionless form.

The exercise consisted in predicting the thresholds of instability with different 1D codes at prescribed inlet fluid conditions. The inlet temperature was specified in dimensionless form and it was requested to express the threshold of instability using a coherent formalism. In particular, the following definitions were assumed [7]:

$$N_{SPC} = \frac{\beta_{pc}}{C_{p,pc}}\left(h_{pc} - h_{in}\right) \tag{1}$$

$$N_{TPC} = \frac{\dot{Q}_{heating}}{W_{in}}\frac{\beta_{pc}}{C_{p,pc}} \tag{2}$$

Although the use of these formulations was suggested to have a common basis for comparison, no matter the specific modeling choices, participants were invited to propose also a different dimensionless formalism, in order to assess the suitability of other available proposals.

The values of inlet and pressure drop conditions specified for the cases of the vertical channel with water and the vertical or horizontal channels with different fluids are reported in Table 1 and Table 2, in which the dummy values of the thresholds and the characteristics of observed instabilities were supposed to be substituted by participants with their own values and the actual observations. Similar tables were proposed to be filled by reporting the value of the ratio of the fluid transit time in the channel to the period of oscillation at the onset of instabilities.

2.2 Reference data

The reference data were generated by the University of Pisa [11, 14] making use of three different tools:

- an in-house code operating in dimensionless form allowing to set up linear stability maps on the basis of linearised balance equations, discretised in space and time [7];

ParticipantName - CodeName			Kout=20	Kout=20	Kout=10	Kout=10	Kout=5	Kout=5	Kout=2	Kout=2
Case	Channel orientation	Nspc	Ntpc,threshold	Type of instability	Ntpc,threshold	Type of instability	Ntpc,threshold	Type of instability	Ntpc,threshold	Type of instability
Label				Oscillatory or Excursive		Oscillatory or Excursive		Oscillatory or Excursive		Oscillatory or Excursive
D0.5V-K20 to K2	Vertical	0.5	1	Oscillatory					3	Oscillatory
D1.0V-K20 to K2	Vertical	1	1	Excursive					3	Excursive
D1.5V-K20 to K2	Vertical	1.5	1	Oscillatory	1.5	Oscillatory	2.5	Excursive	3	Oscillatory
D2.0V-K20 to K2	Vertical	2	1	Excursive					3	Excursive
D2.5V-K20 to K2	Vertical	2.5	1	Oscillatory					3	Oscillatory
D3.0V-K20 to K2	Vertical	3	1	Excursive					3	Excursive

Table 1. Matrix of calculation cases proposed for the first part of the exercise with vertical channel and water at 25 MPa

ParticipantName - CodeName			Water	Water	CO2	CO2	R23	R23	NH3	NH3
Case	Channel orientation	Nspc	Ntpc,threshold	Type of instability	Ntpc,threshold	Type of instability	Ntpc,threshold	Type of instability	Ntpc,threshold	Type of instability
Label				Oscillatory or Excursive		Oscillatory or Excursive		Oscillatory or Excursive		Oscillatory or Excursive
F0.5V	Vertical	0.5	1	Oscillatory	2	Oscillatory	3	Oscillatory		
F1.0V	Vertical	1	1	Excursive	2	Excursive	3	Excursive	4	Oscillatory
F1.5V	Vertical	1.5	1	Oscillatory	2	Oscillatory	3	Oscillatory	4	Excursive
F2.0V	Vertical	2	1	Excursive	2	Excursive	3	Excursive	4	Oscillatory
F2.5V	Vertical	2.5	1	Oscillatory	2	Oscillatory	3	Oscillatory		
F3.0V	Vertical	3	1	Excursive			3	Excursive		
F0.5H	Horizontal	0.5	1.5	Oscillatory	2.5	Oscillatory	3.5	Oscillatory		
F1.0H	Horizontal	1	1.5	Excursive	2.5	Excursive	3.5	Excursive	4.5	Oscillatory
F1.5H	Horizontal	1.5	1.5	Oscillatory	2.5	Oscillatory	3.5	Oscillatory	4.5	Excursive
F2.0H	Horizontal	2	1.5	Excursive	2.5	Excursive	3.5	Excursive	4.5	Oscillatory
F2.5H	Horizontal	2.5	1.5	Oscillatory	2.5	Oscillatory	3.5	Oscillatory		
F3.0H	Horizontal	3	1.5	Excursive			3.5	Excursive		

Table 2. Matrix of calculation cases proposed for the second part of the exercise with different fluids and vertical or horizontal channel

- the RELAP5/MOD3.3 code [15];
- an in-house transient code (named TRANSDIM) for the analysis of single-channel instabilities

already used in previous analyses [16].

The choice to make use of different codes in proposing data for a benchmark exercise was dictated by the prudence that is necessary in such actions. In particular, while the two in-house codes, both in dimensional and dimensionless form, share a unique root in terms of conception of balance equations and purpose of application, RELAP5 is a code that can be considered completely independent from the models set up at the University of Pisa, though it shares with them the basic assumptions adopted for 1D flow description.

In this respect, it is necessary to point out that no model specifically conceived for application to supercritical pressure conditions was adopted in the three tools used for generating reference data. This fact represents the main limitation in this exercise, to be duly commented in view of the results that one of the participants (VTT) obtained with models suggested for supercritical pressure applications. This limitation must be regarded considering the uncertainty about the applicability of correlations specifically proposed for heat transfer and flow resistance with fluids at supercritical pressure.

Figure 2 and Figure 3 present some of the results generated by the three codes and disclosed to participants only after submission of their data. As it can be noted, the stability boundaries generated by the linear code (continuous lines) match very well with the results obtained for selected operating conditions by RELAP5 and TRANSDIM in dimensional form (reported by markers). The dashed lines reported in Figure 2 highlight the effect of truncation error on the computed stability boundaries.

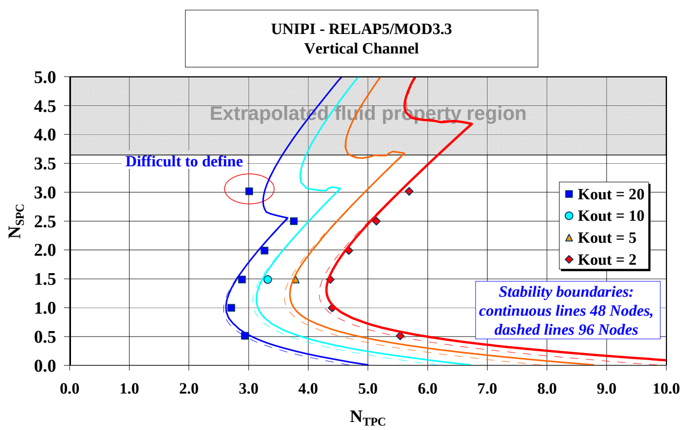

Figure 2. Reference data proposed for the first part of the exercise related to water and vertical channel

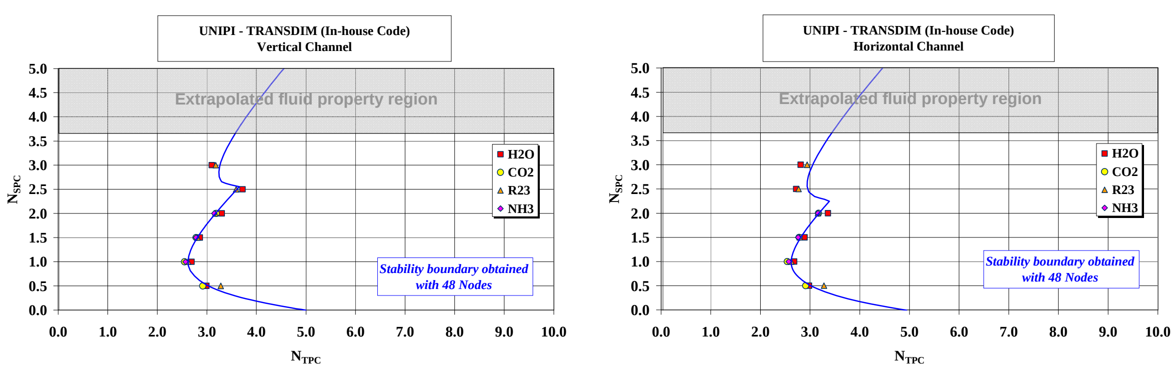

Figure 3. Reference data proposed for the second part of the exercise related to different fluids and vertical or horizontal channel

A thorough discussion about the implications of the indications obtained from these data is reported in [11]. Here, it is necessary to point out that:

- both oscillatory and excursive instabilities are predicted to occur, as shown respectively by the presence of *the lower and the upper lobes* in the neutral stability curves;
- the effect of throttling is shown coherently by the linear dimensionless code and RELAP5;
- the response of TRANSDIM closely matches the one proposed by the linear dimensionless code for the four different fluids, with limited differences among them;
- the effect of channel orientation is clearly observed especially on the location of the boundary between oscillatory and excursive instability and is also predicted coherently by the linear and the transient codes.

A final remark on the proposed data, concerns the high fluid temperatures reached in some of the proposed conditions at low value of N_{SPC}; this aspect did not create problems in the case of RELAP5 and TRANSDIM, in which a sufficiently broad range of fluid properties is available. However, too high temperatures identify regions that could not be possibly achieved in actual applications and were included in the exercise just in order to have a meaningful comparison between the lines obtained in dimensionless. It is clear that the impossibility to assess such conditions by any code, due to fluid property limitations, cannot be considered a flaw.

3. Submissions and results

In response to the call for submissions, the Valtion Teknillinen Tutkimuskeskus (VTT) from Finland, the University of Manitoba and AECL from Canada, the Bhabha Atomic Research Centre (BARC) from India, the JRC-IE Petten from The Netherlands, Gidropress from Russia and the McMaster University and the Gruppo di Ricerca Nucleare of San Piero a Grado (GRNSPG), from Canada and Italy respectively, proposed their calculations performed with different in-house or widespread one dimensional codes. In the following, the main obtained data are summarised.

VTT [17] made use of the transient two-phase flow APROS code, adopting a nodal staggered mesh technique for solving the equations. A channel with 40 nodes was used for simulating the problem and the heated structure was made very thin, as suggested in the specifications, in order to avoid any undue inertia due to energy storage in the walls. Specific correlations for friction and heat transfer are adopted. Only water data at 25 MPa for the vertical channel were considered. Figure 4 compares the results obtained by VTT with the reference stability boundaries. As it can be noted, two cases at low pseudo-subcooling were not calculated.

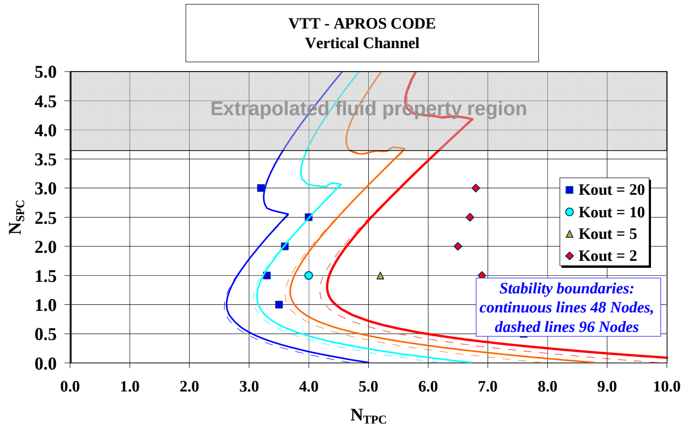

Figure 4. Comparison of the results obtained by VTT against the reference stability boundaries for water in the vertical channel.

The results, calculated with VTT APROS–program, show in general too large stability in comparison with the reference results. The form of the neutral stability curve in N_{SPC} - N_{TPC} plots obtained by VTT is similar as for the reference curves, especially when K_{out} is 20. However, with small K_{out}-values the instability was obtained with very high N_{TPC}–values or the instability was not reached at all.

In the standard APROS the wall friction was calculated with the Kirillov wall friction correlation:

$$\xi_{kir} = \left(1.82\log_{10}\mathrm{Re}_b - 1.64\right)^{-2}\left(\frac{\rho_w}{\rho_b}\right)^{0.4} \tag{3}$$

This correlation is intended also to supercritical pressure region, since it takes into account the fast density change near the heated wall. However, it does not take into account the roughness of the wall, which was defined to be $2.5\cdot10^{-5}$ in this exercise. The other thing which may affect the results of APROS is that the water properties in the program were accurate up to 800 ºC. Above that temperature the material property values are extrapolated. Especially, in case of small K_{out}, the temperature at the outlet was significantly above 800 ºC.

Additional calculations were made by VTT with the intention to clarify how much the wall friction affects instability. The cases were calculated with the following correlations

- Kirillov: $$\xi_{kir} = \left(1.82\log_{10}\mathrm{Re}_b - 1.64\right)^{-2}\left(\frac{\rho_w}{\rho_b}\right)^{0.4} \tag{4}$$
- Filonenko: $$\xi_{fil} = \left(1.82\log_{10}\mathrm{Re}_b - 1.64\right)^{-2} \tag{5}$$
- Colebrook: $$\frac{1}{\sqrt{\xi_{col}}} = 1.74 - 2\log\left(\frac{1}{\sqrt{\xi_{col}}}\frac{18.7}{\mathrm{Re}} + \frac{2\varepsilon}{D_h}\right) \tag{6}$$

As shown in Figure 5, the results with the Filonenko correlation were closer to the reference values than those with the Kirillov correlation. The instability values obtained with the Colebrook correlation are closer to the reference values.

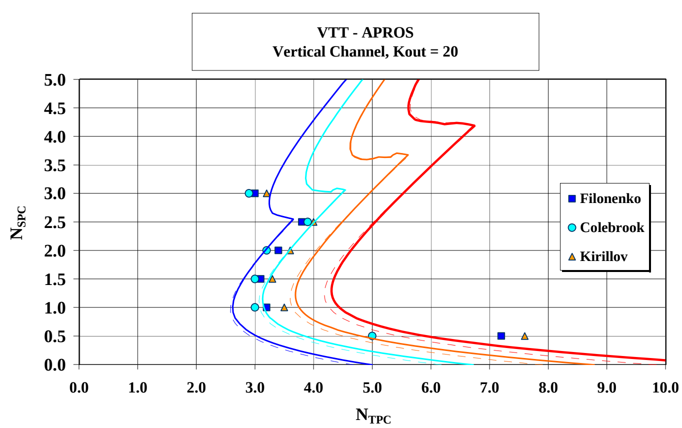

Figure 5. Results of the sensitivity analysis performed by VTT with different correlations for friction

The **University of Manitoba and AECL** submission [18] proposed the use of a stability criterion based on the identification of a point of inflexion in the channel pressure drop vs. flow rate curve at constant heating power. The results of the obtained criterion are compared to those of a linear stability analysis code. In the application, both water at three different pressures (24 cases) and CO2 (12 cases) were considered. Figure 6 summarises the data obtained in the exercise. The compact form of the adopted stability criterion represents a very interesting feature of the application.

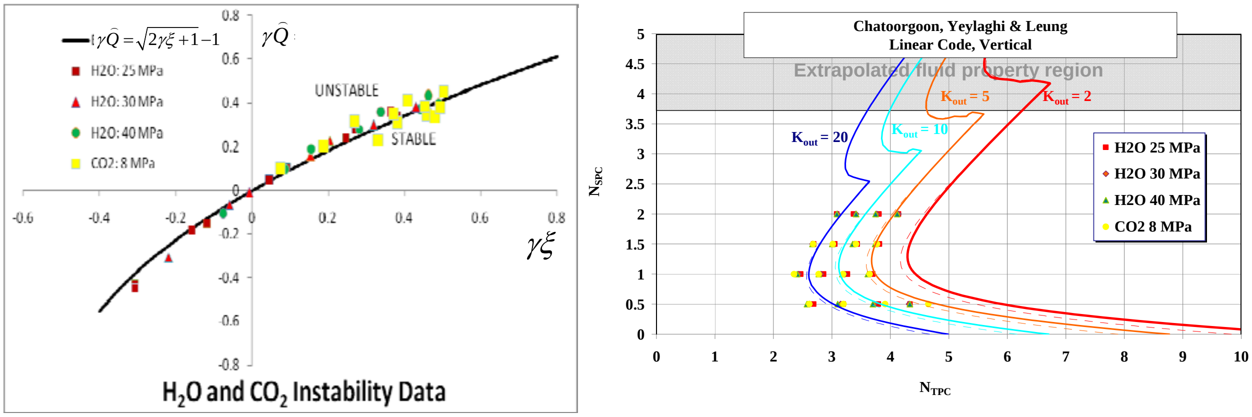

Figure 6. Results obtained by University of Manitoba and AECL with water at three pressures and CO_2 compared with their stability criterion and with the stability margins proposed in the benchmark

BARC proposed two submissions for the benchmark problem [19], one using a linear stability code (SUCLIN) and the other using a non-linear stability code (NOLSTA). The predictions by NOLSTA code are in very good agreement with the reference stability boundaries for the oscillatory density wave instability, whereas SUCLIN code predicts greater stability for the same (Figure 7). The NOLSTA code uses only 28 nodes which can contribute to some amount of numerical diffusion. Apart from numerical diffusion, there are other differences which can also contribute to the mismatch as specified below:

- all the fluid properties (including viscosity) are perturbed in the nonlinear analysis (i.e., NOLSTA analysis), whereas only enthalpy and specific volume perturbation are considered in the linear stability analysis (i.e. SUCLIN analysis).
- the friction factor perturbation is not considered in linear stability analysis, whereas nonlinear analysis accounts for it;
- the perturbations induced in specific volume due to perturbations in enthalpy have been considered in SUCLIN code, whereas perturbations in specific volume due to perturbations in pressure have been neglected; the NOLSTA code accounts for both.

Similar differences were also observed in the stability analysis of natural circulation in a rectangular open loop with supercritical water by NOLSTA and SUCLIN codes as reported in [20].

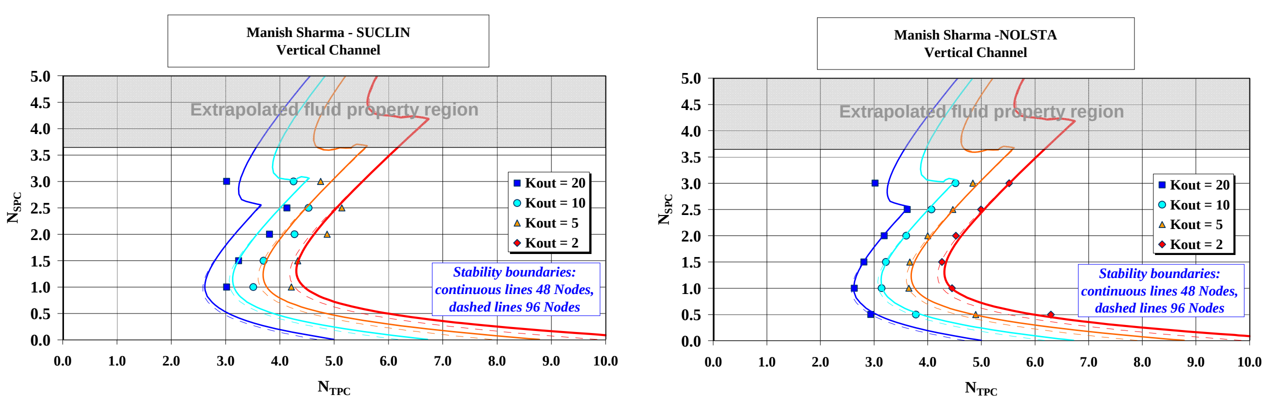

Figure 7. Results obtained by BARC with the SUCLIN and the NOLSTA codes

The submission by **JRC-IE** [21] was made closely following the specifications and provides results in excellent agreement with the reference data for the computed stability thresholds (Figure 8) and in close agreement also for the values of the ratio of the transit time to the period of oscillations. As in previously published work by the University of Pisa, the RELAP5 code was used for simulating a channel with 48 nodes. The exercise was carried out using water as fluid, whose properties are in agreement with IAPWS 97. An attempt was made to perform the exercise with other fluids than water, namely CO_2 and NH_3. However, it is reported that the code was not able to handle these fluids in supercritical conditions.

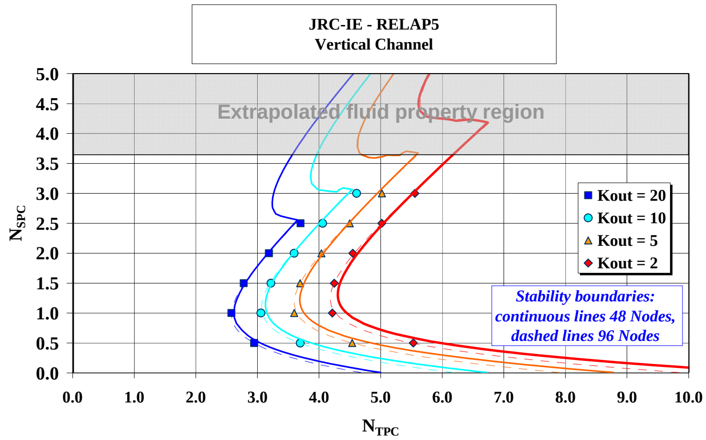

Figure 8. Results obtained by JRC-IE Petten by the RELAP code
for water and vertical channel with the reference stability boundaries

Gidropress [22] adopted the TEMPA-SC code, a transient subchannel code based on 3D conservation equations. The number of nodes adopted for the analysis was 61 and the increasing power strategy was adopted to identify stability. A specific criterion for automatically detecting the onset of instabilities was adopted. The stability thresholds calculated by the TEMPA-SC code for the addressed cases are reported in Figure 9. The match with the reference stability lines is only approximate, especially concerning the effect of outlet throttling. The values of the ratio of the transit time to the period of oscillations reported in the tables show the expected trend.

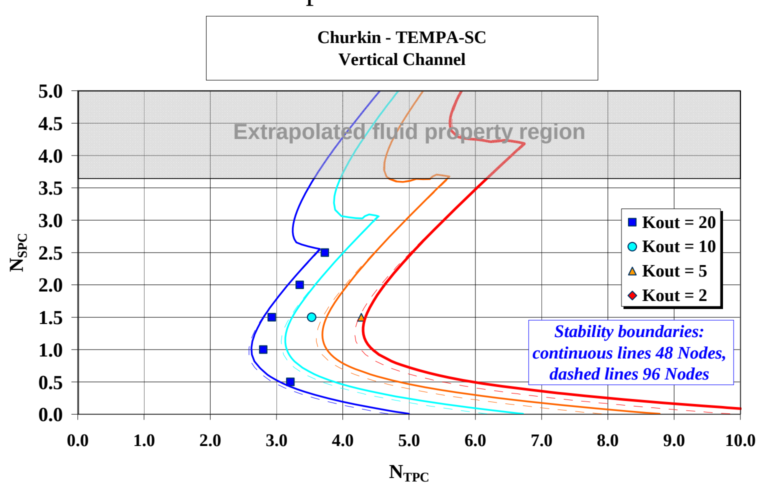

Figure 9. Comparison of the stability boundaries identified by Gidropress with the TEMPA-SC code
for water and vertical channel with the reference stability boundaries

The submission by **the McMaster University and the GRNSPG** is twofold [23-24], making use of the RELAP5 and the TRACE codes, adopted with very similar models. Both the vertical and the horizontal channel with water are addressed calculating many more working conditions than specified. The models for RELAP5 and TRACE include a pipe discretised with 23 nodes and two branches (upstream and downstream) to simulate the plena, in addition to two time-dependent volumes needed to impose inlet and outlet pressures. The procedure adopted for reaching the instability threshold is the one suggested in the specifications for transient codes and used also by other participants, i.e., a progressive increase of channel power at imposed pressure drop across the channel.

The results of the two codes in terms of stability thresholds are compared to the continuous stability boundaries in Figure 10 and Figure 11. A greater stability with respect to the reference date is observed. However, also in this submission the presence of the excursive instability is confirmed at low temperature.

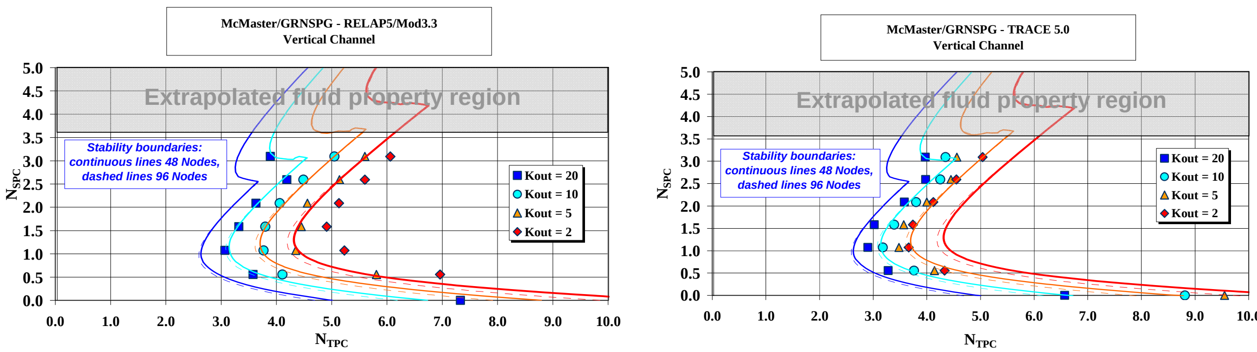

Figure 10. Comparison of the stability boundaries identified by McMaster University and GRNSPG with RELAP5 and TRACE for water and vertical channel with the reference stability boundaries

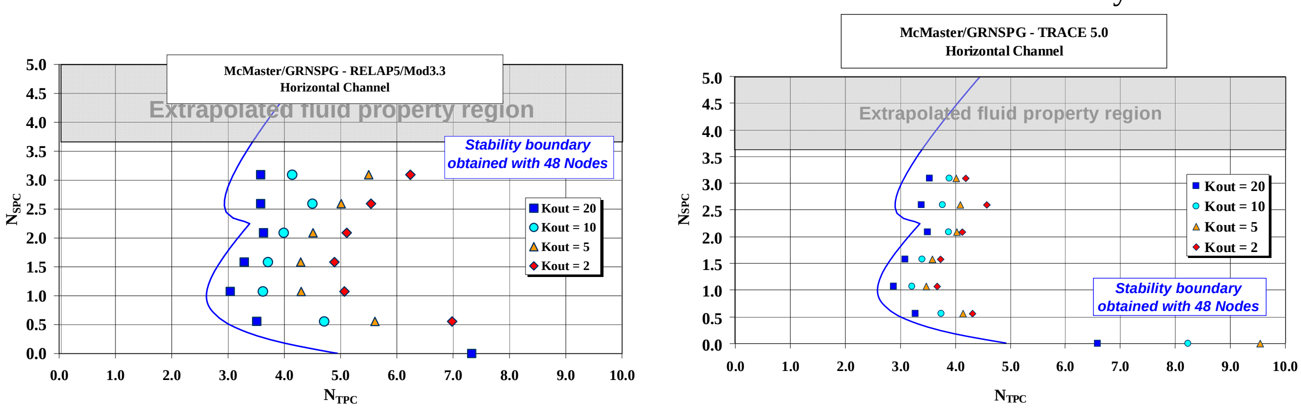

Figure 11. Comparison of the stability boundaries identified by McMaster University and GRNSPG with RELAP5 and TRACE for water and horizontal channel with the reference stability boundaries

4. Conclusion

As mentioned in the Introduction, the results generated by the University of Pisa cannot have the pretence to be exact, being obtained by models whose performance is affected by specific choices in the basic assumptions and modelling techniques, in similarity with those adopted by Participants. Nevertheless, the use of three relatively independent codes provided a reasonable assurance on their adequacy as a consequence of the good match obtained among their results, in the limit of common assumptions adopted by all the models. The predictions by JRC-IE with RELAP5 and by BARC with NOLSTA actually provide additional confirmations of the reference data.

Some features that are common to most the submissions and to the reference data are related to the following aspects:

- the well known effect of outlet throttling in determining lower stability of heated channels with strong density differences;
- the presence of oscillating as well as excursive instabilities, the latter occurring at relatively low inlet temperature, in regions that would be hopefully of little interest to nuclear reactor operation;
- the general shape of the stability boundary in the N_{TPC}-N_{SPC} plane;
- the decreasing value of the ratio of the transit time to the period of oscillations with increasing pseudo-subcooling (not presented in this paper because of space limitations).

Among the various submissions showing different degrees of discrepancy with respect to the reference data, the ones by VTT allow interesting reflections about the use of general models implemented in system codes to the specific case of supercritical pressure fluids, with main attention to friction correlations. As the two applications and the interesting sensitivity studies by VTT showed, correlations for friction and heat transfer to supercritical fluids do exist that are presently not available in many codes. Heat transfer correlations have little role in the present exercise in which heat flux at the wall is specified, except for determining the wall temperature which has, in turn, effect on friction factors; in fact, as shown in the discussion by VTT, some correlations proposed for friction with supercritical fluids and implemented in APROS take into account the properties at the wall.

In this respect, an ongoing study on friction factor correlations for supercritical fluids, being developed at the University of Pisa by the use of a CFD code [25], is highlighting interesting problems in this regard. In particular, the following considerations are relevant for the present discussion:

- the application of correlations for friction with supercritical fluids require an accurate evaluation of wall temperature and, therefore, of heat transfer; considering the difficulty in correctly predicting heat transfer deterioration with engineering correlations or CFD models, estimating friction can be regarded as a relatively challenging task;
- on the other hand, most of the available correlations for friction at supercritical conditions are developed with reference to smooth tube conditions, where the dependence on the Reynolds number is considerable; little information is available on rough tube conditions that, at large Reynolds number, would provide friction factors relatively independent of fluid properties;
- moreover, it is known that in the liquid-like and gas-like conditions, where property variations are milder, classical relationships for friction factor (e.g., the mentioned Colebrook one) are applicable, while the major discrepancies with them occur in the region across the pseudo-critical temperature.

This situation makes the evaluation of friction in supercritical pressure conditions still uncertain on the basis of present knowledge and, considering the influence of this parameter on stability, it is expected that a corresponding uncertainty is induced in stability predictions.

Such an uncertainty represents a further motivation to consider highly desirable the collection of new experimental data on stability that can provide a direct indication about the level of adequacy of presently available models.

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APPENDIX. LIST OF PARTICIPATING ORGANISATIONS AND SCIENTISTS

ORGANISATION	SCIENTISTS
Valtion Teknillinen Tutkimuskeskus, Finland	Markku Hänninen, Jorma Kurki
University of Manitoba and AECL, Canada	V. Chatoorgoon, S. Yeylaghi, L. Leung
Bhabha Atomic Research Centre, India	Manish Sharma, P.K. Vijayan, D.S. Pilkhwal & D. Saha,
Joint Research Centre, Institute for Energy, Petten, The Netherlands	L. Ammirabile
Gidropress, Russia	Andrey N. Churkin
Gruppo di Ricerca Nucleare di San Piero a Grado Pisa, Italy and McMaster University, Canada	F. Fiori, D.R. Novog, A. Petruzzi