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Critical flow prediction by system codes – Recent analyses made within the FONESYS network

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ABSTRACT

A benchmark activity on Two-Phase Critical Flow (TPCF) prediction was conducted in the framework of the Forum & Network of System Thermal-Hydraulics Nuclear Reactor Thermal-Hydraulics (FONESYS). FONESYS is a network among code developers who share the common objective to strengthen current technology. The aim of the FONESYS Network is to highlight the capabilities and the robustness as well as the limitations of current SYS-TH codes to predict the main phenomena during transient scenarios in nuclear reactors for safety issues.

Six separate effect test facilities, more than 90 tests, both in steady and transient conditions, were considered for the activity. Moreover, two ideal tests were designed for code to code comparison in clearly defined conditions. Overall eight System Thermal-Hydraulic (SYS-TH) codes were adopted, mostly by the developers themselves, ensuring the minimization of the user effect. Results from selected tests were also compared against Delayed Equilibrium Model, not yet implemented in industrial version of SYS-TH codes.

Generally, the results of the benchmark show an improvement of the capability of SYS-TH codes to predict TPCF in the last three decades. However, predicting break flowrate remains a major source of uncertainty in accidental transient simulations of Water-Cooled Nuclear Reactors (WCNR). A set of possible actions is proposed to go beyond the current limitations of choked flow models. More detailed guidelines for using 0-D choked flow models is possible by using the experience gained by the benchmark results as well as all available validation results. Progress in understanding and 1-D modelling of flashing and choked flow might be achieved by a deeper physical analysis leading to more mechanistic models based on specific flow regime maps for high speed flow. Also the use of advanced 3-D numerical tools may help to understand and predict the complex 3-D geometrical effects.

1. Introduction

The safety assessment of WCNR under design basis accident conditions as Loss Of Coolant Accident (LOCA) strongly depends on the ability to predict discharged coolant mass flow through the break (F. D'Auria et al., 2017).

The break mass flow rate has a paramount influence on the depressurization rate of the reactor coolant system, the flashing in core, and consequently on the heat transfer in the core. Moreover, the energy transfer to the containment strongly depends from the break mass flow. In the event of LOCA, the different thermodynamic condition between the reactor coolant system and the containment are such that TPCF occurs at the break for most of the transient evolution: the mixture velocity of the discharged flow reaches the local sound velocity and the mass flow rate becomes independent from the downstream flow conditions.

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The ability to calculate discharging mass flow rate at the break allows a better design of the Emergency Core Cooling Systems (ECCS) and the containment safety systems. The importance of accurate TPCF prediction kept the importance for advanced reactor design relying on passive ECCS.

The capability to predict TPCF is important for the design of WCNR components and systems as safety relief valves and Automatic Depressurization Systems (ADS). In this concern the capability of SYS-TH codes in modelling behavior of multiple critical sections (e.g. occurrence of more than one critical section, changes in critical section location), supersonic flow in the discharge piping and possible shock waves should be proven, especially for advanced reactor designs (Aksan and D'Auria, 1996). These phenomena are relevant e.g. for the behavior of ADS 1–3 in AP1000 reactor, which play a key role on ECCS performance. Capability to predict these phenomena is not sufficiently demonstrated (D'Auria et al., 2017).

Many theoretical and experimental studies have been performed, especially in the 60–70 s, e.g. see D'Auria et al. (1980). Still a commonly accepted theory does not exist, and even the most recent best estimate SYS-TH computer codes utilize different approaches to calculate TPCF. Furthermore, some of these codes (e.g. RELAP5, TRACE, MARS, SPACE) include more than one TPCF model.

Considering the above, a benchmark activity on TPCF prediction was started in 2015 within the Forum & Network of System Thermal-Hydraulics Codes in Nuclear Reactor Thermal-Hydraulics (FONESYS) (Lanfredini and Lutsanych, 2020). Launched in May of 2010 upon initiative of the University of Pisa, the FONESYS Network is connecting international organizations and institutions active in the area of nuclear SYS-TH codes development (Ahn et al., 2015; Aksan et al., 2018; FONESYS, 2020).

The key objective of the paper is to outline the current capabilities of SYS-TH codes in predicting this phenomenon based on a common understanding by developers of those codes and to present the proposed Research and Development (R&D) actions to improve the predictive capabilities. Selected results are presented in a way which clearly illustrates the capabilities of codes while respecting the non-disclosure agreement signed among FONESYS Members.

The paper is organized as follows. Section 2 gives an overview on TPCF modelling. Section 3 gives some information about the FONESYS Network. The outline and some insights into the FONESYS TPCF benchmark activity and a roadmap for reflections are discussed in Section 4. Possible R&D actions for further improvements are summarized in Section 5. Conclusions are presented in Section 6.

2. Overview on two-phase critical flow models

The reference situation for studying TPCF consist of a reservoir A at high pressure and the environment B at a pressure much lower than the reservoir pressure, typically at atmospheric pressure. The reservoir and the environment are connected by an opening where critical conditions are established if compressible fluid is in the reservoir. Critical flow basically is related to a situation where the mass flowrate from A to B does not depend on the pressure at point B anymore. This is related to the occurrence of a sonic velocity reached in the flow path between A and B, usually at the minimum cross section area. The situation is very clear in single phase flow where a clear sonic velocity may be defined from the isentropic compressibility coefficient. In a two-phase flow, the sonic velocity is not so well identified since it depends on wave frequency, on the compressibility of both phases but also on the flow regime and interfacial structure which are not identified in such high speed flow (D'Auria, 2017). The existence of a flowrate becoming independent on the downstream pressure (or almost independent) is observed in a two-phase flow but no exact expression of the sonic velocity exists.

The geometry of the opening has a key role in determining the critical flow rate and in modelling.

Notwithstanding some pioneering studies of Sauvage (Sauvage, 1892) and Rateau (Rateau, 1905), the historical background at the origin of TPCF can be fixed as the perfect gas theory in adiabatic condition. The key points of the gas theory can be summarized as follows: a) use of adiabatic energy balance equation and perfect gas state equations; b) obtaining the maximum possible flow as a function of throat pressure; c) setting the maximum possible flow as critical flow based on additional hypothesis not part of the original energy balance equation (the entropy consideration is needed to justify the use of adiabatic energy equation) which surprisingly produces good agreement with experimental data.

In the case of perfect gas, solutions are also available for long pipes, i.e. the Fanno theories (see Shapiro, 1953).

Three categories of models are distinguished:

- Experimental 0-D correlation only based on fitting experimental data;
- 0-D choked flow models based on more or less consistent use of simplified integrated balance equations from upstream conditions to a hypothetical sonic section, using some semi-mechanistic models which require the use of one or more empirical parameters;
- Application of 1-D balance equations from A to B through the nozzle.

An early prototype for the first category is the Zaloudek formula (Zaloudek, 1963) and a later prototype is the Gros d'Aillon formula (see Lavialle, 2013).

Two well established prototype correlations for the second approach are the Moody model (Moody, 1965) and the Fauske model (Fauske, 1962). Both are including what we can call inconsistent steps for arriving at the result. Namely, in the case of Moody model no account is given to momentum equation and to friction, in the case of Fauske equation no direct account is given to energy conservation.

The third approach uses the 1-D partial differential equations which are adopted in SYS-TH codes and which can actually predict the choked flow behavior. An example is described in Lavialle (2013).

Attempts to use those equations have been made – also in the frame of the second method, e.g. see Trapp and Ransom (1982) –, with problems due to closure relations about interfacial transfers which are not well known because of lack of information on flow regimes when fluid velocities are high and close to sonic velocity. This generates a non-suitable solution and those scientists who adopted this approach had to simplify or rewrite the equations which therefore became inconsistent with the original equations part of the concerned code.

Several models based on different assumptions have been developed. Reviews of some available models are given in Elias and Lellouche (1994); Pinhasi et al. (2005); Wallis (1980); D'Auria and Vigni (1980). One may conclude that the philosophies of approach to solve the problem and the methods of mathematical solution are in number more or less equal to the number of models.

Currently, modelling options adopted in SYS-TH codes are based either on coarse meshes and a 0-D type critical flow model such as the Henry-Fauske (Henry and Fauske, 1971) or Ransom-Trapp (Ransom and Trapp, 1980) models, or on a very fine 1-D meshing with a modelling of flashing and interfacial friction which controls the predicted critical flow, e.g. see Lavialle (2013).

It is also important to bear in mind that not only 3-D effect related to various possible opening geometries but also other aspects like presence of non-condensable gases, which tends to significantly reduce TPCF (Park et al., 2007), and chemistry of the water have a relevant impact on TPCF. Models are usually developed without explicitly taking into account all their effect.

2.1. Challenging issues

TPCF conditions are characterized by a strong pressure gradient

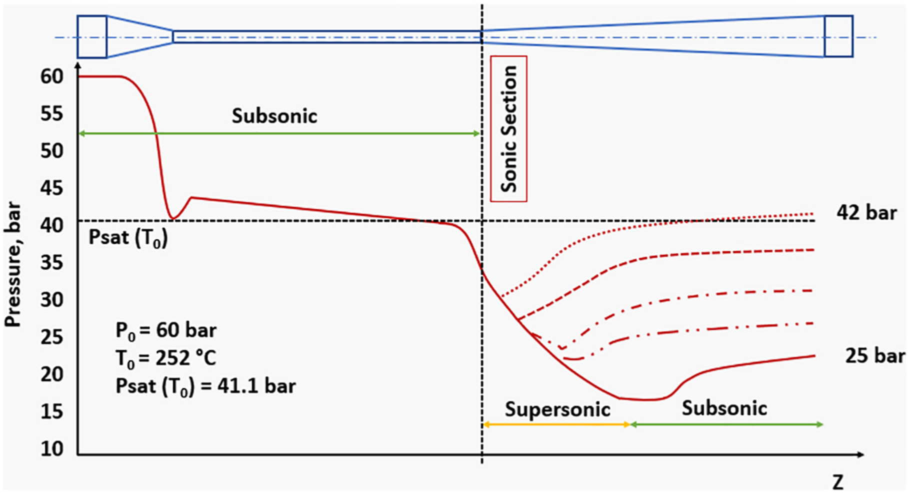

Fig. 1. Example of TPCF as measured in the Super Moby-Dick experiment.

near the critical section (dP/dz, in some case up to 10 MPa/mm or 10^{10} Pa/m) and by fast vaporization called also flashing (vaporization relaxation time scale being of the order of 1 ms). As shown in Fig. 1 the criticality is demonstrated by the flowrate being independent on the downstream pressure (D'Auria et al., 2017). Also the pressure profile P (z) is the same for all 5 tests at least up to the critical section since the information on the downstream pressure cannot travel upstream this sonic section. One also observes a pressure decrease followed by a continuous pressure recovery in the divergent, which is associated to a supersonic region and a return to subsonic flow.

The difficulties for modelling such flow situations in 0-D or even in 1-D approaches are:

- The flashing delay is controlled by nucleation which depends on parameters which are usually not well known such as: presence of impurities, micro-bubbles with non-condensable gases, wall cavities acting as nucleation sites, density of nuclei for vaporization, etc;
- Absence of a clear unique and reliable expression of the sonic velocity in a multi-fluid system;
- Lack of information on flow regime and on bubble and drop sizes in high speed flow, which are necessary for deriving physically based flashing and interfacial friction relaxation times in metastable liquid;
- Possible existence of moving of critical section or even possible multiple-critical sections in some cases;
- The influence of flow detachment in abrupt area change on nucleation with a possible cavitation zone;
- The influence of 2-D and 3-D phenomena which cannot be easily taken into account in 0-D or 1-D modelling of choked flow.

Basically, there is a lack of precise information about those effects and the interaction among them, which unavoidably affects the predictive capability to an extent that can be known only by comparison to experimental data.

3. The FONESYS Network

3.1. Founding motivation and main objectives of the network

The main motivation for starting the FONESYS project was to bring technical evidence addressing possible disbelief in SYS-TH codes or criticism against them (see for instance the disbelief in codes as from the Zuber or Wulff papers, Zuber, 2001 and Wulff, 2011) and to strengthen the current technology. The effort for SYS-TH codes development is decreasing and may even stop but its application cannot be avoided even if new tools such as Computational Fluid Dynamics (CFD) or Computational Multi Fluid Dynamics (CMFD) codes appeared at the beginning of the 2000s.

The motivation is to bring arguments against over-criticism and at the same time to improve the codes simulation capabilities, and to clearly identify the future roles of SYS-TH codes and CFD codes in reactor thermal-hydraulic studies.

Another principal motivation was to form a network of experts and code developers that can challenge future problems that can possibly rise during the development and use of the SYS-TH codes.

FONESYS objectives are to keep the code limitations 'under control' and to provide guidance for code improvements. Strategy and activities were planned and decided within a framework consistent with the standards of international institutions. The main objectives are summarized and listed below:

- To create a common ground for discussing envisaged improvements in various areas of System Thermal-Hydraulics, promoting a cooperation aimed at the improvement of the SYS-TH Codes and their application in the licensing process and safety analysis;
- To identify areas of improvement and share experience on the graphical user interface, SYS-TH code coupling with other numerical tools, such as 3-D neutron kinetics, fuel pin mechanics, CFD, CMFD, etc.;
- To share the experience on code inadequacies and cooperate in identifying experiments and/or code-to-code benchmarks for resolving the deficiencies;
- To share the user experience on code scalability, applicability, and uncertainty studies;
- To establish the acceptable and recognized procedures and thresholds for Verification and Validation processes;
- To maintain and improve the user expertise and the documented user guidelines for applying the codes.

3.2. The FONESYS members and reference SYS-TH codes

Currently, nine international organizations are active members of the FONESYS Network, namely Commissariat à l'Énergie Atomique et aux Énergies Alternatives (CEA), Électricité de France (EDF) and Framatome from France, Gruppo di Ricerca Nucleare San Piero a Grado/Università di Pisa (GRSNPG/UNIPI) from Italy, Korea Atomic Energy Research Institute (KAERI) from Korea, State Power Investment Corporation Research Institute (SPICRI) from China, Canadian Nuclear Laboratories (CNL) from Canada, the VTT Technical Research Center of Finland and the Gesellschaft für Anlagen und Reaktorsicherheit (GRS) from Germany. Moreover, the Korea Institute of Nuclear Safety (KINS) is an observer. The host institution is GRNSPG/UNIPI and acts as secretariat.

Institutions involved in FONESYS use or are developers of the following SYS-TH codes (in alphabetical order): APROS, ATHLET, CATHARE, CATHENA, COSINE, MARS, RELAP5, SPACE and TRACE.

3.3. *The FONESYS benchmarks*

One of the key topics of FONESYS project is to perform various benchmarks in order to share code experience and to cooperate in resolving code deficiencies.

The benchmark activities within FONESYS can be considered as unique in the sense that they are proposed, agreed and conducted mainly by SYS-TH code developers, thus minimizing the user-effect.

The first benchmark conducted by the FONESYS Members was dedicated to the critical heat flux study. In 2019 a benchmark activity on TPTF (Nakamura, 1996) and the Mantilla test facility (Mantilla, 2008) has been launched to complement the on-going comparative study on the scalability of different closure laws, currently focusing on horizontal stratification models and droplet entrainment models. An insight into the TPCF benchmark, finalized in early 2020, is given in Section 4.

4. The FONESYS TPCF benchmark

In 2015, FONESYS Members decided to launch a benchmark activity on TPCF prediction (Lanfredini and Lutsanych, 2020). Overall, participants from 7 different institutions, using 8 SYS-TH codes have contributed to various exercises of the benchmark. The list of participants and the adopted\developed codes is given in Table 1.

The benchmark consisted in two steps: 1) code-to-code comparison carried out defining ideal blowdown tests; 2) code-to-experiment comparison considering selected Separate Effect Test Facilities (SETF).

4.1. *Code-to-code comparison*

The FONESYS Members decided to revisit the TPCF issue starting by code-to-code comparison of hypothetical discharge of a pressurized vessel V1 into another capacity V2 through horizontal or vertical connection $P1$-$P2$ (Lanfredini and Lutsanych, 2020). V1 and V2 volumes are representative of typical PWR vessel and containment. Initial pressure and temperature in V1 are 100 bar and 585 K respectively. Fig. 2 depicts the schematic of the ideal blowdown test facility in both configurations.

The geometrical characterization of the ideal facility and the initial and boundary conditions were rigorously defined by the host institution and approved by all the members. This approach was agreed to further minimize the user-effect, allowing identify and discuss codes discrepancies in predicting TPCF from the point of view of an international group of code developers. An effort was also done to reduce the impact of “confounding effects”, as the impact of different wall friction models or the impact of different void fraction calculated at V1 outlet section, by suggesting proper modelling strategies.

Table 1
TPCF Benchmark Participants and adopted\developed codes.

Organization	Country	Code
CEA	France	CATHARE2
GRNSPG-UNIPI (not developer)	Italy	RELAP5/MOD3.3 TRACE v5.0
GRS	Germany	ATHLET
KAERI	Rep. of Korea	SPACE
KINS	Rep. of Korea	MARS
SPICRI	P. R. China	COSINE
VTT	Finland	APROS

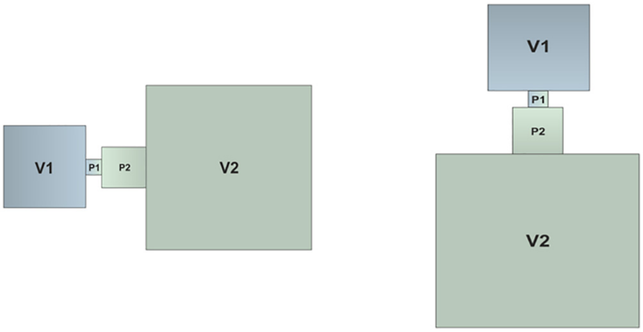

Fig. 2. Ideal blowdown test facility - Horizontal (left) and vertical (right) configuration.

The objectives of the benchmark activity were:

- The prediction of the two–phase choked and multi-choked flow behavior;
- The transition between two-phase critical flow and subsonic flow at the break;
- The supercritical flow downstream of the break;
- The energy transfers at the break;
- The pressurization of the containment;
- The characterization of the thermodynamic evolution process (i.e. the irreversibility).

A detailed discussion of these exercises is out of the scope of this paper. The principal outcome is summarized considering the following example. Some additional conclusions are given in Section 4.3.

The curves in Fig. 3 show the spread of mass flow calculated data in 1980 (left diagram) and 2015 (right diagram): a) results from direct model applications in steady state conditions assuming a stagnation pressure of about 65 bar (see D’Auria and Vigni, 1980) and from the ideal blowdown code calculations in vertical configuration mentioned above are given on the left and the right, respectively; b) quality at the inlet of the exit nozzle and blowdown time constitute the horizontal axis on the left and right, respectively: this may still allow the derivation of the spread in 1980 and in 2015; c) arbitrary normalization of vertical and horizontal axis was selected; d) the parameters to distinguish various curves on the left and the right are the models referenced in literature and the adopted system thermal-hydraulic codes respectively.

Assuming comparable data in both diagrams (i.e. evolution of the non-dimensional time during the transient, right diagram, is considered “equivalent” to the quality variation in the left diagram; unity in the vertical axis has the same value in physical units in both diagrams; still the overall picture shall be considered as qualitative), also avoiding distinguishing results of code calculations from values directly calculated by models, one may conclude what follows:

- The spread in TPCF values decreased (substantially) during four decades;
- The current spread of results, i.e. only looking at the right diagram, remain significant.

4.2. *Code-to-experiment comparison*

After the completion of the code-to-code comparison step, 92 tests conducted with 6 different SETF, both in steady and transient conditions were selected to assess the capability of the codes (Lanfredini and Lutsanych, 2020). Information about the selected experiments are given in Table 2.

Concerning the steady tests, two “long nozzles” having different

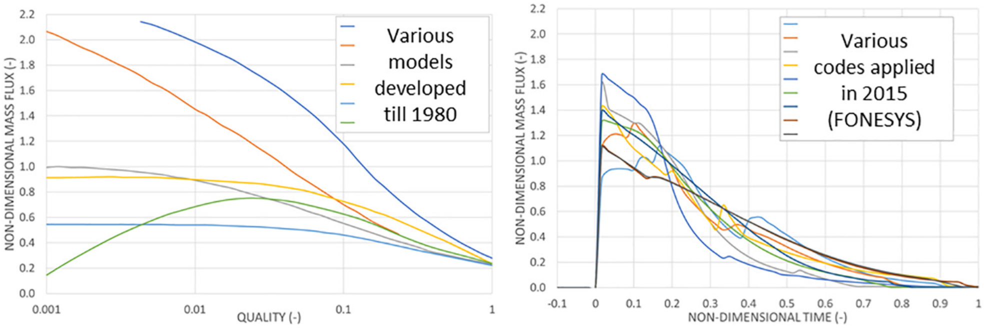

Fig. 3. Spread of TPCF data from models in 1980 and from SYS-TH code application in 2015.

Length-over-Diameter ratio (L/D) and a Venturi nozzle have been considered. Moreover, the experiments performed by the Université Catholique de Louvain (UCL) allow assessing the capability of SYS-TH codes to predict double choked flow conditions.

A large pressure range ranging from 2 bar up to 120 bar was investigated for stagnation equilibrium quality range $-8.5\% < x_0 < 0\%$. The selected Sozzi-Sutherland experiments enlarge the subcooling range down to about $x_0 = -15\%$ keeping the stagnation pressure at about 70 bar.

Relative critical mass flux error calculated applying the codes to the selected Super Moby-Dick (SMD), Sozzi-Sutherland and Brookhaven National Laboratory (BNL) experiments as a function of stagnation inlet equilibrium quality is depicted in Fig. 4. Colors identify the results obtained with different codes, or with codes applied selecting different TPCF models when more than one model is available. The following appear:

- Maximum absolute relative elative error is about 40% close to saturated upstream conditions;
- Even at high subcooling TPCF prediction may be affected by an error of about 20%.

The situation is expected to be even worse in transient condition because many closure laws of the codes were established from analysis of quasi-steady tests and very often also quasi-established flows. Codes can capture the qualitative behavior in fast transients as a blowdown rather well but are never very precise quantitatively.

It was clearly observed that different codes with the same TPCF model may give very different results, especially for the low subcooled tests. Moreover, sensitivity analyses show that different meshing approach may result in a critical flow absolute relative error increase up to about 10%. Furthermore, lack of detailed information about the facilities (and “data preservation issues” in general) may constitute a significative source of error; sensitivity studies on wall roughness for Sozzi-Sutherland experiments (not available in Sozzi and Sutherland, 1975) showed differences in critical flow absolute relative error up to about 10%.

An example of calculated pressure, void fraction, and velocities spatial trends for one of the Sozzi-Sutherland experiment in low subcooled conditions is depicted in Fig. 5. Non-dimensional profiles are plotted versus distance from test section inlet. The pressure is made dimensionless with respect to its value at test section inlet (i.e. the experimental value adopted to set boundary conditions), whereas the liquid and the steam velocities are made dimensionless with respect to their maximum calculated values. The plots show that:

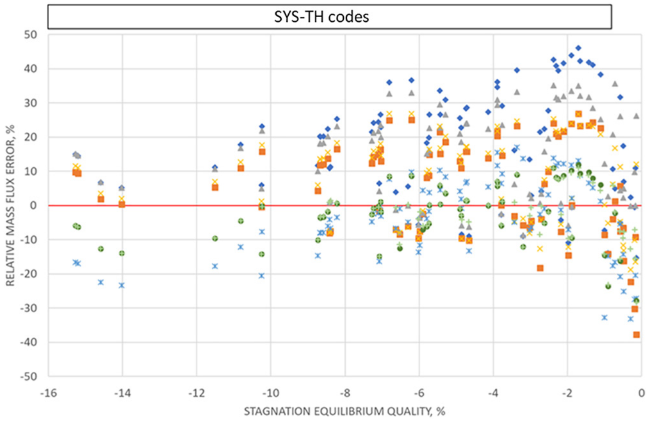

Fig. 4. Relative critical mass flux error vs stagnation equilibrium quality – SMD, Sozzi-Sutherland, BNL tests.

- Pressure ratio (critical pressure to stagnation pressure ratio) ranges from 0.3 to 0.85;
- Void fraction at the critical section ranges from 0.1 to 0.9;
- Non-dimensional liquid velocity at the critical section ranges from 0.15 to 1;
- Non-dimensional steam velocity at the critical section ranges from 0.1 to 1.

Lastly, Fig. 6 depicts the comparison of calculated pressure profiles versus the experimental values measured for one of the UCL experiment considered for the purpose of this benchmark. The peculiarity of UCL tests is that they were designed to obtain the occurrence of two choked sections, one at the middle of the test section and one at the outlet. The selected test is characterized by a stagnation equilibrium quality $x_0 = -0.4\%$. The absolute relative mass flux error, controlled by the capability of the codes in predicting the behavior of the upstream

Table 2
Test selected for Code-to-Experiment comparison.

Facility/Test	Type	Num. of tests	Note
Super CANON (Riegel, 1978)	Transient	1	–
Edwards Pipe (Edwards and O’Brien, 1970)	Transient	1	–
UCL Experiment (Attou et al., 2000)	Steady	5	double choked flow
Super Moby-Dick (Sekri, 1982)	Steady	23	L/D = 18
Sozzi-Sutherland (Sozzi and Sutherland, 1975)	Steady	49	L/D = 50
Brookhaven National Laboratory (Abuaf et al., 1981)	Steady	13	Venturi nozzle

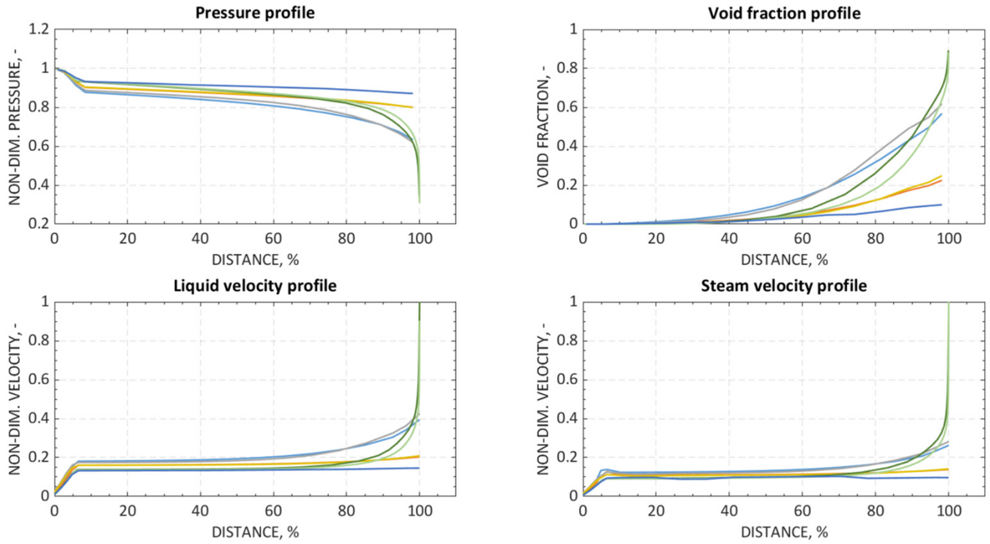

Fig. 5. Calculated pressure void fraction and velocities spatial trend - Selected Sozzi- Sutherland experiment, low subcooling.

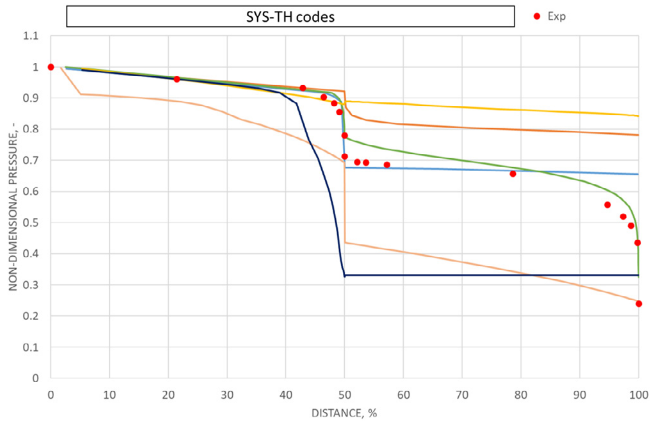

Fig. 6. Calculated pressure spatial trend versus experimental values - Selected UCL test, $x_0 = -0.4\%$.

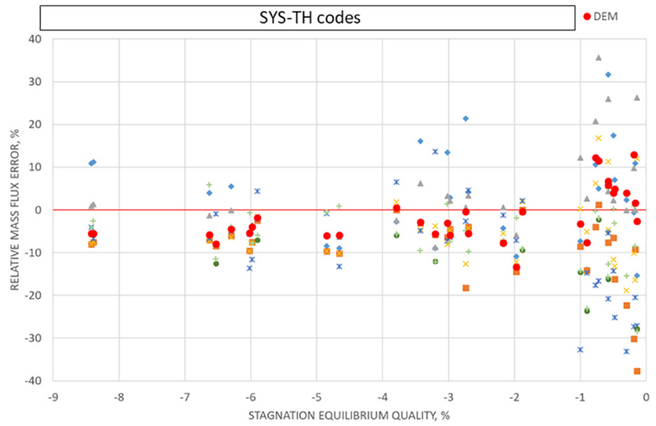

Fig. 7. Relative critical mass flux error vs stagnation equilibrium quality – SYS-TH codes vs DEM comparison, BNL and SMD tests.

choked section, ranges between 6% and 25%.

It clearly appears that the accuracy of calculated profiles is worse downstream the first sonic section. The spread of calculated results is about 50%. This example shows that the predictability of multiple choked-flow behavior constitutes an additional challenge for SYS-TH codes.

FONESYS Members agreed that the lack of knowledge of nucleation conditions and flow regimes in such high velocity flow is one of the main sources of errors. Different flashing models are one of the bigger contributors to the observed discrepancies.

For this reason, results from SMD and BNL tests were also compared against the predictions of the 1-D Delayed Equilibrium Model (DEM) for critical flow rate in steady state or quasi-steady state conditions developed by UCL (Bartosiewicz et al., 2011; Bartosiewicz and Seynhaeve, 2014; De Lorenzo et al., 2017), not yet implemented in industrial version of SYS-TH codes.

Fig. 7 shows the relative critical mass flux error versus stagnation equilibrium quality calculated adopting SYS-TH codes and DEM for the selected SMD and BNL tests. The application of the DEM model also was performed directly by the developers (De Lorenzo et al., 2017; Seynhaeve, 2017).

Differences between DEM and the SYS-TH codes predictions appear mostly for $x_0 > -1\%$ where the effects of presence of metastable liquid and consequently the flashing models play a key role. In such condition the relaxation equation characterizing the DEM model may be a way to model approximately the liquid to interface heat transfer which controls the flashing.

For the considered tests in low subcooled conditions the maximum absolute relative error of DEM is about 10% whereas SYS-TH codes calculations show a maximum absolute relative error of about 35%. This shows that significative improvements are envisaged from the development and the implementation of better flashing models in SYS-TH codes.

4.3. Key results of the benchmark

A detailed discussion of the benchmark results is not possible in a paper. Major issues affecting SYS-TH codes capability in predicting TPCF identified by FONESYS Members are summarized below (Lanfredini and Lutsanych, 2020).

Transient tests show that the discrepancies between the predicted results are larger at the beginning of tests when the flow is in the single-phase with initiating flashing (e.g. time < 0.1 s) and tends to reduce towards the end of test when the depressurization is controlled by the strong evaporation of the liquid phase. These discrepancies can be explained by:

- Different flashing heat transfer correlations of the codes, which have the highest impact on the evolution of the void fraction, and consequently affecting strongly the critical flow rate;

- Different flashing (nucleation) delays and pressure undershoot correlations of the codes, which determine the inception of net vaporization in flashing flows.

The steady-state benchmark results (i.e. UCL, SMD, Sozzi-Sutherland and BNL tests) show that there is a big discrepancy in the predicted critical mass flow rates with respect to the experiment, especially in presence of significative local effect. Approaching the saturation condition tends to increase significantly the error up to about 40%.

Experiments in nearly saturated conditions are the most challenging from the modeling point of view, posing numerous difficulties and questions in front of the code developers:

- How to express a two-phase sonic velocity which is necessary for 0-D choked flow models?
  - o Using characteristic velocities of the system of equations is clearly not a very good approach since it represents only the sound speed for high frequency pressure waves which are not controlling the critical flow since high frequency waves are damped in two-phase flow. In a 1-D modelling of critical flow the critical flow is reached before reaching the characteristic velocity like in the case illustrated in Fig. 1. This shows that the sound speed which controls the flow blockage is different from and lower than the characteristic velocity.
  - o Using mixture compressibility expressions associated to some oversimplifying assumptions such as the frozen model or the homogeneous equilibrium model or other may provide reasonable predictions in some particular flow conditions but very large errors in other conditions.
- The heat transfer (between liquid and interface) and interfacial friction affect the propagation of the pressure wave. Their impact depends on the flow regime and on the size of bubbles or droplets:
  - o How to predict the nucleation? Nucleation depends on water chemistry, dissolved non-condensable gasses, wall roughness, etc.
  - o How to predict the size of bubbles and droplets?
  - o No existing flow regime map is validated in such high speed flow. One may expect small bubbles in low void fraction range and droplet flow at high quality but what flow regime exists between bubbly flow and droplet flows?
- What is the best way to account for the geometrical effects (e.g. abrupt area change)?

Major limitations identified for the 0-D TPCF models are (Bestion, 2016):

- No reliable two-phase sound speed model is possible;
- using a characteristic velocity for the sound speed is not relevant;
- No simplified momentum and energy balance equation from upstream conditions to critical section is valid in all conditions;
- 3-D geometrical effects not easy to be taken into account (e.g. use of discharge coefficient with possible user-effect).

1-D TPCF models can model thermal and mechanical non-equilibrium and do not need of critical section models. Despite this, 1-D models suffer from the following limitations (Bestion, 2016):

- Lack of information on flow regime, on bubble size and drop size at high velocity;
- Both convection and conduction around bubbles may control flashing, transient conduction is not easy to model particularly when the interface structure is not known;
- 3-D geometrical effect (flow detachment, abrupt area change) not easy to take into account.

Considering the above it appears that compensating errors significantly contribute to get reasonable results with both 0-D and 1-D TPCF models in some favorable cases.

5. Actions for research and development

Notwithstanding the continuous advancements of the SYS-TH codes (e.g. see Fig. 3), the number of difficulties still open in the modelling of TPCF requires further efforts and novel approaches.

To go beyond the current limitations of choked flow models, FONESYS Members identified the following four possible R&D actions:

1. Improving the use of 0-D choked flow models:
   - o Reduce the user effect for applying 0-D models by first understanding why the same model sometimes does not predict the same critical flow in several codes and then by collecting all validation calculations to derive precise recommendations giving precise guidelines for:
     - ■ The mesh size to be used depending on the geometry.
     - ■ The selection of the 0-D model depending on the geometry and on the upstream conditions.
     - ■ The discharge coefficient to be used depending on the geometry and on the upstream conditions.
   - o Estimating the prediction accuracy of every 0-D model depending on the geometry and on the upstream conditions.
2. Improving the 1-D modeling by developing a new stand-alone 1-D choked flow model:
   - o Develop a fully implicit two-fluid solver and implement the closure laws applicable to break choked flow:
     - ■ Use all existing experimental data to:
       - Improve flow regime maps in high speed flow and bubble and droplet size models;
       - Develop a flashing delay model;
       - Implement convective heat transfer and conduction heat transfer coefficients with free parameters to be tuned on the database;
       - Optimize the model parameters to better fit with a large database using a trial and error approach or using more modern machine learning method.
   - o Alternatively to the item above, developers may also implement a two-fluid 6-equation version of the DEM model as it was done in the WAHA code (Bartosiewicz and Seynhaeve, 2014).
   - o Improve predicting capabilities of 1-D modeling of choked flow by developing a physically based treatment of abrupt area change.

   When mature enough, the new stand-alone model can be implemented in SYS-TH codes.
3. Using a 3-D CFD code to investigate 3-D effects in choked flows in view of improving the 0-D and 1-D models.

   On this concern the implementation of the DEM model into NEPTUNE_CFD code (Duponcheel et al., 2015) or other investigation conducted (e.g. Liao and Lukas, 2017a, 2017b) constitute examples of this strategy.

   Furthermore, applications of CMFD within a multiscale approach (also called Multi-Phase Multi-Scale -MPMS- approach) may also improve prediction of 1-D tools, e.g. by help modelling two-phase pressure losses in singular geometries, possibly determining proper discharge coefficients for TPCF models implemented in SYS-TH codes.
4. Defining new meaningful basic experiments.

   The objective is to bring progress in a better understanding of flashing and choked flow. A reflection and discussions between people doing physical modeling and experimentalists could help defining possible new experiments which could bring something new as more detailed information on the flow structure. On this concern, the development of suitable instrumentations and measurement techniques constitutes a big challenge.

Considering this list, joint activities are envisaged within the framework of the FONESYS Network.

6. Conclusions

The TPCF is recognized as a dominant phenomenon in Nuclear Thermal-Hydraulics.

It is clear that predictability of TPCF is not satisfactory nowadays. The present benchmark showed that accuracy (i.e. error against experimental data) in critical mass flow can be bounded by 40% and spread (i.e. only looking at predictions) can be bounded by 70%. However, spread (and eventually errors or indicator of calculation precision) for single local parameters (e.g. void fraction, dP/dt, dP/dz, fluid velocities) at the critical location occur as large as a few 100%.

Design and safety of WCNR is not dramatically challenged or not challenged at all by the result above because of adopted countermeasures (including conservatism in safety analyses) and by considering various break sizes. However, the analysis of many phenomena in Integral Effect Tests (IET) suffers from the big uncertainty in both measured and predicted break flowrate. Improving TPCF prediction accuracy will greatly help in the analysis of IET and may allow improving the prediction of many other flow processes.

The huge research investment focusing on TPCF has not been enough. It is a pity that:

- Those investments cannot be repeated not even in nowadays condition of nuclear technology;
- Currently, no common research project is devoted to increase modelling precision.

However possible ways of improvement and connected actions for further R&D have been established.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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