RELAP/SCDAPSIM/MOD4.0 MODIFICATION FOR TRANSIENT ACCIDENT SCENARIO OF TEST BLANKET MODULES INVOLVING HELIUM FLOWS INTO HEAVY LIQUID METAL

M. Pérez, J. Freixa, E. Mas de les Valls
Thermal-Hydraulics Studies Group GET, Technical University of Catalonia
Av. Diagonal 647, 08028 Barcelona, Spain
marina.perez@upc.edu, jordi.freixa-terradas@upc.edu, elisabet.masdelesvalls@gits.ws

T. Sandeep, V. Chaudhari
Institute for Plasma Research Name of University
Bhat, Gandhinagar 382428, India
ktsandeep27@gmail.com, vilas.ipr@gmail.com

ABSTRACT

The Institute for Plasma Research (IPR), India, is currently involved in the design and development of its Test Blanket Module (TBM) for testing in ITER (International Thermo nuclear Experimental Reactor). The Indian TBM concept is a Lead-Lithium cooled Ceramic Breeder (LLCB), which utilizes lead-lithium eutectic alloy (LLE) as tritium breeder, neutron multiplier and coolant. The first wall facing the plasma is cooled by helium gas.

Thermal hydraulic safety analyses are being carried out with the system code RELAP/SCDAPSIM/MOD4.0 which was initially designed to predict the behaviour of light water reactor systems during normal and accident conditions. The code is being developed as part of the international SCDAP Development and Training Program (SDTP) coordinated by Innovative Systems Software (ISS). The modeling strategy of the RELAP code for the simulation of two-phase flows is based on a single-fluid two-phase approach with a set of momentum, energy and mass equations for each phase. The two phases are liquid-water and gas phase mixture of steam and non-condensable gases. Phase interactions, such as interphase friction and heat transfer, are modelled by closure relations based on experimental/numerical correlations that depend on the flow regime. In cooperation with ISS, the IPR team has implemented LLE liquid phase thermodynamic properties as a working fluid alternative to water and appropriate wall-to-LLE heat transfer correlations. However, in order to analyze some of the postulated off-normal events, there is a need to simulate the mixing of helium and Lead-Lithium fluids In the standard RELAP/SCDAPSIM/MOD4.0 version it is not possible to simulate a mixture of a non-water fluid with a non-condensable. In addition to that, t he available flow regime maps for vertical and horizontal flows in RELAP are specific for steam/water pair, which may not be suitable for LLE/helium pair.

The Technical University of Catalonia is cooperating with IPR to adapt the RELAP/SCDAPSIM/MOD4.0 code to allow the simulation of LLE and he mixture. This paper presents the results of the first step of the project, which includes a state of the art on simulation of liquid metals mixed with non-condensable using system codes, the implementation of the necessary code modifications to allow for a LLE/he mixture and preliminary results using the modified code version for horizontal and vertical configurations.

KEYWORDS
liquid metal, non-condensable gas, system codes, fusion technology

1. INTRODUCTION

Institute for Plasma Research (IPR), Gandhinagar (India) is currently involved in the design and development of its Test Blanket Module (TBM) for testing inthe International Thermo nuclear Experimental Reactor (ITER). ITER will be designed, constructed and operated with a high level of safety as an essential requirement. It is the main goal of ITER to demonstrate the safety and environmental potential of fusion and thereby provide a technically feasible precedence for the safety of future fusion power plants. In this sense, it is necessary to account for the experimental nature of the ITER facility and study the related design and material choices and operational requirements. In order for construction and operation of ITER to be authorized, the requirements of the regulatory authorities in France must be met. In preparation of the regulatory safety files for ITER-TBM, it is essential to select a number of postulated off-normal event sequences that have the potential to lead to hazardous consequences. These events are to be analyzed to demonstrate that these potential consequences are minimized, and kept below the prescribed limits, by physical processes and features of the TBM system and process design. The postulated events need to be analyzed by an internationally recognized and well-validated code like MELCOR or RELAP.

The Indian TBM concept is Lead-Lithium cooled Ceramic Breeder (LLCB), which utilizes lead-lithium eutectic alloy (liquid metal) as tritium breeder, neutron multiplier and coolant. Lead-Lithium is made to flow through rectangular channels made of Reduced Activation Ferritic Martensitic Steel (RAFMS). The plasma facing first wall made of RAFMS is cooled by helium gas. LLCB concept also utilizes ceramic breeder, Li2TiO3 in the form of pebble beds sandwiched between two Lead-Lithium channels (see Figure 1 from [1]).

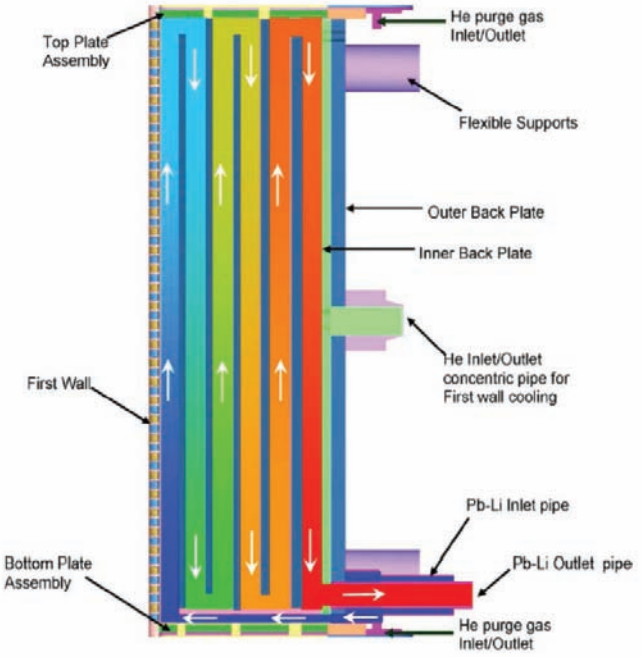

Figure 1 Schematic of LLCB blanket concept [1]

IPR has signed SCDAP Development and Training Program (SDTP) agreement with Innovative Software System (ISS), for joint development of PbLi models and correlations into RELAP/SCDAPSIM/MOD4.0 system code (hereafter referred as to RS/MOD4.0). IPR and ISS have jointly upgraded the code to be suitable for PbLi systems [2, 3]. However, in order to address transient accident scenarios of LLCB TBM involving the interaction of Lead Lithium Eutectic (LLE)-helium, helium-air, LLE-air, helium-Water further modifications of the code are needed. An example of such

scenario is the rupture of a refrigeration tube with He located in the First Wall (see Figure 1) with the result of the injection of high pressure He into the low pressure Pb-Li pipe.

The present paper describes the first stage of the work performed by the Group of Theraml-Hydraulic Studies (GET)from the Technical University of Catalonia (UPC) under an agreement with IPR organization with the main goal of applying RS/MOD4.0 code to simulate steady-state and accident scenarios of LLCB TBM. The work has been divided into two main steps as described in Section 2. As of today, Step 1 of the project has been successfully accomplished and its description and results are summarized in this paper. Step 2 of the project is currently ongoing and its results will be presented in a future paper.

2. PROJECT DESCRIPTION

The main goal of the present work is to modify the RS/MOD4.0 code to be capable of simulating off-normal transient situations in the LLCB TBS [4] involving the mixture of LLE and non-condensable gases. The project has been organized into two main steps. The first step has been completed and consisted in the modification of the RS/MOD4.0 code to allow for the simulation of LLE/non-condensable gas mixtures. Step 2 is ongoing and is focused on the implementation of dedicated flow regime maps for the LLE/non-condensable gas mixture:

2.1 Step 1 – Simulation of an LLE and He mixture

The RS/MOD4.0 hydrodynamic model (see Ref.[5], Volume I) is a one-dimensional, transient, two-fluid model for flow of a two-phase steam/water mixture that can contain non-condensable components in the steam phase and/or a soluble component in the water phase. The basic differential equations are a system of 6 conservation equations: mass, energy and momentum for the liquid and the vapour phase of water. To include the non-condensable component in the gas phase, the following assumptions are considered:

- The non-condensable gas velocity is the same as the vapour water velocity.
- The non-condensable gas temperature is the same as the vapour water temperature.

The general approach for inclusion of the non-condensable component consists of assuming that all properties of the gas phase are mixture properties of the steam/non-condensable gas mixture. The two mass continuity equations for liquid and vapour are unchanged and an additional mass conservation equation for the total non-condensable component is added.

The standard RS/MOD4.0 version of the code can simulate systems with other fluids than water. However, it cannot simulate a mixture of a new fluid with any available RS/MOD4.0 non-condensable gas. The goal of Step 1 is to modify the RS/MOD4.0 code to simulate a mixture of LLE and dry helium.

This step was subdivided in the following tasks which are presented in this paper:

- State of the art on system codes and liquid metals and non-condensable gas mixture simulations (Section 3).
- Modification of the RS/MOD4.0 code to allow for an LLE and He mixture simulation (Section 4).
- Code testing of RS/MOD4.0 modified version (Section 5).

2.2 Step 2 – Implementation of preliminary flow regime maps for the two-phase two-component mixture

The standard RS/MOD4.0 version is only prepared for running single phase with other fluids than water: it includes thermodynamic properties of new fluids, and, in some cases like for LLE, wall-to-fluid heat transfer correlations [6]; however new fluids require specific correlations and flow regime maps [7].

The modeling strategy of the RS/MOD4.0 code for the simulation of two-phase flows is based on a two-fluid approach, where each phase is simulated with its own momentum equation. Phase interactions, such as interphase friction and heat transfer, are modelled by closure relations based on experimental/numerical correlations that depend on the flow regime. Hence, the flow regime must be known as a function of main variables such as phase fraction and mixture mass flux, among other . This is carried out by the use of flow regime maps.

In the standard version of RS/MOD4.0, the available correlations are specific for the steam/water pair. Thus, the LLE/He pair correlations available in the literature must be implemented. Similarly, in the current version of RS/MOD4.0, the available flow regime maps for vertical and horizontal flows are specific for the steam/water pair. However, flow patterns might occur under different flow conditions for the LLE/helium pair. Thus, the implementation of a LLE/helium specific flow regime map in RS/MOD4.0 is required.

At present, no flow regime map specific for LLE/helium can be found in the literature and, hence, the development of such a map, either based on experiments or numerical simulations, must be achieved and validated.

The goal of step 2 is to develop a preliminary flow regime map for LLE and helium two-phase flow, based on numerical simulations with OpenFOAM CFD toolkit. As a first approach, the incompressible VOF method has been chosen to reproduce the two-fluid flow in vertical and horizontal pipes. This method, when applied with the right mesh resolution and boundary conditions has proved to provide enough accuracy to grossly capture each flow regime [7]. However, a more advanced two-fluid model, with the adequate closure relations, is expected to be required to accurately capture the exact transition between flow regimes.

The on-going work for this step consists of two phases: (1) simulation of vertical and horizontal pipes at different flow conditions, i.e. mixture velocity and phase fraction, and analysis of results; (2) adaptation of the results into RS/MOD4.0 flow diagram structure.

Step 2 is an on-going work and the corresponding results will be presented in the future. Thus, the validation shown in Section 4 used the steam/water pair flow diagrams and correlations.

3. STATE OF THE ART OF SYSTEM CODES

A review of the state-of-the-art of the capabilities of the different system codes available in the scientific community to simulate liquid-metal (LM) and non-condensable gas mixtures has been performed. Table I lists the codes that have been identified capable of the simulation of liquid metal on the system behaviour level. Most of the analyzed system codes were initially developed to simulate liquid water and steam interactions for light water reactors and are now being modified to be capable of simulating liquid metal systems as well.

All codes analyzed have been tested for the simulation of single-liquid single-phase systems with success. For sodium fluids, there is a rather long experience in the simulation of single-liquid two-phase systems. In this direction, the results obtained with TRACE and CATHARE are remarkable [8, 9]. However, little experience have been found in the simulation of two-fluid two-phase systems (LM/non-condensable gas mixture), especially when the two fluids interact. A more detailed description of the state-of-the-art review is provided in the internal report [10]. For the purpose of the

present work, the most important conclusion of the study is that only two codes are capable of simulating LM and non-condensable gas mixtures: SIMMER III and RELAP5 MOD3.3 ENEA. In particular Suzuki et al. [11] reported experimental and simulation results of N_2 jet flows into a Lead-Bismuth molten pool with SIMMER III. Additionally Vivaldi et al. published two-fluid numerical simulations with SIMMER III for underexpanded CO_2 gas jets into liquid-Sodium [12]. On the other hand, in ref. [13] it was stated that the capability of RELAP5 MOD3.3 ENEA to simulate a two component (liquid Lead-Bismuth and gas) was assessed using the CIRCE gas-lifting tests (Brasimore Italy), these results have been recently published [14]. In [15] it is stated that ATHLET includes now the possibility of simulating LM/non-cond. gas mixtures, although at the time of writing of this paper, we could not find any publication that showed this new feature of ATHLET. SAA/SASSYS-1 has a module (Sodium voiding model) [16] that allows the simulation of Sodium in combination with released fission product non condensable gases, however, this model is intended to simulate the generation and collapse of bubbles and is not suitable for the intended analysis in the present project.

Table I. Capabilities of system codes in the simulation of multi-fluid multi-phase systems

System Code	LM	LM/non-cond.	LM (two phase)	LM/water
RELAP5 3D	Yes	No	No	No
TRACE	Yes	No	Yes (sodium)	No
RELAP5/MOD3.3 ENEA	Yes	Yes	No	Stated yes
SIMMER III	Yes	Yes	No	Yes
SAS4A/SASSYS-1	Yes	No	Yes (Sodium)	No
CATHARE	Yes (Sodium)	No	Yes (Sodium)	No
NETFLOW++	Yes	No	No	No
ATHLET	Yes	stated yes	No	No
MELCOR	Yes	No	No	No
RS/MOD4	Yes	Yes (in development)	No	No

4. MODIFIED RS/MOD4.0 CODE VERSION

The RELAP/SCDAPSIM/MOD4.0 [17] code is being developed as part of the international SCDAP Development Training Program (SDTP), a cooperative program that includes more than 90 organizations in 30 countries [18]. Innovative Systems Software (ISS) administers the program and is responsible for the configuration control and distribution of the RELAP/SCDAPSIM system thermal hydraulic code version[19].
The current status of the standard code version is described in ref.[20] including the latest features added to RS/MOD4.0 which are the addition of (a) an uncertainty analysis package developed jointly by UPC and ISS (see ref.[21]) (b) alternative working fluids, (c) additional advanced numerical solution techniques, (d) a standardized interface for a user supplied 3D reactor kinetics package (NIRK3D), and (e) the advanced graphical user interfaces; an overview of the validation and verification of the code; and examples of some of the current applications of MOD4.0 including applications to thermo-solar systems, Generation III+/IV reactors, and fusion technology (ITER).

The standard RS/MOD4.0 code capabilities include the mixture of water with non-condensable gas. The nature of this phenomenon implies that some water vapour is mixed with the non-condensable gas. For the purpose of simulating a mixture of LLE and non-condensable gas, there is the need to modify RS/MOD4.0 coding in order to avoid the generation of LLE vapour when the non-condensable gas appears.

The main modification consisted in the computation of the gas phase properties without making use of the vapour properties of the main fluid. The saturation temperature of LLE will only appear in the results when there is no gas phase, just like it happens with the standard version of RS/MOD4.0 code.

The resulting coding allows a mixture of dry non-condensable gas, i.e. non-condensable gas alone without vapour from the main fluid, and the liquid phase of the main fluid keeping the interphase energy transfer between the two fluids but cancelling the mass transfer between the two phases (between the two fluids).

The approach followed takes advantage of the available non-condensable gas properties, so that any previously available non-condensable gas can be selected in addition to LLE fluid.

5. CODE TESTING

In order to verify the consistency of the modifications described in Step 1 of the previous Section, the nodalization shown in Figure 2 has been built. This is a test section pipe of ten cells of 0.1 m each and a cross section area of 0.1 m^2. Liquid metal is injected at the inlet and a pressure boundary condition is imposed at the exit. Four different exercises have been performed: a vertical set-up, a horizontal set-up, a horizontal set-up with pressurizer and a vertical set-up with a break valve.

The BIC conditions are chosen from the reference design data for the FW helium cooling system and the LLE ducts, provided by IPR [1].

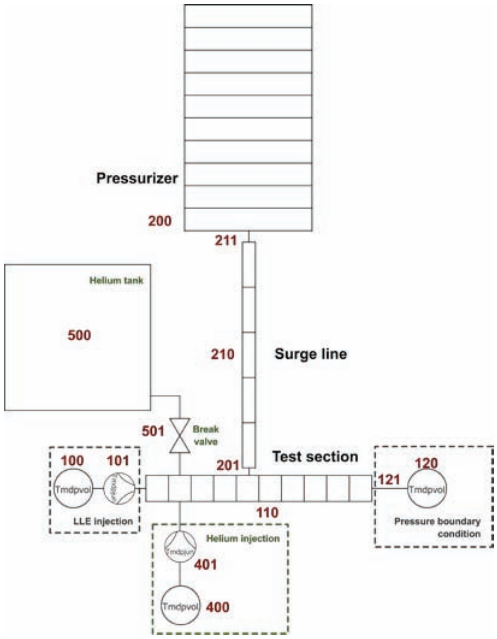

Figure 2 Nodalization scheme for the verification calculations

5.1. Vertical Set-Up

The nodalization of this exercise is similar to the one in Figure 2, where the pressurizer and surge line have been removed and the orientation of the test section (pipe 110) has been set to vertical. The break valve remained closed throughout the calculation. A mass flow of 12.5 kg/s of LLE at 623 K is injected at the bottom. Helium gas at 573 K is injected at the second cell of the test section. The injection of helium starts 10 seconds after the start of the calculation and in 5 seconds the mass-flow is gradually increased to 0.1 kg/s. The pressure of the system is defined at the outlet and is 1.2 MPa.

It is possible to calculate the resulting temperature in the case the two fluids mix perfectly by using the following approximation:

$$T_{mix} = \frac{(\dot{m}C_pT)_{LLE}+(\dot{m}C_pT)_{He}}{(\dot{m}C_p)_{LLE}+(\dot{m}C_p)_{He}} \qquad (1)$$

For the conditions of the vertical and horizontal set up, T_{mix} is 614 K considering the C_p for helium and LLE coded in RELAP5. In Fig. 4, one can see that this is actually the temperature both fluids are tending to at the end of the test section.

Results obtained with the modified RS/MOD4.0 code are shown in Figure 3 and Figure 4. For computational cells filled with only LLE, the code sets the gas properties to the saturation values of LLE as for a regular water system run, and therefore these values have no physical meaning. Once the liquid void fraction starts to decrease (gas appears at the cell) the gas temperature is properly calculated using built-in He properties. The non-condensable gas quality changes abruptly from 0 to 1.0 as soon as some helium appears, i.e. dry non-condensable gas conditions are established.

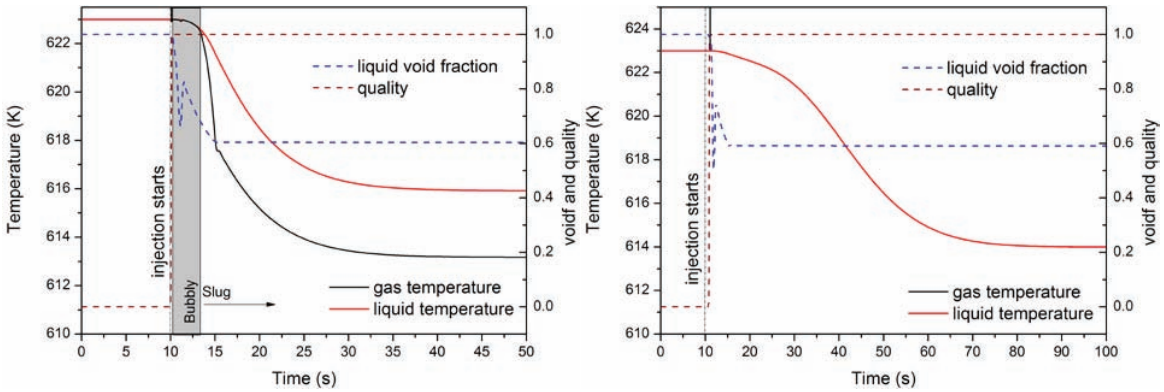

Figure 3 Fluid temperatures, quality and liquid void fraction for the vertical set-up at the injection point (left) and at the test section exit (right)

The left graph of Figure 3 shows the evolution of the main parameters in cell 3, close to the helium injection. Even though the gas enters the test section at a temperature of 573 K, due to the small quantity of helium in the cell, the gas and liquid instantaneously reach thermal equilibrium at a temperature close to LLE injection value. This temperature decreases with the increase of helium injection between 10 and 15 seconds. At 12 seconds the proportion of gas has increased enough so that a transition in the flow regime map from bubbly to slug flow takes place. At this moment the two fluids are no longer in thermal equilibrium and the gas temperature slowly plunges to 613 K while the LLE levels off at 616 K. This is because the heat transfer between the two phases decreses when we are in slug flow.

The right graph of Figure 3 shows the evolution of the main parameters at the test section exit. This part is far enough of the helium injection point that the two fluids are in thermal equilibrium during the whole calculation. When the He injection arrives to the test end section both fluids are in equilibrium at a temperature close to the LLE injection temperature. As time advances, both temperatures plunge to 614 K which is the expected temperature of the perfect mixing of the two injected fluids.

In the left graph of Figure 4, the profile temperatures across the test section of the liquid and gas phases are shown. The time is the end of the calculation when all main parameters have stabilized. One can observe that there is thermal non-equilibrium conditions at the bottom of the test section and both temperatures equalize as we measure them upwards. This guarantees that heat transfer between both phases takes place. Both temperatures tend to 614 K as we approach the test section exit, this value is in accordance to Eq. 1.

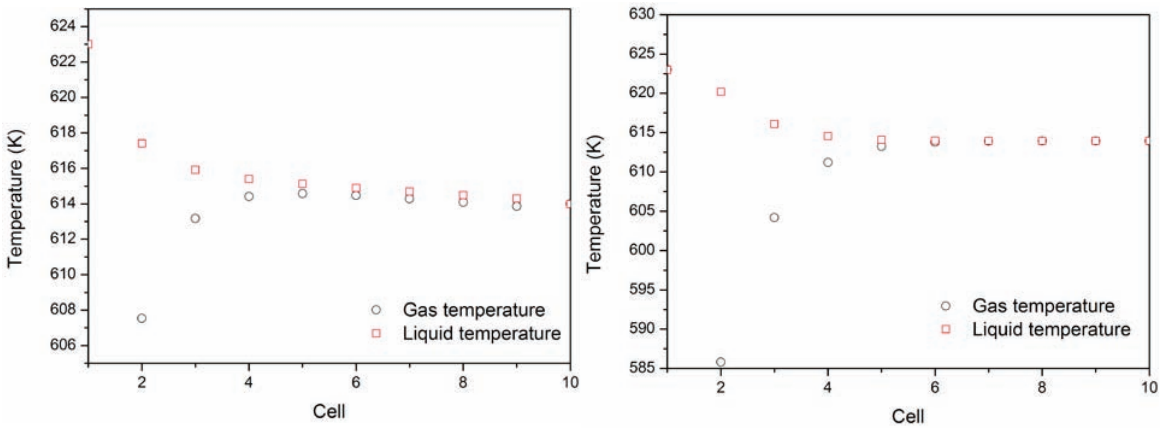

Figure 4 Gas and liquid temperature profiles across the test section for the vertical set-up (left) and the horizontal set-up (right)

5.2. Horizontal Set-Up

The boundary conditions of this exercise are the same as in the previous exercise except that the orientation of the test section is now horizontal. Results are shown in Figure 4 and Figure 5. The change in quality and gas temperature is consistent with the vertical set-up, however the results observed are quite different. The left graph in Figure 5 shows the evolution of the main parameters in cell 3, close to the helium injection. With the horizontal set-up, the temperature of the gas phase changes much slowly. This is a consequence of the horizontally stratified flow regime taking place in this configuration which hinders the interphase heat transfer. Actually during few seconds the gas temperature remains around 573 K. With time the temperature stabilizes around 604 K while the LLE levels off at 616 K.

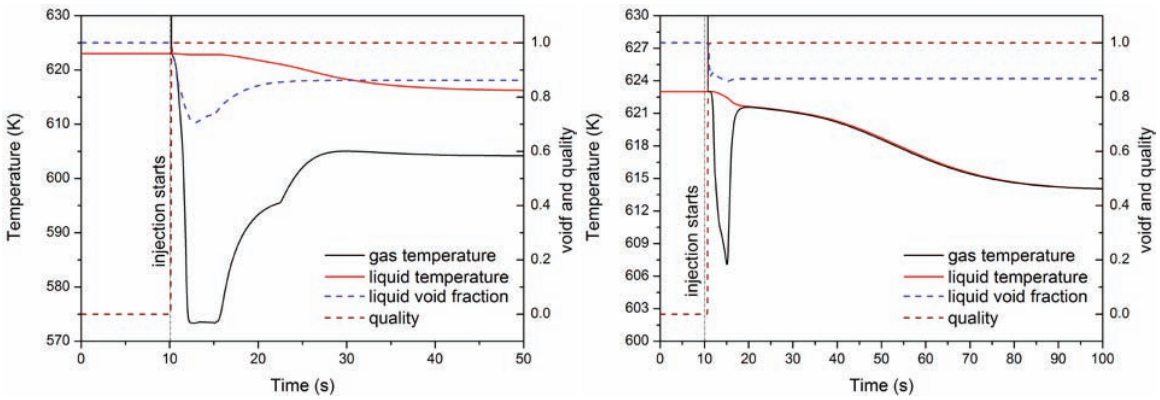

Figure 5 Fluid temperatures, quality and liquid void fraction for the horizontal set-up at the injection point (left) and at the test section exit (right)

At the exit of the test section (right graph of Figure 5), the initial behaviour is similar as in cell 3 but at the end of the calculation the helium and the LLE are almost in thermal equilibrium. Figure 4 (right) shows the profile temperatures of the liquid and gas phases across the test section. For the horizontal set-up it takes a bit longer to reach thermal equilibrium between the two fluids than in the vertical set-up, this is due to the horizontally stratified flow regime which translates in a reduced interphase area. Both temperatures tend to 614 K as we approach the test section exit, this value is in accordance to Eq. 1.

5.3. Horizontal Set-Up with Pressurizer

In this exercise, a pressurizer (PZR) and the corresponding surge line (pipe 210) have been added to the horizontal set-up. The pressurizer has 10 cells of 0.1 m each and is filled up to the half with LLE, the remaining top part is filled with helium gas at 540 K. The surge line (pipe 210) connects the test section (cell 5) with the bottom of the PZR (pipe 200). In junction 201, which connects the test section and the surge line, the pull-through model is activated for upward oriented connections.

The conditions of the injections of LLE and helium are the same as in the previous section. The only difference is that the injection of helium starts after 100 seconds to ensure that the PZR level is stable.

Figure 6 and Figure 7 display the most relevant results for the pressurizer case. The behaviour of the PZR is relevant in this scenario. As can be observed in the left graph of Figure 6, the PZR level decreases with a constant rate until the pressurizer is only filled with helium. We observe that some bubbles flow from the test section into the PZR and flow upwards to the helium bubble formed on the top part of the PZR. Figure 6 (right) shows the liquid void fraction and the quality at the bottom of the pressurizer along with the gas and liquid velocities at the PZR entrance. Once the helium injection starts, the void fraction at the bottom of the pressurizer stabilizes at a value below 1.0 and the quality remains at 1.0, this can be understood as a small flow of bubbles flowing upwards. The gas velocity is positive at this point and the liquid velocity is slightly negative. Therefore there is a constant flow of bubbles to the pressurizer which is compensated by liquid entering the test section.

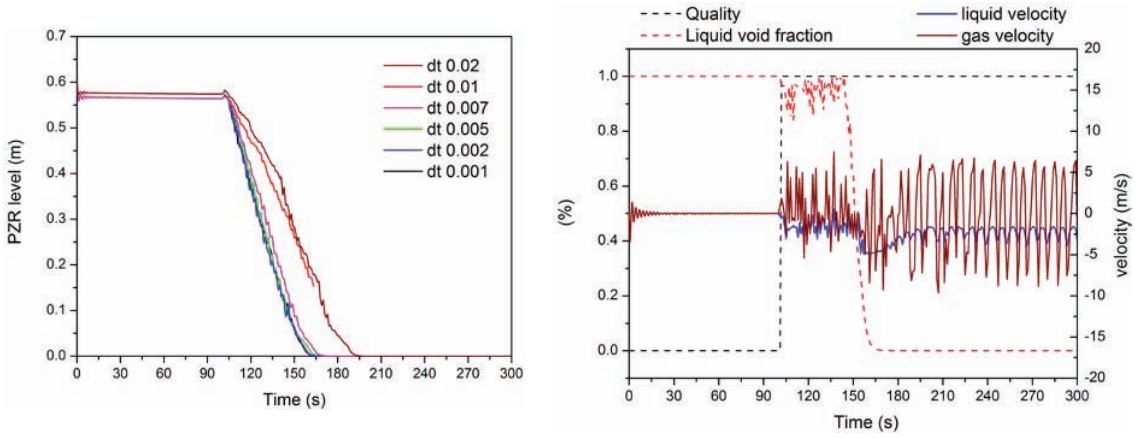

Figure 6 Horizontal set-up including a PZR. PZR collapsed water level (left). Quality and liquid void fraction at the bottom of the PZR

Figure 7 displays the profiles for the liquid void fraction and fluid temperatures across the PZR at time=90s (steady state) and time=120s. During steady state, LLE remains at the bottom until mid-cell 6 and the rest is filled with He. Both temperatures remain close to their initial values. There is some heat transfer in cells 6 and 7. At 120 seconds, the LLE in the pressurizer is flowing into the system. At the bottom of the PZR there is only a small portion of bubbles and the top of the pressurizer is filled with helium. At the same time the temperature of both fluids is in thermal equilibrium until only helium remains. The helium bubble at the top of the PZR becomes thermally stratified from 623 K at the bottom to 547 K at the top.

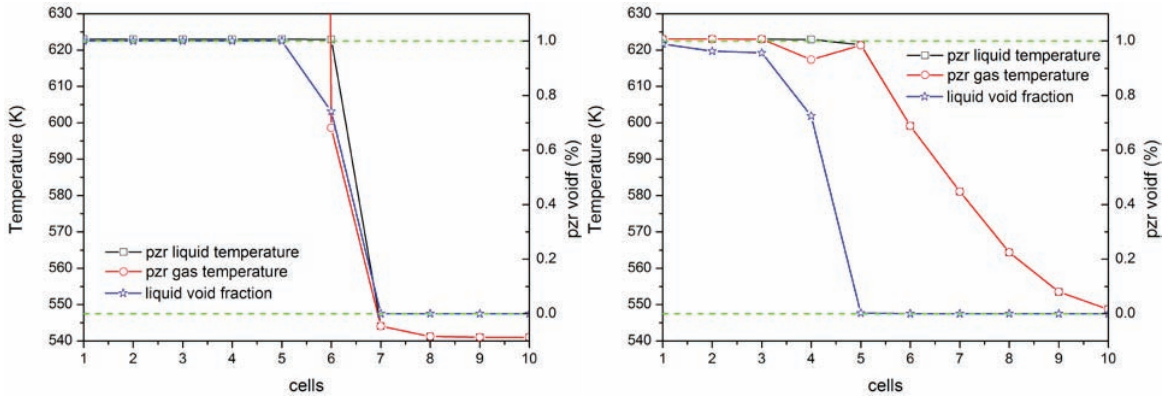

Figure 7 Profiles for liquid void fraction and fluid temperatures across the PZR for the horizontal set-up including a PZR at time=90s (left) and time=120s (right)

A sensitivity on the effects of time step for this calculation has been performed. It has been observed that the time step had some effect on this set-up (see left graph of Figure 6). In particular, for time steps higher than 0.007 the amount of helium flowing to the PZR was slightly lower, and these cases might crash because of too high time step. Convergence was met for all cases with dt below 0.005 including dt=0.005.

5.4. Break Set-Up

In this exercise, the test section has a vertical configuration. The helium injection is not activated. Again, a mass flow of 12.5 kg/s of LLE at 623 K is injected at the bottom. The pressure of the system is defined at the outlet and is 1.2 MPa. At the second cell of the test section there is a valve connecting to a tank with helium at 573 K and 8 MPa. The tank is modelled with a single volume of 100 m^3. A time dependent volume is not employed here because the purpose of the exercise is to see the depressurization process of the helium tank. If a time dependent volume would be used, both the test section and He tank pressures would be constant, and therefore a constant mass flow would be imposed at the valve and the exercise would be equivalent to the one described in Section 4.1. At 50 seconds the valve fully opens and helium expands from the tank into the test section.

Results obtained with the modified RELAP code are shown in Figure 8 to Figure 10. This calculation is more demanding than the previous ones given the fact that a large delta P appears at the moment when the break is opened. Three calculations are shown in Figure 8 with dtmax 0.002, 0.001 and 0.0005. Differences between the different dtmax are only observed for the liquid temperature close to the break (bottom graph), although the cases 0.002 and 0.001 converge well. The rest of variables show very good convergence. The small bump appearing at around 170 s takes place when the choke conditions at the throat end.. Because the pressure difference between the helium tank and the test section decreases, the velocity at the throat decreases as well. When the velocity is below the speed of sound, the flow at the throat is no longer choked. At this point, the choked flow model is deactivated and a small bump appears in this transition..

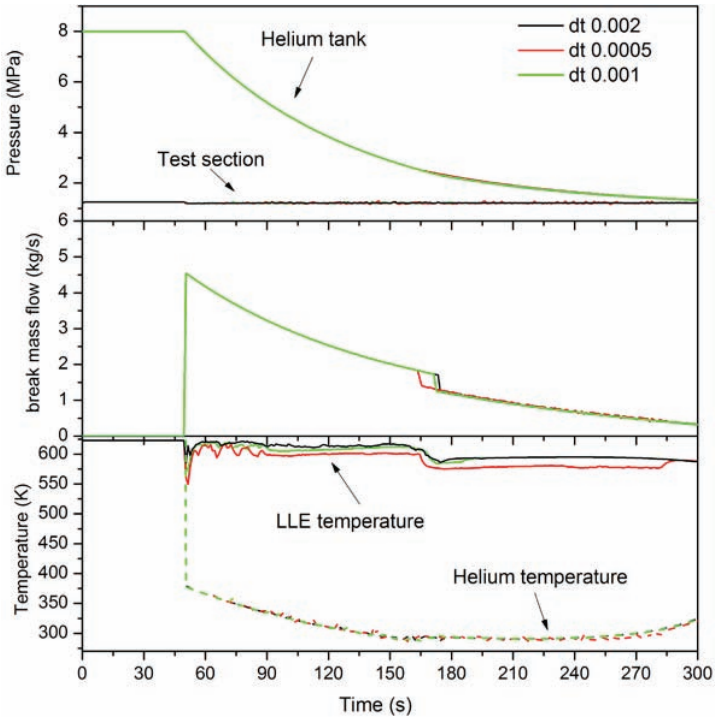

Figure 8 Results for the break set-up with different time steps. Top graph: helium tank and test section pressures. Mid graph: break mass flow. Bottom graph: LLE and He temperatures in the test section, cell 2

Figure 9 shows the evolution of the main parameters in cell 3 and at the exit of the test section (dtmax 0.001). The temperature of the He entering the system decreases quickly due to the sudden depressurization to 1.2 MPa. Temperature keeps decreasing until the gas velocity at the break is below the speed of sound, the choke flow model is not used anymore. This means that there is no longer a thermal expansion at the throat (break valve). Until this point, the gas temperature at the throat was independent of the Test section temperature. In addition, the speed at which the gas is crossing the test section has decreased so that He can absorb more energy from the liquid metal. This is the reason why the gas temperature rise is more noticeable at the exit of the test section.

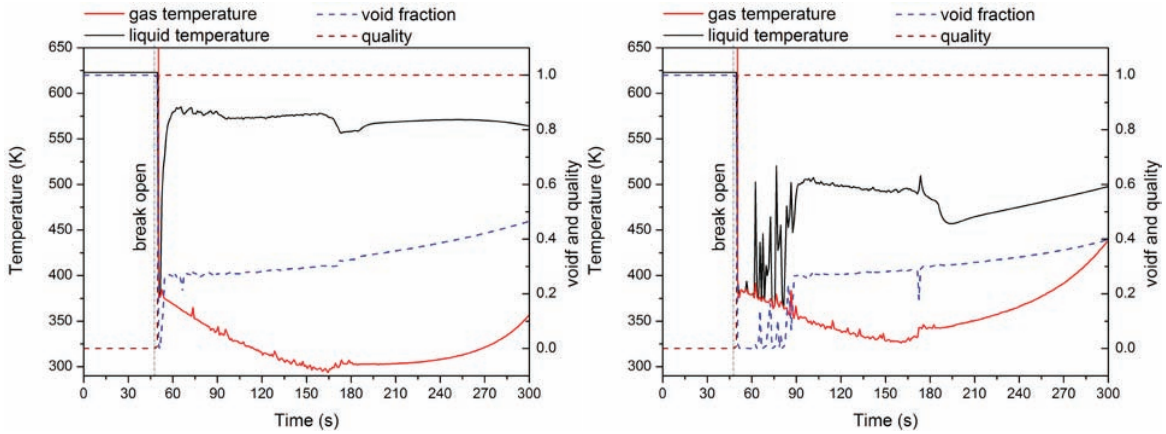

Figure 9 Fluid temperatures, quality and liquid void fraction for the vertical set-up with break at the break connection (left) and at the test section exit (right)

In Figure 10, the profile temperatures of the liquid and gas phases along the test section are shown for three different times of the exercise (100 s, 200 s and 300 s). The He temperature increases as we move upwards in the test section while the LLE temperature decreases. This indicates that there is

effective heat transfer from LLE to He. The slopes are clearly increasing in absolute value as the time advances because the velocity of the gas phase in the test section decreases with time. The increase of the liquid temperature observed in the last cell of the test section is numerical due to the boundary conditions imposed at the test section exit.

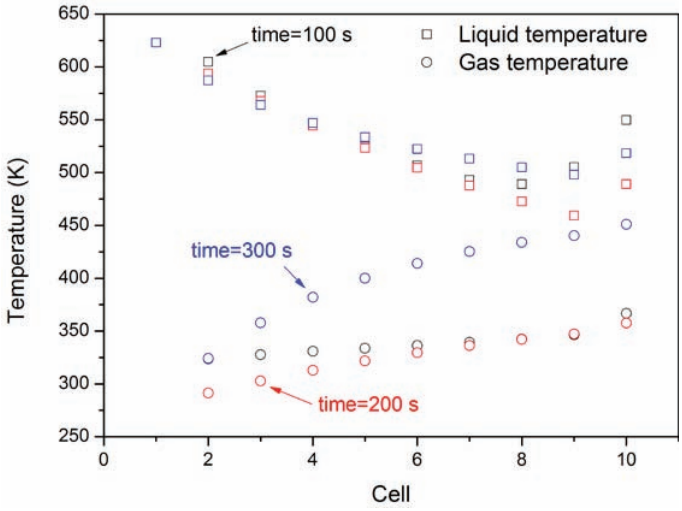

Figure 10 Gas and liquid temperature profiles across the test section for the vertical set-up

6. CONCLUSIONS

The required source code modifications to allow the simulation of a liquid metal and non-condensable mixture have been implemented in RS/MOD4.0. The main advantage of the followed approach is to utilize the built-in data for the available non-condensable gases in a standard RS/MOD4.0 code version.

In order totest the new code version to simulate thermal-hydraulic systems where LLE and He interact, 4 different thermal-hydraulic set-ups have been designed:

- vertical pipe with He injection;
- horizontal pipe with He injection;
- horizontal pipe with He injection and a PZR; and
- vertical pipe connected to an He tank at different pressures.

The results obtained in these exercises show that the new code version is able to handle the mixture of He and LLE in different situations. The following are the main conclusions of the calculations:

- it has been observed that there is heat transfer between the gas and liquid phases and that this heat transfer depends strongly on the flow regime;
- for horizontal set-up the flow regime observed is always horizontally stratified;
- for the vertical set-up the flow regime might be either slug or bubbly;
- time step effects are negligible for steady state calculations;
- for transient calculations such as the PZR and the break set up, time steps below 0.002 are recommended;
- choked flow model works well with the non-condensable gases;

The code testing was designed with reference data from the TBM design, and only a qualitative analysis could be concluded as the specific flow regime maps have not yet been implemented and there are currently no experimental data available for such LLE/helium mixture. IPR is planning on

the design of an experiment facility in the near future. The second step of the work will consist in the derivation of the horizontal and vertical flow regime maps for the LLE/helium mixture on the basis of numerical simulations with OpenFOAM CFD toolkit, their implementation to RS/MOD4.0 code, and testing of the modified code version by using the complete TBS model.

ACKNOWLEDGMENTS

This project has been possible thanks to the SDTP agreement between ISS and UPC to have access to RELAP/SCDAPSIM code versions, including RELAP/SCDAPSIM/MOD4.0.

REFERENCES

1. E.R.Kumar, C.Danani, I. Sandeep, Ch. Chakrapani, N. Ravi Pragas, V. Chaudhari, C. rotti, P.M. Raole, J. Alphonsa and S.P. Desphande, Preliminary design of Indian Test Blanket Module for ITER, *Fusion Engineering and Design* **83** (2008) 1169-1172
2. TBM Division. Functional Requirement Document for the Addition of PbLi (Lead Lithium) Models and Correlation's into RELAP/SCDAPSIM/MOD4.0. Technical report, Institute for Plasma Research, India, 2012.
3. A. Tiwari, B. Allison, J. K. Hohorst, R J Wagner, and C. M. Allison. Insertion of lead lithium eutectic mixture in RELAP / SCDAPSIM Mod 4.0 for Fusion Reactor Systems. *Fusion Engineering and Design*, **Volume 87**(2):156–160 (2012).
4. P. Chaudhuri, E.R. Kumar, A. Sircar, S. Ranjithkumar, V. Chaudhari, C. Danani, B. Yadav, R. Bhattcharyay, V. Mehta, R. Patel, K.N. Vyas, R.K. Singh, M. Sarkar, R. Srivastava, S. Mohari, K. Bhanja, A.K. Suri., "Status and progress of Indian LLCB test blanket systems for ITER" *Nuclear Engineering and Design*, **Vol. 87**, pp. 1009-1013 (2012).
5. "USNRC Relap5/Mod3.3 Code Manual" Volumes I to VIII, 2001, NUREG/CR-5535/Rev1
6. A.K. Trivedi, K.T. Sandeep, C.M. Allison, A. Khanna, V. Chaudhari, E.R. Kumar, P. Munshi, "Incorporation of lithium lead eutectic as a working fluid in Relap5 and preliminary safety assessment of LLCS" *Fusion Engineering and Design*, **Vol. 89** (12), pp. 2956-2963 (2014).
7. E. Mas de les Valls, M. Pérez, J. Freixa, L. Batet, and F. Reventós. Preliminary Lead Lithium Eutectic – Helium Flow Regime Map. Intermediate Report. Technical Report B1-1, UPC-GET, 2014.
8. A. Chenu. Single- and Two-Phase Flow Modeling for Coupled Neutronics/Thermal-Hydraulics Transient Analysis of Advanced Sodium-Cooled Fast Reactors. *PhD thesis*, École Polytechnique Fédérale de Lausanne, 2011.
9. D. Tenchine, D. Pialla, P. Gauthé, and A. Vasile. Natural convection test in Phenix reactor and associated CATHARE calculation. *Nuclear Engineering and Design* , **Volume 253** (2012):23–31, December 2012.
10. J. Freixa, M. Pérez,.E. Mas de les Valls, L. Batet, and F. Reventós. State-of-the-Art of System Codes Capabilities to Simulate Liquid Metal and Non-Condensable Mixture. Technical Report A2-1, UPC-GET, 2014.
11. T. Suzuki, Y. Tobita, and S. Kondo. Analysis of gas-liquid metal two-phase flows using a reactor safety analysis code SIMMER-III. *Nuclear Engineering and Design* , **Volume 220** (2003):207–223.
12. D. Vivaldi, F. Gruy, S. Nicole, and C. Perrais. Experimental Studies and Two-Fluid Numerical Approach for Underexpanded Co2-Gas Jet into Liquid-Sodium. *Proceedings of NURETH-15*, 2013.
13. G. Bandini, P. Meloni, M. Polidori, P. Gaggini, M. Tarantino, and A. Ciampichetti. "Analysis of Integral Circulation and Decay Heat Removal Experiments in the Lead-Bismuth CIRCE Facility with RELAP5 Code", *NURETH-14*, 2011.
14. G. Bandini, M. Polidori, P. Meloni, M. Tarantino, I. Di Piazza, RELAP5 and SIMMER-III code assessment on CIRCE decay heat removal experiments, *Nuclear Engineering and Design*, **Volume 281**, January 2015, Pages 39-50.

15. Gesellschaft für Anlagen und Reaktorsicherheit (GRS) " ATHLET Mod 3.0 Cycle A, Program Updates since Mod 2.2 Cycle A, September 2012.
16. Argonne National Laboratory, "The SAS4A/SASSYS-1 Safety Analysis Code System. Chapter 12: Sodium Voiding Model". ANL/NE-12/4, January 2012
17. C.M. Allison, R.J. Wagner, L.J. Siefken, J.K. Hohorst, "The Development of RELAP/SCDAPSIM/MOD4.0 for Reactor System Analysis and Simulation", *Proceedings of the 7th International Conference on Nuclear Option in countries with Small and Medium Electricity Grids*, Dubrovnik - Croacia, 25-29 May 2008, Paper No. S-05.01.
18. C.M. Allison and J.K. Hohorst, "SDTP - Development Technology for the Nuclear Industry", *Proceedings of ICONE-13*, Beijing - China, 13-20 May 2005, Paper No. 50979.
19. www.relap.com
20. M. Perez, C.M. Allison, R.J. Wagner, V. Martinez, Z. Fu, J.K. Hohorst, A. Abarca, "The development of RELAP/SCDAPSIM/MOD4.0 for advanced fluid systems design analysis", *Proceedings of ICONE-23*, Chiba - Japan, 17-21 May 2015, Paper No. 1623.
21. M. Perez, F. Reventos, R.J. Wagner, C.M. Allison, "Integrated Uncertainty Analysis Package using RELAP/SCDAPSIM/MOD4.0", *Proceedings of NURETH-13*, Kanazawa - Japan, 27 September - 2 October 2009, Paper No. 1252.