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TESTING THE OFFTAKE AND THE CCFL MODELS IN TRACE5. Application to SLOCA scenarios

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Abstract

In the Small Break Loss-Of-Coolant Accident (SBLOCA) scenarios there are important physical phenomena that affect the behaviour of the whole system. The aim of this work is to test some special models of TRACE5 applied to SBLOCA transients in the frame of the OECD/ROSA Project Test 1-2, simulating a small break LOCA in the hot leg. The special models tested have been: the Offtake model for stratified flow in a horizontal pipe and the Counter-Current Flow Limit model (Wallis and Kutateladze options) to reproduce reflux condensation in U-tubes of steam generators.

Introduction

Focus on SBLOCA transients grew up after the Three Mile Island accident. Considered of less importance until that moment, interest on these cases increased because of the special conditions they produce in a situation of High Pressure Injection (HPI) systems failure. During a SBLOCA transient, depressurization is slow enough to delay the Accumulators (ACC) entry for a long time. Actuation of HPI is then necessary in order to maintain the core temperature low enough to avoid core boil-off. Along with the HPI effect, break-size is a variable of interest in the study of SBLOCA. Several literature on this subject can be found [1, 2, 3]. As the break-size is increased, faster primary depressurization is achieved, allowing the primary pressure to fall below the ACC entry set point before a Peak Cladding Temperature excursion.

The purpose of this work is to test the effect of the orientation of the break (upwards/downwards) in the hot leg. With this aim, the thermal hydraulic code TRACE5 has been used to simulate the Large Scale Test Facility (LSTF) [4] in the frame of the OECD/ROSA Project. In order to investigate the effect of the orientation of the break, some special models of TRACE5 have been tested. Some special models involved in this type of transients are the Offtake model and the Counter-Current Flow Limit for reflux condensation model. These special models have been tested in a LOCA in the hot leg for 1% break size.

1. TRACE5 model

TRACE (TRAC/RELAP Advanced Computational Engine), developed by the United States Nuclear Regulatory Commission (USNRC), is an advanced best-estimate reactor systems code for analyzing thermal-hydraulic behaviour in Light Water Reactors. TRACE consolidates the capabilities of the four codes, TRAC-P, TRAC-B, RELAP 5 and RAMONA, into one modernized code. TRACE5 uses two-fluid, two-phase field equations which are based on mass, energy, and momentum conservation for liquid and gas. Heat transfer is considered from the interface to gas and interface to liquid, and surfaces of structures to the fluid.

The LSTF, which reproduces a PWR, has been modelled with 82 hydraulic components (7 BREAKs, 11 FILLs, 24 PIPEs, 2 PUMPs, 1 PRIZER, 22 TEEs, 14 VALVEs and 1 VESSEL). In order to characterize the heat transfer processes, 48 HTSTR (Heat Structure) components (Steam Generator U-tubes, core power, pressurizer heaters and heat losses) have been considered. Fig. 1 shows the nodalization of the model using SNAP (Symbolic Nuclear Analysis Package) [5].

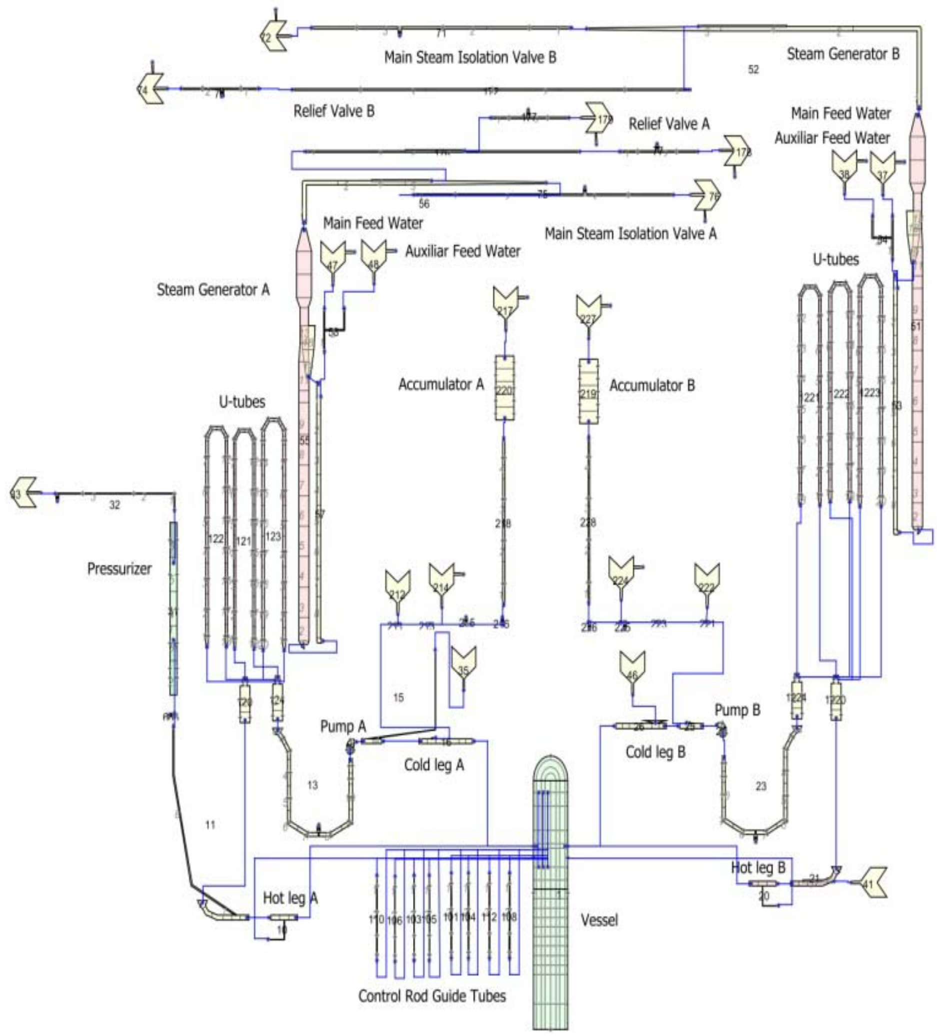


Figure 1 ROSA model with SNAP.

In order to model the Pressure Vessel (PV), a 3D–VESSEL component has been considered. A nodalization consisting of 19 axial levels, 4 radial rings and 10 azimuthal sectors has been selected. Levels 1 and 2 correspond to the lower plenum. Active core is located between levels 3 and 11. Level 12 simulates the upper core plate. Levels 13 to 15 characterize the vessel upper plenum. In level 16, the upper core support plate is located. Finally, upper head is defined between levels 17 to 19. 3D-VESSEL is connected to different 1D components: 8 Control Rod Guide Tubes (CRGT), hot leg A and B (level 15), cold leg A and B (level 14) and a bypass channel (level 15). Control rod guide tubes have been simulated by PIPEs components, connecting levels 13 and 19 and allowing the flow between upper head and upper plenum.

30 heat structure components (HTSTRs) simulate the heater assemblies in the active core. A POWER component manages the power supplied by each HTSTR to the 3D-VESSEL. Heater

elements were distributed into 3 rings: 154 elements in ring 1, 356 in ring 2 and 498 in ring 3 and also characterized by HTSTR components. In both axial and radial direction, peaking factors were considered. The power ratio in the axial direction presents a peaking factor of 1.495. On the other hand, depending on the radial ring, different peaking factors were considered (0.66 in ring 1, 1.51 in ring 2 and 1.0 in ring 3).

Break is simulated with a break nozzle-type in the hot leg without pressurizer. Break nozzle has been simulated using a VALVE component connected to a BREAK component in order to establish the boundary conditions. This BREAK has been modelled following the recommendations of the TRACE5 user's manual [6]. In this case, since the break is simulated to discharge in a big volume space (the storage tank), a dxin=$1.0*10^{-6}$ (cell length) and a volin=$1.0*10^{6}$ (cell volume) has been selected with the purpose of providing a large discharge area. The VALVE is connected to the side-junction of a TEE that belongs to the PWR hot leg without pressurizer.

Regarding the break simulation, it is important to take into account the necessity of activating the Choked flow model in the break when it is expected to appear critical flow conditions. Choked model predicts for a given cell the conditions for which choked flow is expected to occur, providing three different flow regimes models in one: subcooled-liquid, two-phase and single-phase vapour model. This model has been activated in all the cases studied in the paper.

2. Transient Description

In this work, some transients have been simulated with TRACE5 reproducing the main control logic of the Test 1.2 [7] in the frame of the OECD/ROSA Project. Test 1.2 simulates a 1% SBLOCA transient in the hot leg without pressurizer in the Large Scale Test Facility (LSTF). In Table 1 it is listed the main actions considered in the transient.

Table 1 Control logic and of major events in the transient.

Item	Action
Break	Time zero
Generation of scram signal	Primary pressure drops to a determined value
Pressurizer heater off	Generation of scram signal or PZR liquid level below a determined value
Initiation of core power decay curve simulation	Generation of scram signal
Initiation of primary coolant pump coastdown	Generation of scram signal
Turbine trip	Generation of scram signal
Closure of MSIVs	Generation of scram signal
Termination of MFW	Generation of scram signal
Generation SI signal	Determined value of primary pressure
Initiation of AFW	Generation of SI signal
Initiation of SG depressurization as AM action by fully opening relief valves	Core exit temperature reaches 623 K.
Initiation of accumulator system	Determined value of primary pressure

Test 1.2 began with the opening of the break valve in the hot leg without pressurizer. Primary pressure began then to fall because of the coolant escape. When the primary pressure fell below the

scram signal set point, pump coastdown and reactor scram were initiated. Reactor scram was simulated by a power decay curve. Simultaneously, in the secondary-side, Main Steam Isolation Valves (MSIV) were closed along with the Main Feedwater (MFW) termination.

Transient continued with the Safety Injection (SI) signal activation when primary pressure fell below the SI set point. Auxiliary Feedwater (AFW) in secondary-side is actuated. Accumulators were actuated when primary pressure fell to a predetermined pressure, softening the pressure drop. Test 1.2 finished with the closure of the break valve when the primary and secondary pressures were stabilized.

All results shown in this work have been normalized to the steady-state value. It is important to remark that graphics shown in this paper only include TRACE5 results.

3. Break orientation (upward/downward): Offtake model

When the break is produced in the hot and cold leg, stratification phenomena are expected to occur. This stratification characterizes the change of phase in the flow break. The offtake entrainment option is intended to simulate small breaks in large horizontal pipes where the stratified flow in the horizontal pipe affects what is convected out the break.

The Offtake model predicts the offtake flow quality that exits the break based on conditions in the main pipe in a manner similar to that developed for use in the RELAP5/MOD3.3 code [8]. When the entrance plane to the break is submerged, the offtake flow consists mostly of liquid with possibly an entrained gas component. When the entrance plane is above the liquid level, the offtake flow is mostly gas with possibly an entrained liquid component. TRACE calculates an offtake void fraction from flow correlations for the particular offtake geometry being modelled. A first prediction of the offtake void fraction is then sent through one interpolation based on the liquid level, one weighting based on the degree of horizontal stratification and one limit based on the maximum allowable entrainment volume to arrive at the final offtake void fraction.

In order to apply the Offtake model in TRACE, it is necessary to meet three conditions: 1) The side tube of the TEE component is required to be either top, bottom, or centrally located off the main tube. 2) The angle from the low-numbered side of the main tube to the side tube must be 90º and 3) the main-tube-junction cell must be horizontal.

Offtake model has been activated in a SBLOCA in the hot leg. Two different cases have been analyzed varying the position of the break (top and bottom) in a horizontal pipe simulating the hot leg.

A different behaviour of the discharged coolant inventory and the mass flow rate through the break was expected for upwards and downwards configurations. In fact, in the case corresponding to a bottom break it is expected larger values of mass flow rate through the break during the two-phase liquid and vapour flow in comparison to the upwards configuration. Consequently the slope of the discharged inventory curve during this period should be higher for the bottom break case. The higher loss of coolant in the downward case would produce a faster Peak Cladding Temperature (PCT) and the Core Exit Temperature (CET) excursion. On the other hand, the larger amount of coolant during the two-phase flow period would affect also to the primary and secondary pressure evolution.

However, the results obtained with TRACE5 differ from this explanation. In the following figures, TRACE5 results are analyzed, firstly providing an explanation of the transient simulation and secondly analyzing the results of the Offtake model.

After the break valve opening, primary pressure drops immediately as shown in Figure 2. Pressure drop is momentary stopped after falling below the scram pressure set point. MSIV valves are closed producing a pressure rise in the secondary-side. Primary-side pressure continues falling, almost reaching the secondary-side pressure, remaining slightly above the secondary-side pressure since then. Secondary-side keeps removing heat from the primary system while primary-loop natural circulation is still on, thus raising the secondary pressure. Relief Valves (RV) must be actuated in order to maintain constant the secondary pressure. This cyclical behaviour of the relief valves supports the primary pressure above the secondary-side pressure. Then, secondary-side pressure stabilizes and primary-side pressure begins to fall below the secondary-side. When primary pressure reaches the accumulator entry set point (at 1800 s approximately), the pressure drop is slightly softened. When primary and secondary-side pressures are in a nearly-equilibrium state, and the primary loops have recovered their liquid level transient is terminated.

In the upward case, when the mass flow through the break changes to one-phase vapour (at 900 s as it can be seen in Figure 3) it is produced a faster decreasing in the primary pressure in comparison to the downward case. It can be stated that a higher amount of vapour is released through the break in the upward case respect to the downward case. This ‘extra’ amount of released vapour produces a greater loss of internal energy and enthalpy transferred to the environment, producing a faster depressurization.

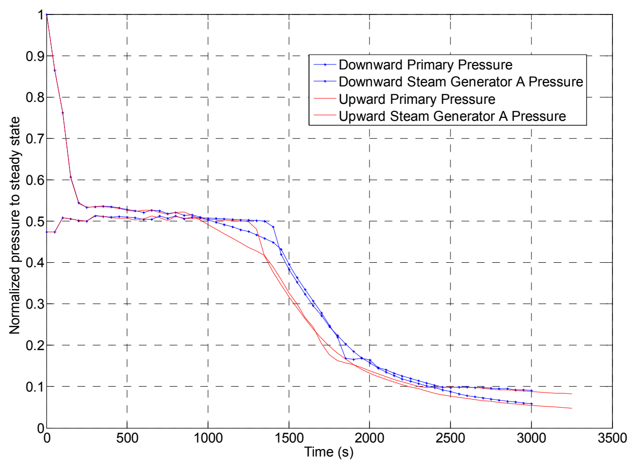


Figure 2 Primary and secondary pressures.

In Figure 3 it is shown the break liquid and gas flow rate for the upward and downward offtake cases. In Figure 4 it can be seen the discharged inventory through the break. The break mass flow rate is entirely one-phase liquid for the first moments of the transient, from the beginning until 100 s. From this moment on, break flow is turned into a two-phase mixture. This two-phase fluid regime is maintained until hot legs are emptied at 1000 s, when fluid regime changes to one-phase vapour. Due to the large amount of vapour leaving the system and the relatively high enthalpy loss produced during this period, primary pressure starts to fall below the secondary-side pressure. In this figure it can be seen that results obtained with TRACE5 are quite similar for both cases, even a slight higher loss of coolant is registered during the one-phase vapour (between 1000 and 1800 s) in the upwards case.

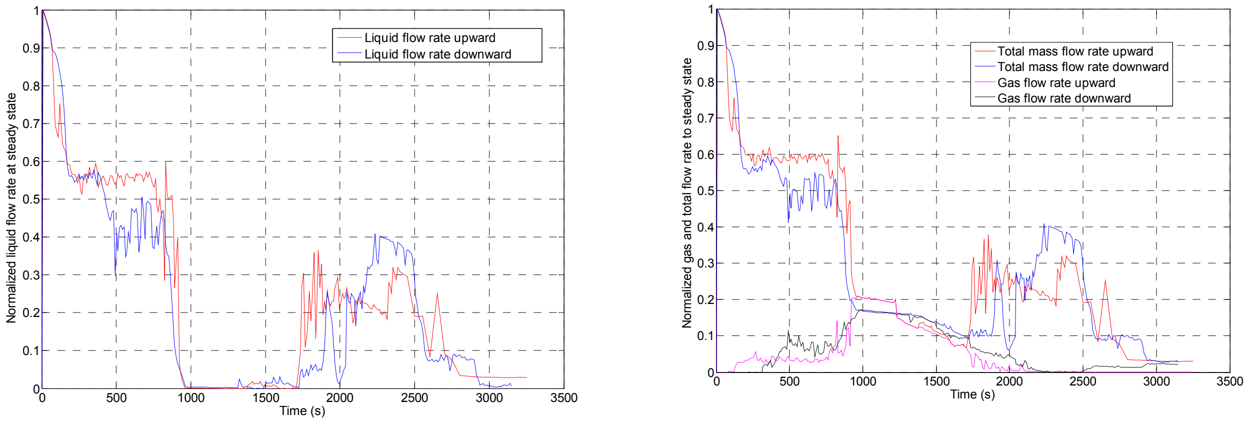


Figure 3   a) Break liquid flow rate and b) break gas and total mass flow rate.

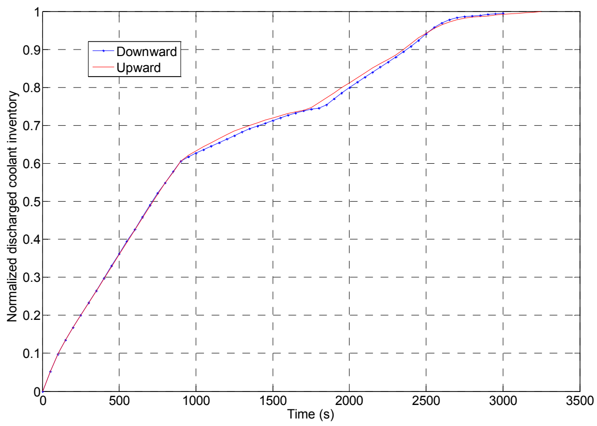


Figure 4   Discharged coolant inventory.

In Figure 5 it can be seen the collapsed liquid level calculated in the active core and in the upper plenum of the Pressurized Vessel. Results obtained with TRACE5 for these variables are coherent with those shown in Figure 3. During the two-phase liquid-vapour flow through the hot leg, it is produced a slight faster evaporation of liquid in both the active core and the upper plenum. Due to the fact that primary pressure drops slightly before in the upward case, the accumulator system is also activated earlier in this case, producing the reflood in the active core 100 seconds earlier than in the downward case. Figure 6 shows the downcomer collapsed liquid level. The same conclusions can be stated for the downcomer liquid level.

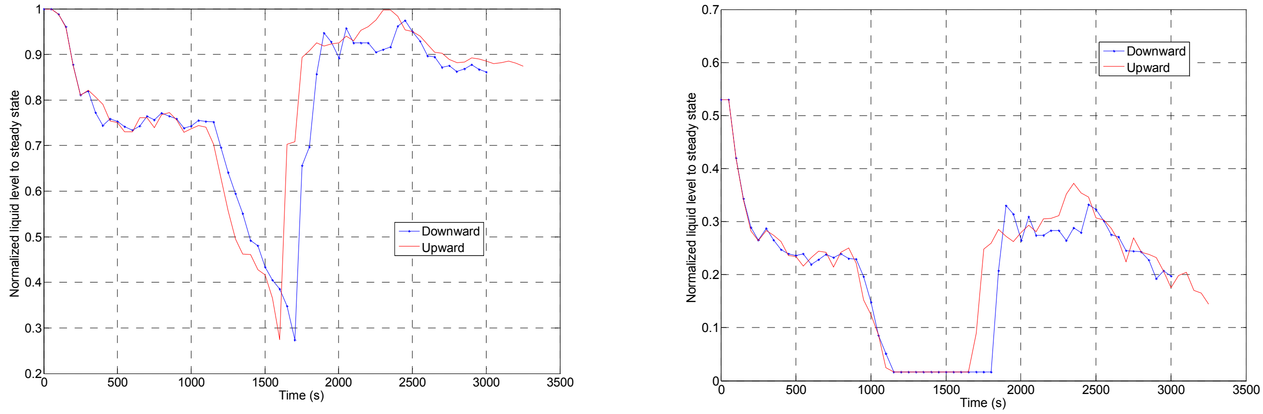


Figure 5 a) Collapsed liquid level in PV core and b) upper plenum.

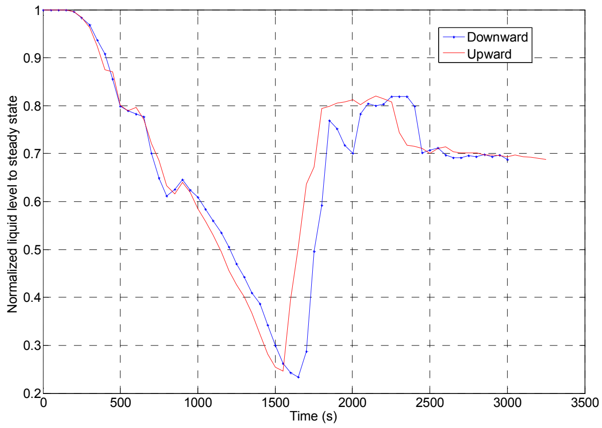
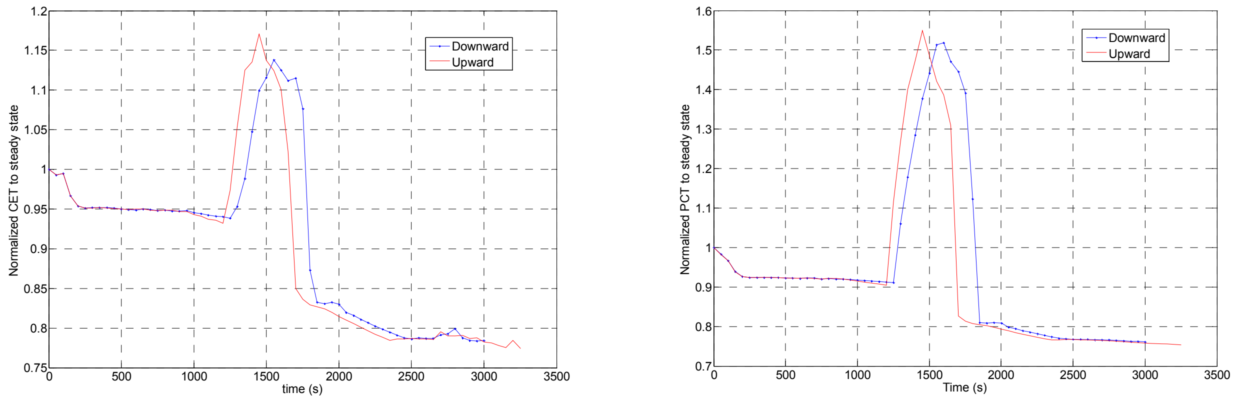


Figure 6 Collapsed liquid level in the downcomer of the Pressurized Vessel.



Figures 7 a) Core Exit Temperature (CET) and b) Maximum Peak Cladding Temperature (PCT).

As a consequence of the different depressurization rate predicted in the upward and downward orientation, the evolution of the Core Exit Temperature (CET) and the Maximum Peak Cladding Temperature (PCT) is modified. The upward configuration predicts the excursion of temperature 100 seconds before the downward case (see Figure 7).

4. Counter-Current Flow Limit (CCFL) model

Depending on the break (SBLOCA) location in the facility (vessel, cold leg, hot leg…), the coolant inventory discharged, even through the same break flow area, will be different due to the different coolant distribution. The relevance of these kinds of transients in the simulation with TRACE is the fact that allows testing important models such as the Counter-Current Flow Limit (CCFL).

The accurate prediction of the flow rates is dependent on the interfacial drag between the phases. In a given flow system, CCFL usually occurs at a flow-area restriction. Typically, without the use of the CCFL model, TRACE5 will predict the complete turnaround point but overpredicts the amount of liquid downflow in the region of countercurrent flow. To improve the prediction in the countercurrent region, a special model exists in TRACE that allows you to invoke characteristic CCFL correlations at specific locations in 1D vertical components.

When the primary coolant inventory decreases, natural circulation ends and steam begins to be condensed in steam generator tubes and flows back to the reactor vessel through the hot legs. This is known as reflux condensation phenomenon.

Reflux condensation and natural circulation become important in heat removal when the break size is 1% or lower [9]. When CCFL occurs under the reflux condensation, it means that the pressure drop across the hot leg increases. This causes a pressure increase in the upper plenum of the reactor vessel and the decrease of the liquid level in the reactor core, which results in an increase of the fuel temperature.

A special model in TRACE allows applying CCFL correlations at specific locations. In the context considered, Counter-Current Flow Limit model has been activated in U-tubes, since this model is only effective in vertical cells [10]. In these cases the Offtake model has been disabled. In TRACE5, CCFL is simulated by means of the Bankoff correlation and Wallis scaling (diameter dependence) and Kutateladze scaling (surface-tension dependence). In fact, Bankoff [11 12, 13, 14, 15] has shown a good correlation with the relationship:

$$H_g^{1/2} + M_B H_l^{1/2} = C_B \qquad (1)$$

where

H_g is the dimensionless gas flux,

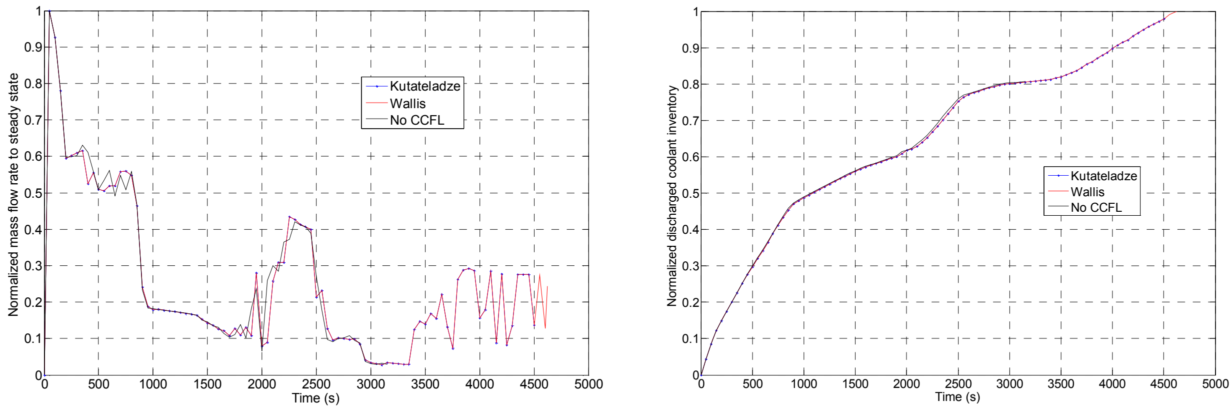
H_l is the dimensionless liquid delivery,

M_B is the slope.

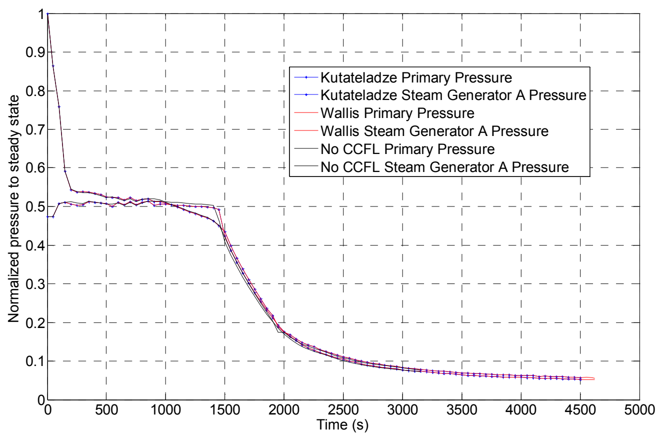
C_B is the Bankoff interpolation constant for interpolating between Wallis characteristic length dimension to Kutateladze characteristic length dimension.

In order to test the CCFL model of TRACE5, a SBLOCA transient with the break in one hot leg has been simulated. In this case a 1% break in downward orientation in the hot leg is produced. Three different cases have been run: 1) CCFL disabled, 2) CCFL enabled in hot legs and U-tubes of steam generators with Kutateladze model activation and 3) CCFL enabled in hot legs and U-tubes of steam generators with Wallis model activation. The transient produced in all these cases follow the logic control explained in Section 2. In the following figures (8-12) it is shown the main results achieved for the three cases studied.

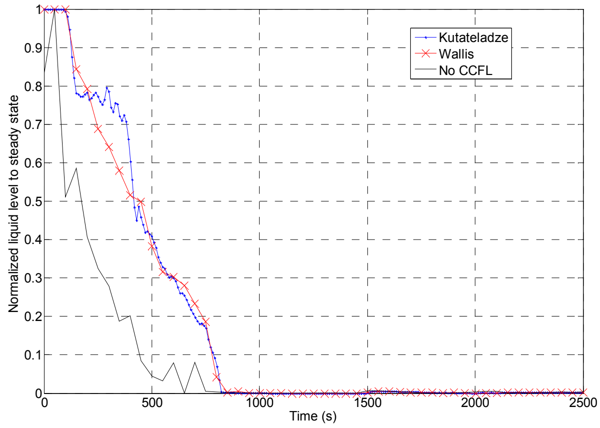
From results it can be stated that the activation of the CCFL options has a minor effect on the inventory discharged through the break in the hot leg. In Figure 8 it is represented the mass flow rate through the break and the discharged coolant inventory. Wallis and Kutateladze produce almost the same estimation of discharged coolant. The use of the CCFL correlation options do not produce any important variation in the general behaviour of both primary and secondary pressures, as it can be seen in Figure 9. However, the use of the CCFL model options (Wallis and Kutateladze) in U-tubes produce an important change in the collapsed liquid level of these tubes (see Figure 10), increasing the water level in U-tubes. These differences in collapsed liquid level in U-tubes modify the pressure of the hot leg and the upper plenum of the pressurized vessel, affecting the primary mass flow rate in both loops, as it can be seen in Figure 11.



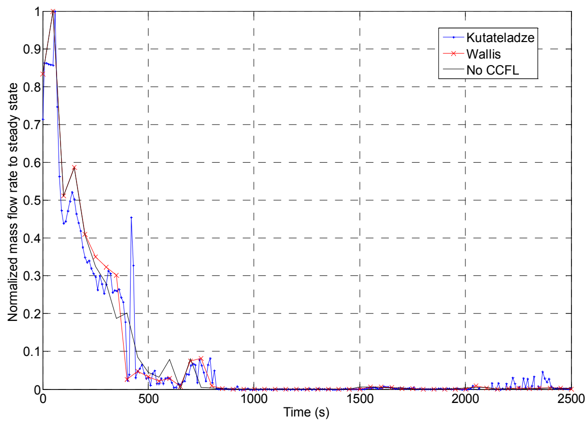
Figures 8 a) Break mass flow rate and b) discharged coolant inventory.



Figures 9 Primary and secondary pressures.

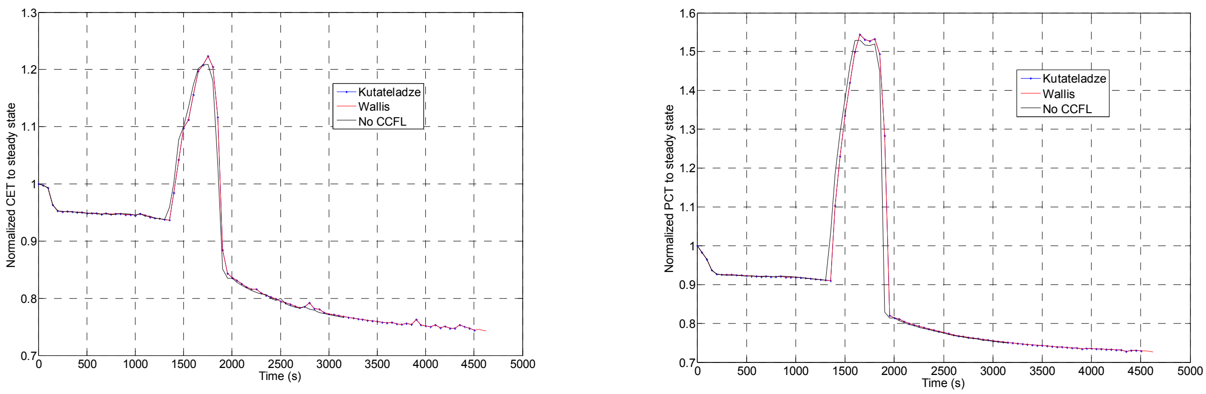


Figures 10 Collapsed liquid level in U-tubes of Steam Generator A.



Figures 11 Primary mass flow rate in loop A.

Finally, in Figure 12 it is shown the Core Exit Temperature (CET) and the Maximum Peak Cladding Temperature (PCT) for the three cases. From this figure, it seems that enable the CCFL options do not produce any relevant change in the behaviour of both CET and PCT.



Figures 12 Core Exit Temperature (CET) and Maximum Peak Cladding Temperature (PCT).

5. Conclusion

In this work some special TRACE5 models have been tested in a SBLOCA scenario in the frame of the OECD/ROSA Project. Different simulations have been performed taking the same control logic in the transient, modifying the orientation of the break in the model (top and bottom of the pipe). The main goal of these calculations is to test TRACE5 models such as the Offtake and Counter-Current Flow Limit with reflux condensation.

In the case of the hot leg SBLOCA, stratification in a horizontal pipe might produce a different mass flow rate depending on the orientation of the break (upward or downward). It has been observed that the TRACE5 simulation does not produce relevant differences in the transient when the orientation of the break is changed using the Offtake option. In these cases Counter-Current Flow Limit model could be important in order to take into account reflux condensation in the steam generator U-tubes. In the present calculations, it seems that the activation of the CCFL model options (Wallis and Kutateladze) do not strongly affect the pressure system and the mass flow rate through the break. Anyway, the activation of the CCFL is important to have into account the temporary accumulation of water in the bottom of U-tubes of steam generators.

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