Top Flooding Modeling with MAAP4 Code

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ABSTRACT

An engineering top flooding model was developed in MAAP4.04d.4, the severe accident code used in EDF, to simulate the thermal-hydraulic phenomena that should take place if emergency core cooling (ECC) water was injected in hot leg during quenching. In the framework of the ISTC (International Science and Technology Centre), a top flooding test was proposed in the PARAMETER facility (Podolsk, Russia). The MAAP calculation of the PARAMETER top flooding test is presented in this paper. A comparison between top and bottom flooding was made on the bundle test geometry. According to this study, top flooding appears to cool quickly and effectively the upper plenum internals.

1 INTRODUCTION

Most of experimental and numerical investigations are made on bottom quenching (like for instance the Cora/Quench facilities). The knowledge on top quenching is poor, that’s the reason why EDF decided to study thoroughly this phenomenon. There are two possibilities for top quenching occurrence. First, in case of severe accident, the steam in steam generator tubes can condensate and water thus produced can return to the core via the hot leg. Then, when the injection point of safety injection system is located on the hot leg, one can expect that a part of the injected water rate can directly go to the core through the nozzle of the hot leg.

An engineering top flooding model was developed in MAAP4.04d.4, the severe accident code used in EDF, to simulate the thermal-hydraulic phenomena that should take place if emergency core cooling (ECC) water is injected in hot leg during quenching. This model was based on the analysis of existing top flooding studies. The most relevant tests and models were PERICLES and UPTF tests and top flooding model used in CATHARE and ATHLET-CD code. The top flooding model benched from this study was integrated in MAAP4 code. It takes into account counter-current flow phenomena occurring in hot leg and in the core. Heat transfers in the upper plenum and in the core between cladding and coolant are also modelled for top flooding flow patterns. This model allows also to determine the location of the top quench front.

2 MODELING

In case of top and bottom flooding, two quench fronts appear. An upper quench front due to top injected water and a lower quench front due to bottom injected water. Two flooding patterns occur at the same time. A co-current flow at the bottom of the core: this flow pattern is similar to the well-known bottom flooding flow pattern. First, a liquid phase at the bottom of the rods, then when the cladding temperature increases, a nucleate boiling zone
appears. This flow pattern is surmounted by a transition boiling zone at the quench front, a film boiling region, an inverted annular flow, a dispersed flow and a simple phase steam ascending flow like in figure 1.

The top water injection induces a counter-current flow pattern with an ascending steam flow and a descending water flow. This pattern flow is composed of a simple liquid phase at the upper end of the rods and a water annular down flow with a dispersed steam flow appears when the temperature of the cladding increases. At the upper quench front, the liquid film dries out.

The location of this drying point of the water film is needed to consider the sharp change in the heat transfer between the region of dry and wetted wall and as a consequence to get the steep temperature decrease during quenching. To know this location, a counter-current flow limitation criterion is needed.

![Figure 1: combined flooding - flow patterns](image)

**2.1 Counter-current flow modelling**

To work out a top flooding model in MAAP4.04d4 code, three counter-current flow limitations are needed. A counter-current flow limitation in the hot leg, to determine the flow of water that enters the core, represented as number 1 in figure 2. And a counter-current flow limitation at the upper plenum to determine the water flow rate which can reflood the core effectively, represented as number 2 in figure 2. And a countercurrent flow limitation in the core to find out the upper quench front position.
The counter-current flow limitation (CCFL) phenomenon is extremely dependant of the geometry of the flow. Many authors have made experiments to determine this limitation in many geometries. Most of these experiments are not realized for reactors applications, that is why the important physical numbers in a reactor case are not fully representative during these experiments. The correlations chosen for top flooding modeling in MAAP4.04d4 code were based on UPTF (Upper Plenum Test Facility) experiments [1]. The advantage of this facility is the geometry of the test bench which represents the primary system of a 1300MWe pressurized water reactor (PWR) with upper plenum, downcomer and primary main coolant pipe in 1:1 reactor scale.

2.1.1 Counter-current flow limitation in hot leg

The CCFL correlation chosen to determine the water flow rate which enters to the core was validated on UPTF experiments. The inner diameter of the UPTF hot leg is 75 cm. The French 900MWe PWRs have an inner diameter of the hot leg of 73,6 cm and the 1300MWe, an inner diameter of 74 cm. The geometry tested in UPTF experiments is very close to which we are interested in.

The counter-current flow limitation can be described by a Wallis-type equation (1), where \(u_{GS}^*\) is the dimensionless superficial velocity of the gas, based on the diameter of the hot leg, and \(u_{LS}^*\) the dimensionless superficial velocity of the water, based on the diameter of the hot leg.

\[
0.7u_{LS}^{1/2} + u_{GS}^{1/2} = 0.61. \quad (1)
\]

The expression of dimensionless velocities are described in (2) and (3), where \(u_{GS}\) (resp. \(u_{LS}\)) is the superficial velocity of the gas (resp. water) (m.s\(^{-1}\)), \(\rho_G\) (resp. \(\rho_L\)) is the density of the gas (resp. liquid) (kg.m\(^{-3}\)), \(g\) is the gravitational acceleration (m.s\(^{-2}\)), and \(D\) is the diameter of the hot leg (m)

\[
\begin{align*}
    u_{GS}^* &= u_{GS} \rho_G^{1/2} \left[ gD (\rho_L - \rho_G) \right]^{-1/2}. \quad (2) \\
    u_{LS}^* &= u_{LS} \rho_L^{1/2} \left[ gD (\rho_L - \rho_G) \right]^{-1/2}. \quad (3)
\end{align*}
\]

2.1.2 Counter-current flow limitation at the upper plenum

The correlations, which characterize the counter-current flow limitation in a horizontal geometry (for example in hot leg), and the correlations which characterize the counter-current flow...
flow limitation in a vertical geometry (for example in a configuration related to what can occur in a reactor core) are not similar. CCFL correlation in vertical geometries is more complex and is extremely dependent on the cross section of the fluid and on the gravity.

Based on this observation, and starting from the UPTF results, Glaeser and al. [1] worked out a Kutateladze-type correlation (4) valid in case of heterogeneous and asymmetrical flow, where $K^*_G$ (resp. $K^*_L$) is the dimensionless superficial velocity of the gas (resp. water); based on surface tension. $\nu_g$ is the kinematic viscosity of the gas (m$^2$.s$^{-1}$), $g$ is the gravitational acceleration (m.s$^{-2}$), and $L$ is the characteristic geometrical length (m).

$$K^*_G = \left( \frac{\nu_g^{2/3} \rho_g}{g^{1/3} L} \right)^{1/2} + 0.014 K^*_L^{1/2} = 0.027 .$$

(4)

The expression of dimensionless velocities are explicated in (5) and (6), where $\sigma$ is the surface tension (kg.s$^{-2}$),

$$K^*_G = u_{GS} \left( \frac{\rho_g^2}{g \sigma (\rho_L - \rho_g)} \right)^{1/4} .$$

(5)

$$K^*_L = u_{LS} \left( \frac{\rho_L^2}{g \sigma (\rho_L - \rho_g)} \right)^{1/4} .$$

(6)

2.1.3 Counter-current flow limitation in the core

Glaeser and al. [1] worked out a Kutateladze-type correlation (6) valid in case of counter current flow in the core.

$$K^*_G + 0.77 K^*_L = 1.64 .$$

(7)

With $K^*_G$ and $K^*_L$ like (5) and (6).

3 PARAMETER MODELLING

The PARAMETER facility is designed to study the behaviour of VVER type rod bundles under loss of coolant or severe accident conditions [2].

The main component of the test facility is the bundle test section. A system of injectors located on the top of the bundle allows to reflood the bundle from the top. Before flooding, steam as coolant together with argon as a carrier gas enter the test bundle at the bottom. The steam flow is stopped just before the reflooding phase and the bundle is reflooded from the top after a heating phase with water.

The whole experimental bundle is located in a hexahedron shroud made of Zr1%Nb (figure 3). The test bundle is made of 19 fuel rods with a length of approx. 3100 mm, connected each other by means of six spacing grids. The geometry of the assembly is a VVER geometry. The assembly has a hexagonal geometry with a triangular pitch of 12,75 mm. All the rods, despite the central rod, are heated electrically over a length of 1275 mm. Heating is carried out using 4 mm diameter tungsten heating elements which are located in the centre of the rods, surrounded by annular UO$_2$ fuel pellets. Above and bellow the heated region, electrodes of molybdenum and copper are connected to the tungsten heaters and to cables leading to power supply. The cladding of the rods is in Zr1%Nb. The central rod is only composed of UO$_2$ fuel pellets surrounded by the cladding.
The bundle is equipped with thermocouples and pressure measurement system in the rods. Thermocouples are placed on the fuel rods, on the hexahedron shroud and on the thermal insulating shroud at various elevations and radial positions. 71 thermocouples are placed on the outer surface of the fuel rods. 9 thermocouples are placed on the shroud and 9 thermocouples are mounted on the thermal insulation shroud.

3.1 Specification of PARAMETER modelling in MAAP4.04d code

An electrical heater rod model is used for this out-of-pile test facility. The electric heater model computes the local heat release in the heated zone as well as in the electrodes zones (molybdenum and copper). The resistance of each node is calculated at each time step as a function of the fuel pellet temperature, the cross section, the height and the number of rods of each row. Resistivities (8), (9) and (10), are those recommended in the specification document for ISP-45 [3] (with T in Kelvin):

\[
\rho_{\text{tungsten}} \left( \frac{\Omega \cdot \text{mm}^2 \cdot \text{m}^{-1}}{} \right) = -2,610 \times 10^{-2} + 2,630 \times 10^{-4} T + 2,200 \times 10^{-8} T^2
\]

(8)

\[
\rho_{\text{copper}} \left( \frac{\Omega \cdot \text{mm}^2 \cdot \text{m}^{-1}}{} \right) = -7,890 \times 10^{-3} + 9,900 \times 10^{-5} T - 5,490 \times 10^{-8} T^2 + 3,160 \times 10^{-11} T^3
\]

(9)

\[
\rho_{\text{molybdenum}} \left( \frac{\Omega \cdot \text{mm}^2 \cdot \text{m}^{-1}}{} \right) = -2,290 \times 10^{-2} + 5,360 \times 10^{-5} T - 1,380 \times 10^{-7} T^2 - 2,220 \times 10^{-11} T^3
\]

(10)

Along its whole height, the core region is surrounded by a ZrO<sub>2</sub> insulation, which is called the core barrel in MAAP4.04d4. Axial heat conduction through the core barrel is considered. But the insulation geometry has to be interpreted as regards as heat transfers. In MAAP4.04d4, the thickness of the core barrel is supposed to be small compared to its radius. As a consequence, the inside surface is supposed to be approximately the same as the outside surface, so that in terms of conductive heat transfers, the core barrel behaves as a plane wall. For PARAMETER, the equivalent area used for conductive heat transfer calculations trough the wall is an average value of the inner and outer area.

In MAAP4.04d4, the core zone is modelled in two dimensions and the nodalization is symmetrical compared to the centre of the bundle, and is divided in coaxial. That’s why the nodalization is composed of 3 channels and 58 rows. The 48 equidistant central rows represent the heated zone of the PARAMETER test facility. Above and below the active core, ten nodes allow modelling the non-active parts of the rods. The inactive nodes represent the molybdenum and copper electrode zones above and below the heated region.
In MAAP4.04d4, the oxidation of the shroud is not possible when the shroud is located in the core barrel. To take into account the shroud oxidation, the shroud mass is redistributed in the most outer radial ring from axial elevation -300 mm to 1447 mm. This way, the whole shroud mass can potentially contribute to the oxidation process.

4 TOP FLOODING CALCULATION

In this section, the reference case of the PARAMETER top flooding calculation done with MAAP4.04d4 is presented. The sensitivity studies have not been carried out yet. When the simulation begins the electrical heating power is working. Here, the time 0 s of the simulation corresponds to the moment 1836 s of the test. The reflooding phase begins at 13000 s in the simulation. In this section, the results on hydrogen production and bundle temperature are compared.

The hydrogen production is shown in figure 4. The calculation predicts an amount of hydrogen product of 9.5 g before reflooding and 48 g at the end of the test. Before reflooding the experimental data show an amount of hydrogen of about 15 g. The difference can result from the fact that the by-pass of the steam occurred during the pre-oxidation phase of the bundle, is not modeled. At the end of the test, the hydrogen production amount is about 90 g. The fact that MAAP4.04d4 does not take into account the oxidation of heater elements may mainly explain this difference.

![Figure 4: Hydrogen production](image)

The maximal temperature of the bundle is shown on figure 5. This temperature named Tmax is compared with the highest found temperature profiles. Before the reflooding phase, the calculated temperature is lower than the experimental temperatures; this is in agreement with the fact that less hydrogen is produced in the calculation than in the experiment. This difference is probably due to uncertainties modeling on thermal losses through the zirconia insulation and on the resistivity of the sliding contacts. As the test is conducted at low pressure (circa 1 bar), the calculation of pressure is not relevant as in real core.
At this time, we have no indication of dedicated top-flooding modeling in other Severe Accidents softwares. It is usual to approximate top-flooding as bottom-flooding by adding the top flooding water pouring rate to the bottom mass flow rate.

5 COMPARISON TOP / BOTTOM FLOODING

The parameter test scenario was simulated with top and with bottom flooding, in this section the results on temperature are compared. The bottom flooding model used in MAAP4.04d code is validated on QUENCH experiments.

In table 1 is shown a comparison between temperature profiles predicted with a bottom flooding and with a top flooding, for the same scenario.

In case of a top flooding the upper inactive nodes, which model the non-active parts of the PARAMETER rods, are quickly cooled. Compared to the bottom flooding case, the maximal temperature of the bundle increase at quenching time for top flooding case. See table 1 at 13050 seconds. The steam produced at the quench front in case of top flooding is only distributed above the quench front and oxidizes the upper part of the bundle. The maximum temperature increases due to oxidation reaction. In case of a bottom quenching, the steam produced at the quench front oxidizes the cladding but at lower temperature than the maximal temperature of the bundle.
In case of top flooding, the bundle degradation is more important at the maximal bundle temperature elevation than in the bottom flooding case. This is the consequence of the temperature elevation due to oxidation of the bundle and repartition of the steam produced at the quench front in case of top flooding.

6 CONCLUSIONS

A top flooding model was developed in MAAP4.04d code. It takes into account the counter current flow limitations, which can occur if the injection point of the safety injection is located in hot leg. Three limitations are modeled, one in the hot leg, one in the upper.
plenum and the other in the core. These limitations are needed to have a good estimation of the effective mass flow rate, which enters and cools the core.

A top flooding simulation using this model and a bottom flooding simulation were made while following the scenario of PARAMETER top flooding experiment with MAAP4.04d4 code. The comparison between the efficiency of top and bottom flooding shows that top flooding allows to cool effectively the upper plenum internals, which are represented in the simulation by the five upper non-heated nodes. But on the other hand, the degradation of the bundle is more important for top quenching than for bottom quenching.

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REFERENCES

