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CODE SIMULATION OF QUENCHING OF A HIGH TEMPERATURE DEBRIS BED: MODEL IMPROVEMENT AND VALIDATION WITH EXPERIMENTAL RESULTS

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ABSTRACT

The loss of coolant accidents with core degradation e.g. TMI-2 and Fukushima demonstrated that the nuclear safety analysis has to cover accident sequences involving a late reflood activation in order to develop appropriate and reliable mitigation strategies for both, existing and advanced reactors. The reflood (injection of water) is possible if one or several water sources become available during the accident. In a late phase of accident, no well-defined coolant paths would exist and a large part of the core would resemble to a debris bed e.g. particles with characteristic length-scale: 1 to 5 mm, as observed in TMI-2. The French “Institut de Radioprotection et de Sûreté Nucléaire” (IRSN) is developing experimental programs (PEARL and PRELUDE) and simulation tools (ICARE-CATHARE and ASTEC) to study and optimize the severe accident management strategy and to assess the probabilities to stop the progress of in-vessel core degradation at a late stage of an accident. The purpose of this paper is to propose a consistent thermo-hydraulic model of reflood of severely damaged reactor core for ICARE-CATHARE code. The comparison of the calculations with PRELUDE experimental results is presented. It is shown that the quench front exhibits either a 1D behavior or a 2D one, depending on injection rate or bed characteristics. The PRELUDE data cover a rather large range of variation of parameters for which the developed model appears to be quite predictive.

1. INTRODUCTION

In case of severe accident in a nuclear reactor, water sources are not available for a long period of time and the reactor core heats up due to the residual power. If the water source is not renewed, the integrity of the fuel rods is lost and the structural materials of the core are damaged. Any attempt to inject water during late core degradation can lead to further fragmentation of core material during quenching. The fragmentation of fuel rods can result in the formation of a “debris bed” where the particles size might be just few millimeters, making it difficult for water to progress quickly inside. If the core cannot be cooled down, core melt-down occurs and the melt relocates down to the lower plenum, which leads to failure of the vessel lower head and, in turn, release of core material into the cavity.

The prediction of the core evolution in case of reflood requires an accurate modelling of both the heat transfer and the oxidation of metal (possibly molten). Maintaining a coolable configuration of the debris bed depends on water flow rate which can be sustained through the bed under the available driving head. Being able to predict the conditions for which it is possible to stop the progression of severe accident may significantly contribute to the extension of safety margin of pressurized water reactors. On the other hand, it must also be recognized that at elevated core temperatures, the rate of oxidation of metals may be very high if vapor is available. Therefore, reflood is likely to lead to an enhanced hydrogen formation and the risk of containment damage. However, from a safety point of view, it is important to evaluate chances of coolability of the reactor core during a severe accident. This is in line with the safety philosophy of defense in depth which requires to foresee and to analyse all options to stop an accident at any stage.

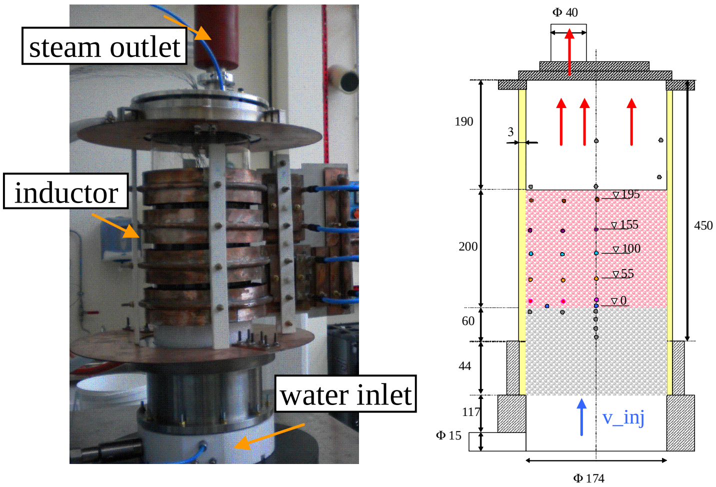

Fig. 1: PRELUDE experiment (dimensions in mm)

2. PRELUDE EXPERIMENTAL PROGRAM

Currently, IRSN sets up two experimental facilities to study debris bed reflooding: PRELUDE and PEARL (planned in 2012), and to validate safety models. The PRELUDE program [1] was launched in 2009 and studies the complex two phase flow (water/steam) in a debris bed. The bed consists of 24 kg of stainless steel spherical particles (porosity 0.4, Ø 180 mm, h=200 mm, see Fig. 1). It is heated by means of induction system (up to 400°C or 700°C). The debris bed is homogeneous, the diameter of particles is either 4, 2 or 1 mm. The initial temperature of the bed varies between 400°C and 700°C. Water is injected at the bottom. Inlet superficial velocities are in the range of 0.555–5.55 mm/s (in the range to that foreseen in the PEARL test matrix - 2 to 50 $m^3/h/m^2$). The first objective of PRELUDE experiment was to optimize the induction heating and the measurement devices that should be used in PEARL facility. The PRELUDE has thus smaller dimensions and runs only at atmospheric pressure. However, a series of experiments that were performed in 2010-2011 in the PRELUDE facility have provided yet a large amount of new data that significantly enhance the database of experimental results. This includes the prediction of debris coolability, quench front propagation, steam production and pressure increase during the quenching after the water injection. They provide relevant data to understand the progression of the quench front and the intensity of heat transfer. On the basis of those experimental results, thermal hydraulic features at the quench front have been analyzed. For the analysis of experimental results discussed in this paper, about 40 tests were selected. Reproducibility tests were also analyzed in order to confirm the experimental results.

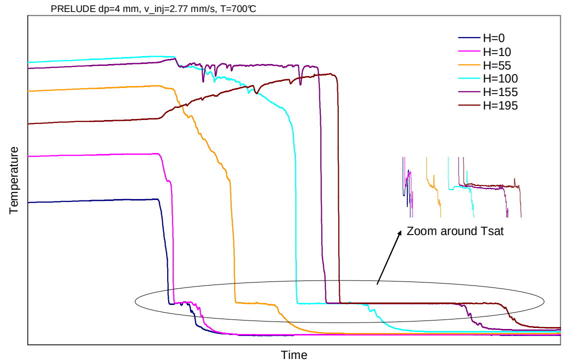

Fig. 2: Temperature evolution in one PRELUDE test (Results of this program are not yet open, the figure is without scale)

2.1. Analysis of PRELUDE experimental results

On Fig. 2 we can see an example of temperature evolution at the center in one PRELUDE test. From the temperature measurements, the velocity of the quench front can be analysed. The quench front velocity is identified from the determination of the elevation where temperature is below the saturation temperature. It may be evaluated within the bed for three different radii and different elevations. It should be noted that the accuracy on the instant of quenching depends on the reference temperature that is taken for comparison. We concluded that the saturation temperature is not a good reference because it is measured with some error (few degrees) due to temperature instability around this value. In order to be more accurate, it is better to choose T_{sat}+5 K or T_{sat}-5 K as a reference temperature but they do not provide the same information (see Section 4, Table 1, Table 2). T_{sat}+5 K identifies a position where water is significantly present and a strong cooling occurs. T_{sat}-5 K identifies a position where the particles have been completely quenched. The most of thermocouples are located in pores and, therefore, indicate a temperature that is slightly lower than the surrounding particles. Consequently, the interpretation of temperature measurements can lead to an uncertainty as high as 50% on the quench front velocity. Moreover, the short height of debris bed (200 mm) and limited number of thermocouples impact the accuracy e.g. especially when the transient effects following the entrance of water into the bed persist up to a significant part of the bed height.

Despite of that, it is possible to conclude that there exists a steady state propagation of the quench front for all the cases considered. The quench front velocity is identified to be the same for the central and mid-radius positions. But, for some tests, the quench front velocity is significantly faster near the wall.

We evaluate the ratio between the minimum and maximum quench front velocity for each PRELUDE test. This ratio measures the multi-dimensional effects i.e. it is considered one-dimensional as long as this ratio is close to 1. On Fig. 3 we can see, how the multi-dimensional effects depend on pressure gradient caused by the steam flow. This pressure gradient is estimated from the generalized Darcy equation for vapor phase (see Fig. 3) where the steam velocity in the porous medium is calculated from the steam flow measurements at the outlet of test section, i.e. during steady-state. If the water reached the top of the bed before steady-state was established, the value of peak as well as mean value are used in calculations, which results in an interval of uncertainty shown on Fig. 3. The criterion for multi-dimensional effects seems to appear when the pressure gradient is above $2.8\rho_l g$. It is important to note, that this criterion was obtained analyzing the PRELUDE experimental results, where the facility is, in its conception, 1D (no designed by-pass). In realistic bed configurations, additional factors would induce multi-dimensional effects, such as non-uniform porosity, variable height or non uniform temperature.

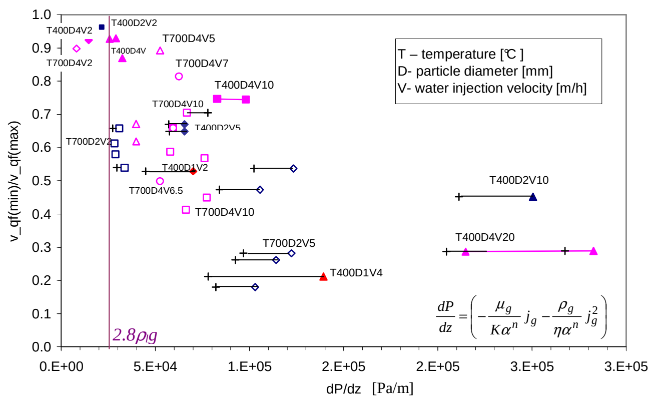

Fig. 3: Multi-dimensional effects and their dependence on pressure increase. Tests with identical initial conditions have the same marker.

3. ICARE-CATHARE REFLOOD MODEL

ICARE-CATHARE [2] is a computer code developed by IRSN, designed to describe accurately light water reactor accidental sequences up to a possible vessel failure. It involves advanced models (two-phase multi-dimensional thermal-hydraulics and degradation models) and is built from the coupling of the thermal-hydraulics code CATHARE [7] to the severe accident code ICARE. The code is also used to benchmark the integral code for severe accident analysis ASTEC.

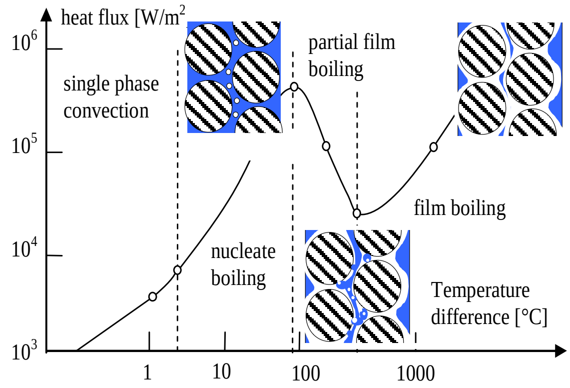

Fig. 4: Flow boiling curve

The model for reflood of debris bed in ICARE-CATHARE is based on three energy balance equations and two momentum balance equations [3]. The extension of Darcy's law for each fluid phase is used. The heat transfer relations are described in ICARE-CATHARE for different boiling regimes and the code selects the appropriate regime according to local physical properties e.g. temperature and void fraction. In our model, specific *heat transfer coefficients* were obtained solving the macroscopic conservation equations together with local closure problems. Analytical solutions for the local closure problems were obtained in simplified geometrical configurations as the stratified cell and Chang's cell [4]. For a stratified unit cell, two typical phase repartitions were considered, namely the *solid-liquid-gas* (SLG) and the *solid-gas-liquid* (SGL) repartition. The first refers to liquid being the wetting phase, the second refers to vapor being the "wetting" phase. We assume that, for an oriented liquid flow in porous media, we can expect a phase repartition where one phase will be "wetting" and the second phase will eventually flow in the remaining pores under the form of bubbles or slugs. Because of this assumption, the effective properties obtained for a stratified unit cell are combined in our model. The coefficients are valid for a laminar flow, they include the dependence on fluid properties and also on a pore scale geometry:

$$h_{cv,l}^{SLG} = \frac{72 k_l}{(4\varepsilon_s \kappa_{ls} + 3\varepsilon_l) H^2} \qquad h_{cv,g}^{SGL} = \frac{72 k_g}{(4\varepsilon_s \kappa_{gs} + 3\varepsilon_g) H^2} \qquad (1)$$

However, the stratified flow assumed in our model is applicable mostly in the case of film condensation (below saturation temperature) or film boiling (above Leidenfrost temperature) only. Consequently, an improvement of the model is proposed for the nucleate boiling and transition boiling regimes.

The extension of the model which is proposed for nucleate boiling regime comes from the theory of flow boiling in small hydraulic diameter channels. Recent studies [5] concluded that neither the nucleate boiling nor turbulent convection are the controlling mechanisms in minichannels. The important process seems to be a transient thin film evaporation where the minichannel flows are typically laminar [6]. Under such conditions, our model could describe this thin film evaporation but it would require the knowledge of the thickness of such liquid film. Not knowing that, it is proposed to enhance the existing heat transfer by introducing a term representing this process, as follows:

$$h = g(\alpha)h_{nb} + ((1-\alpha)h_{cv,l} + \alpha h_{cv,g}) \qquad (2)$$
$$g(\alpha) = 1-\alpha$$

In the above mentioned equation, the function $g(\alpha)$ represents the fraction of particle surface in contact with water. Using that, the "nucleate boiling" will be strongly reduced with an increase of vapor quality, which inhibits bubble growth and leads to dry-out at high vapor qualities. Currently, there is still a lack of information about the critical heat flux in porous media during reflood. Our model, in the absence of specific determination for porous media, uses the Groenveld critical heat flux correlation [7] including its dependence on a hydraulic diameter. In order to describe the increasing heat transfer with decreasing surface temperature in the transition zone, a simple parabolic dependence on a surface temperature was prescribed (parameter $\xi = 2$):

$$Q = g(\alpha)(1 - f(\theta,\xi))Q_{CHF} + f(\theta,\xi)(1-\alpha)Q_{cv,g}$$
$$g(\alpha) = 1-\alpha \qquad (3)$$
$$f(\theta,\xi) = \left(\frac{Tw - Tbo}{Tmfs - Tbo}\right)^{\xi}$$

Another important point is to identify properly the conditions for which the liquid makes substantial contact with the surface during reflood. Subsequently, the vapor film of the film boiling collapses onto the surface and the film boiling regime changes to transition boiling (see Fig. 4). The collapse of the vapor film has traditionally been related to the minimum-heat-flux-point of a boiling curve, as found by Nukiyama. Nowadays, there is no correlation available in literature for minimum film stable temperature for a flow in a porous medium.

In our model we propose to identify the boiling regime according to the position of quench front and a *heat transfer layer length*. The heat transfer layer length was previously defined by Tutu [9] as the distance between 5% and 95% of the dimensionless solid temperature profile (see Fig. 5). Tutu et al. concluded that it depends on water injection velocity, and is higher for higher velocities, but they did not estimate the dependency. A similar conclusion was obtained by Ishii and coworkers from visual experiments [10] on cylinders where they qualified the regime length introducing its dependence on Capillary number [10] :

$$L_1 = f(v_{inj}^{0.5}) \qquad (4)$$

In our model the heat transfer layer length is calculated as follows:

$$L_1 = 0.47We^{0.33}$$
$$We = \frac{\rho_l v_{pore}^2 \left(\frac{d_p \varepsilon}{1-\varepsilon}\right)}{\sigma} \qquad (5)$$

The dependence of heat transfer layer length on Weber number was obtained analyzing the PRELUDE experimental results. The axial temperature profile for each test was reconstructed and the heat transfer layer length was identified. From experimental results we identified a distance between the position of quench front and the elevation where the solid temperature reaches 95% of its initial temperature (see Fig. 5). The heat transfer layer length represents the region where the transition boiling occurs. Above the heat transfer layer length, the film boiling regime occurs. A similar modelling based on a heat transfer length was already integrated into ICARE-CATHARE model for intact fuel rods and validated [11]. It consists in tracking the quench front location and integrating the small-scale heat flux profile over the heat transfer length in the transition boiling regime. Here, we use a similar tracking of the quench front but, contrary to that modelling, the porous medium model uses the physical correlations in each regime to calculate the heat flux profile and the heat transfer layer length is used only to identify the condition for which the film boiling regime changes to transition boiling.

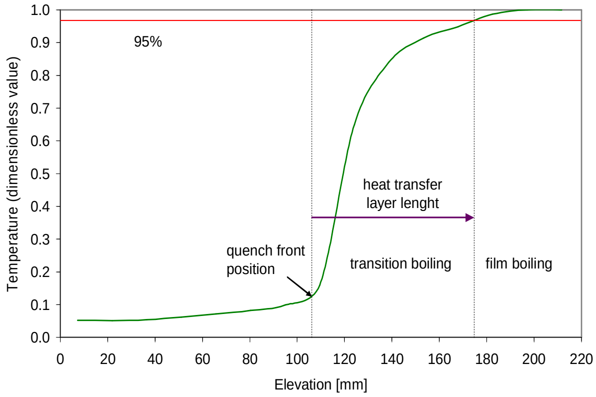

Fig. 5: Definition of heat transfer layer length

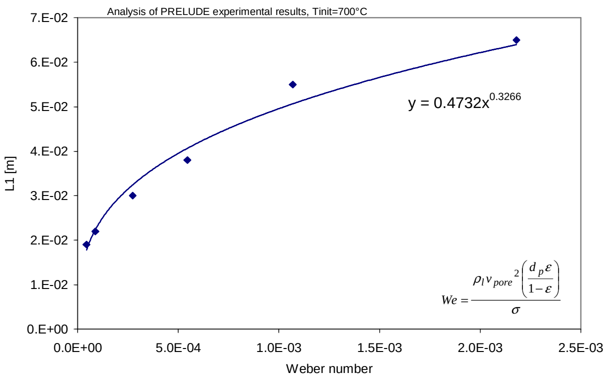

Fig. 6: Dependence of heat transfer layer length on Weber number

4. CALCULATIONS OF PRELUDE TESTS

The ICARE-CATHARE calculations were performed for PRELUDE tests with initial debris bed temperatures 400°C and 700°C. The objective of the calculations was to validate the model predictions of progression of quench front, pressure increase in the bed and steam production.

The geometry of PRELUDE experimental facility was properly modeled (see Fig. 1). The steel particles with diameter 4, 2 or 1 mm were placed above a bed of quartz particles which was installed in PRELUDE facility in order to avoid placing a metallic grid which would heat-up because of induction. The calculations were performed at atmospheric pressure and for different bottom water injection velocities (0.555-5.55 mm/s). The test facility is, in its conception, one dimensional (no designed by-pass) so the first ICARE-CATHARE calculations were done with 1D meshing. These calculations were presented in [12] and the results are summarized in Table 1. The quench front velocity for different inlet flow rates and particle diameters is well predicted. The uncertainty in the predictions is within the range of the experimental one.

Table 1: Quench front velocities for different tests with initial temperature 400°C. ICCV2- 1D meshing calculations, PRELUDE- mid radius and center quench front velocities.

dp			Tref=105°C	Tref=95°C	Difference
4 mm	v_inj=1.38 mm/s	ICCV2	1.98 mm/s	1.32 mm/s	7.04-9.17%
		Prelude	2.17-2.18 mm/s	1.42-1.43 mm/s	
	v_inj=2.77 mm/s	ICCV2	3.88 mm/s	2.66 mm/s	2.58-19.29%
		Prelude	3.44-3.78 mm/s	2.94-3.3 mm/s	
	v_inj=5.55 mm/s	ICCV2	6.12 mm/s	5.62 mm/s	11.94-29.89%
		Prelude	5.04-6.95 mm/s	3.94-4.24 mm/s	
	v_inj=0.555 mm/s	ICCV2	0.77 mm/s	0.31 mm/s	0.77-31.1%
		Prelude	0.776-0.78 mm/s	0.42-0.45 mm/s	
2 mm	v_inj=1.38 mm/s	ICCV2	2.13 mm/s	1.32 mm/s	0-36.6%
		Prelude	1.35-1.59 mm/s	1.32-1.35 mm/s	
	v_inj=2.77 mm/s	ICCV2	4.75 mm/s	3.02 mm/s	12.25-43.5%
		Prelude	2.68-3.17 mm/s	2.46-2.65 mm/s	
	v_inj=5.55 mm/s	ICCV2	0.79 mm/s	0.38 mm/s	2.47-15.5%
		Prelude	0.81-0.89 mm/s	0.44-0.45 mm/s	
1 mm	v_inj=1.11 mm/s	ICCV2	1.74 mm/s	1.186 mm/s	2.19-43.68%
		Prelude	1.17-0.98 mm/s	1.02-1.16 mm/s	
	v_inj=0.555 mm/s	ICCV2	0.94 mm/s	0.63 mm/s	10-23.4%
		Prelude	0.72-0.81 mm/s	0.7-0.72 mm/s	

The calculations presented in this section concern the most recent PRELUDE experiments with initial temperature 700°C. In these experiments, the two-dimensional effects were enhanced and differences in the quench front velocity were observed at the external border, at mid-radius and at the center (see Section 2.1). Consequently, the calculations were performed with 2D meshing (five radial meshes). The selected tests correspond to particle diameter 4 mm and liquid injection velocities 0.555, 1.38, 1.94 and 2.77 mm/s. The five radial meshes have identical cross sections. The radial and axial distribution of power was prescribed according to the experimental data. We assume that near the wall, the porosity might be slightly higher, so we have prescribed arbitrarily a porosity 0.42 for the last two meshes, as it is usually slightly higher near the walls.

Fig. 7 shows the progression of water across the porous medium where the quench front appears clearly 2D because of the faster velocity of water along the side wall. On Fig.8, an example of temperature evolution for different tests is shown. The small differences in the initial temperature of the bed before quenching may be due to external heat losses. The experimental tube was not isolated and the heat losses were not estimated.

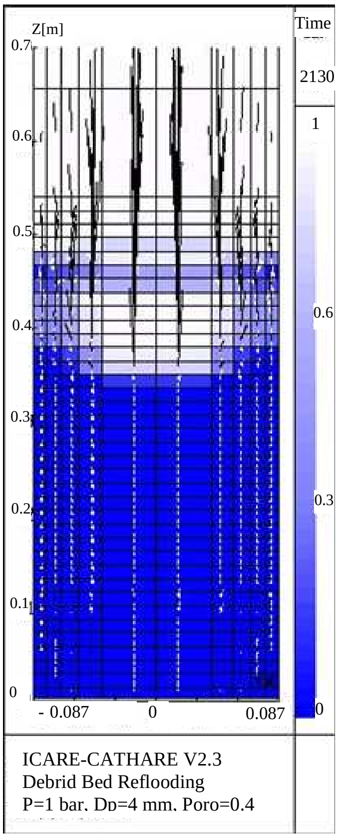

Fig. 7: Distribution of calculated void fraction showing the faster progression along the side wall

Table 2: Quench front velocities for different tests with initial temperature 700°C and particle diameter 4 mm. ICCV2- 2D meshing calculations, PRELUDE- minimum and maximum quench front velocities.

		Tref=105°C	Tref=95°C	Difference
v_inj=0.555 mm/s	ICCV2	0.69-0.7 mm/s	0.41-0.43 mm/s	3.16-21.56%
	Prelude	0.71-0.8 mm/s	0.49-0.55 mm/s	
v_inj=1.38 mm/s	ICCV2	1.44-1.9 mm/s	1.18-1.21 mm/s	0-7%
	Prelude	1.39-1.87 mm/s	1.1-1.21 mm/s	
v_inj=1.94 mm/s	ICCV2	1.9-2.82 mm/s	1.8-1.86 mm/s	8.7-18.9%
	Prelude	2.07-2.54 mm/s	1.65-2.3 mm/s	
v_inj=2.77 mm/s	ICCV2	2.02-3.94 mm/s	2.05-2.4 mm/s	0.6-35.7%
	Prelude	2.04-2.9 mm/s	2.11-2.41 mm/s	

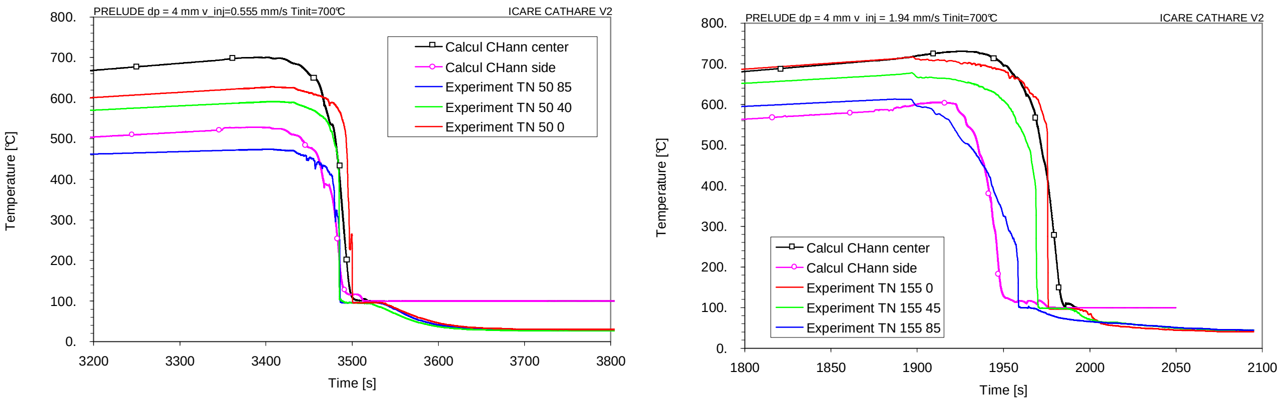

Fig. 8**:** Example of temperature profile at selected elevation for different PRELUDE tests

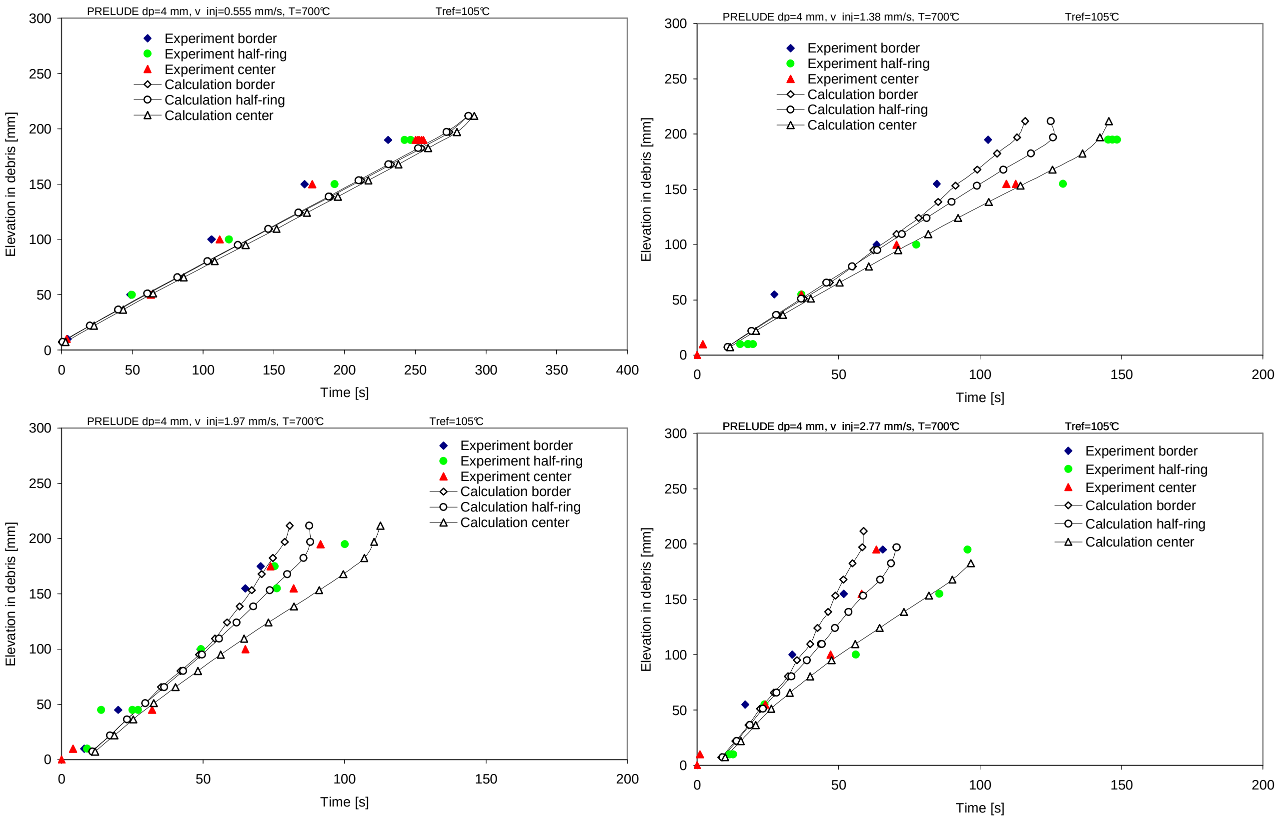

Fig. 9: Quench front velocity for PRELUDE tests with Tinit=700°C

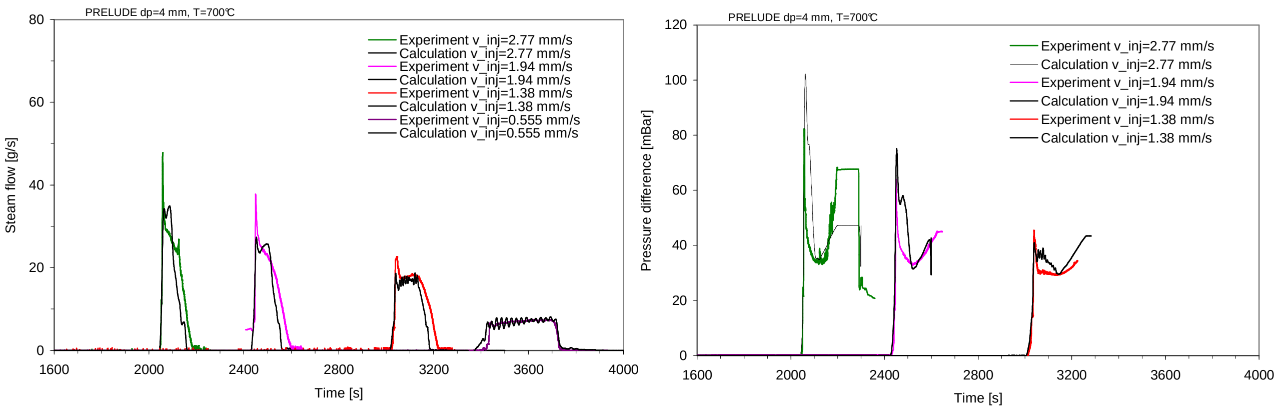

Fig. 10: Steam production (left) and pressure increase (right) for PRELUDE tests with Tinit=700°C

The calculated and experimental quench front velocities are summarized in Table 2. The calculations show that the two-dimensional effects increase as the liquid injection velocity increases. It is in agreement with experimental results (see Fig. 9). The model also predicts correctly the interval of maximum and minimum quench front velocities. However, the minimum quench velocity was calculated to be located at the center, for all tests. This is not in agreement with experimental results when the injection velocity is 1.38 and 2.77 mm/s. In those cases, the minimum quench front velocity was identified to be at mid-radius. Further experimental data are needed to understand the 2D instability of the quench front. Additional tests are planned.

On Fig. 10 (left) the steam flow at the outlet is plotted as a function of time. We can see that the time interval in which steam is produced as well as the mean value are well predicted. The value of the peak is missed but the pressure peak (Fig. 10 -right) is well calculated. It indicates that the model behaves consistently.

Finally, sensitivity calculations regarding user-defined parameters and model parameters were performed. As it was already mentioned, the porosity near the wall might be slightly higher and thus was prescribed at 0.42. On Fig. 11 we can see the impact of that value of porosity. The calculation showed that the porosity at outer ring has a small impact on quench front progression. As expected, increasing the porosity at the border, the 2D effects are slightly enhanced. The water progresses with higher velocity through the outer ring where the pressure drop is lower and consequently, the quench front velocity at the center ring slightly decreases. However, it can be seen that the different porosity in the bed is not the main criterion to trigger 2D effects. The instability in quench front progression was observed also in calculations with homogeneous porosity 0.4 (see Fig. 11).

On Fig. 12 we can see the impact of heat transfer layer length on calculation results. The correlation to calculate this parameter was estimated analyzing the experimental results and thus might be considered with some uncertainty. For the tests with injection water flow 2.77 mm/s, L1 was estimated around 70 mm. On Fig. 12 the calculations with L1=40 mm and L1=100 mm are presented. Thus, and uncertainty ±43% in L1 was tested. The impact on the quench front velocity is about ±12%. For a higher heat transfer layer length the quench front velocity at border and mid-radius increases, and the instability (2D effect) in the progression of quench front increase. It is interesting to note that a similar conclusion was drawn by Tutu et al. [8] who proposed a criterion for 2D effects based on this heat transfer layer length.

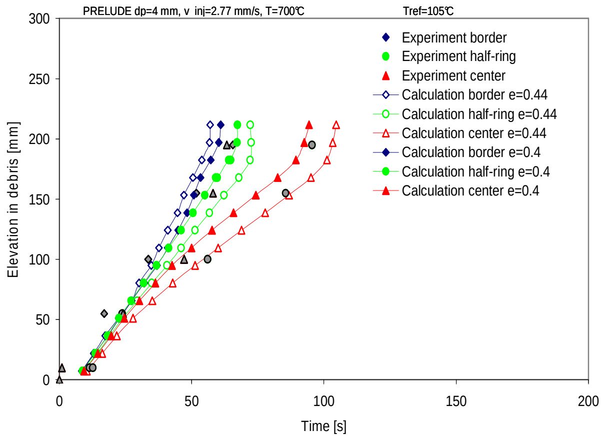

Fig. 11: Effect of porosity at border on calculation results

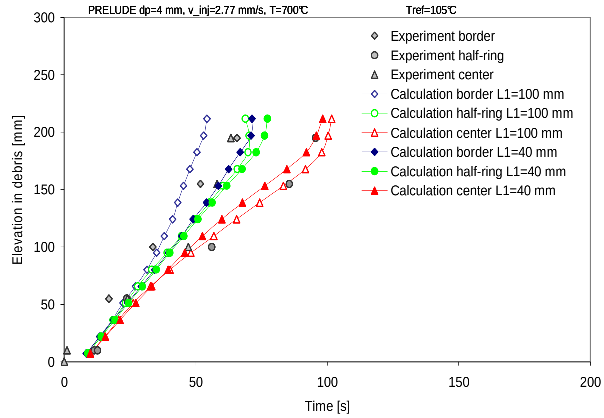

Fig.12: Effect of heat transfer layer length on calculation results

5. CONCLUSIONS

The quenching of a superheated particle bed was studied, using the first series of PRELUDE tests with initial temperature 400°C and 700°C. The results brought new data that contribute to understanding of quenching of a particle bed with bottom cooling injection. The presented analysis concerns the experiments with a debris bed consisting of 4, 2 or 1 mm particles. The liquid flow injection at the bottom of test section was 0.555-5.55 mm/s. The modelling of heat transfers in nucleate and transition boiling regimes was improved. A criterion characterizing the transition between the film boiling and transition zone was proposed. The criterion is based on the identification of a length where the transition boiling occurs. The correlation for this heat transfer layer was proposed analyzing the PRELUDE experimental results. The 2D meshing calculations were performed for the tests with initial temperature 700°C. The calculations show that the model well predicts 2D effects with different quench front velocities at border, mid-radius and center. The maximum and minimum quench front velocities are well predicted. However, for the tests with water injection velocity 1.38 and 2.77 mm/s, the maximum quench front velocity was observed at the center. It is not in agreement with calculation results where it was observed at mid-radius. Further analyses are ongoing. The calculation results show that the model is able to predict quenching velocity for different inlet flow rates and different particle diameters, in the whole range covered by PRELUDE experiments. The time dependent steam production calculated for the selected tests is also in agreement with experimental results. Calculations clearly show the propagation of a two-phase quench front separating the superheated steam region and the subcooled water region. After a transient evolution resulting in a peak of the quench front velocity, the evolution is quasi-steady. The pressure difference across the debris bed is also well predicted which indicates that the model behaves consistently. Such results are encouraging for application of the model to reactor accident simulations at a late stage of degradation, with formation of a large debris bed during reflooding.

NOMENCLATURE

Q_{CHF}	critical heat flux
hcv,l	heat transfer coefficient in convection to liquid
hcv,g	heat transfer coefficient in convection with gas
d_p	particle diameter
g	gravitation acceleration
hnb	nucleate boiling heat transfer coefficient (Thom's correlation)
H	characteristic length
k	thermal conductivity
L1	heat transfer layer length
Q	heat flux
T_{sat}	saturation temperature
T_{ref}	reference temperature
T_w	solid temperature
T_{max}	maximum (initial) temperature
T_{bo}	critical heat flux temperature
T_{mfs}	Leidenfrost temperature
t	time
v	velocity
v_inj	water injection velocity (out of pore)
v_{pore}	water injection velocity (in pore)
v_qf	quench front velocity
z	axial elevation

Geek letters

α	void fraction
ϕ	diameter
ε	porosity
ρ_l	density of liquid
σ	surface tension
κ	Fraction of thermal capacities
θ	Temperature function
ζ	Exponent in temperature function in transition zone

ACKNOWLEDGMENTS

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