Quenching of a highly superheated porous medium by injection of water

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Abstract. Understanding of two-phase flow through porous medium with intense phase change is of interest in many situations, including nuclear, chemical or geophysical applications. Intense boiling occurs when the liquid is injected into a highly superheated medium. Under such conditions, the heat flux extracted by the fluid from the porous medium is mainly governed by the nucleation of bubbles and by the evaporation of thin liquid films. Both configurations are possible, depending on local flow conditions and on the ratio of bubble size to pore size. The present study is motivated by the safety evaluation of light water nuclear reactors in case of a severe accident scenario, such as the one that happened in Fukushima Dai-ichi plant in March, 2011. If water sources are not available for a long period of time, the reactor core heats up due to the residual power and eventually becomes significantly damaged due to intense oxidation of metals and fragmentation of fuel rods resulting in the formation of a porous medium where the particles have a characteristic length-scale of 1 to 5 mm. The coolability of the porous medium will depend on the water flow rate which can enter the medium under the available driving head and on the geometrical features of the porous matrix (average pore size, porosity). Therefore, it is of high interest to evaluate the conditions for which the injection of water in such porous medium is likely to stop the progression of the accident. The present paper addresses the issue of modelling two-phase flow and heat transfers in a porous medium initially dry, where water is injected. The medium is initially at a temperature well above the saturation temperature of water. In a first part, a summary of existing knowledge is provided, showing the scarcity of models and experimental data. In a second part, new experimental results obtained in an IRSN facility are analysed. The experiment consists in a bed of steel particles that are heated up to 700°C before injecting water. The facility is briefly described. The velocity of the “quench front” (location where particles are quickly cooled down) and the total pressure drop across the medium are estimated. The dependencies of those quantities with respect to the inlet water flow rate, the initial temperature of the medium and the diameter of particles are obtained. In a third part, a model is proposed, based on a previously developed model which is improved in order to take into account intense boiling regimes (in particular nucleate boiling). The model includes a function that takes into account the contact area between water and the particles which depends on the temperature of particles and on the void fraction. That function affects the local intensity of phase change. The model involves a few parameters which cannot be evaluated analytically. Those parameters are bounded, following the analysis of experimental data. Finally, the model is assessed by comparison of calculations with those new experimental data. The satisfactory agreement shows that the model is almost predictive in the range of parameters studied. The experimental results also show that the quench front becomes unstable under certain conditions. This is also analysed and compared with the predictions of the model.
1. Introduction

In case of a hypothetical severe accident in a pressurized water reactor (PWR), the destruction of fuel rods and melting of materials lead to the accumulation of core materials, which are commonly called "debris beds". A debris bed may result from the quenching of very hot rods during the reflooding of the core; this was observed in TMI-2 reactor after the accident, with debris size of the order of a few millimeters [1]. Surprisingly, the reflooding of hot debris beds has not been studied extensively. Only a few experimental studies are available [2, 3, 4, 5, 6] and a few models have been proposed [5, 7, 8]. The existence of large temperature differences between the solid particles, the water and the steam makes modeling and experimental measurements more difficult. Furthermore, flow patterns cannot be observed easily but they are complex since, for very high temperature particles, steam becomes the "wetting" phase due to the presence of a stable steam film around the particles. This was observed experimentally only on single spheres, by [9]. However, the results obtained for spheres are difficult to apply to particle debris beds. Because of the lack of experimental data on real debris beds, models must rely on several assumptions. In this paper, we propose a model for two-phase flow in a porous debris bed, having the capability of dealing with the intense boiling that occurs during quenching. The progression of water and the timing of quenching are compared with experiments made by [10] in a quasi one-dimensional configuration, with initial temperatures up to 700°C. Some characteristic features of the flow are also described, and in particular the stability of the front.

2. The non-equilibrium two-phase flow model

A model for the three-dimensional two-phase flow in a heat-generating porous medium was earlier developed and assessed [11, 12, 13, 14]. For heat transfers, that model used formulations that were derived from simple configurations of stratified cells, where either the gas phase or the liquid phase is wetting the solid (they will be called SGL and SLG configurations in the paper). Actually, such configurations are only possible when the interface is rather stable, i.e. when either a liquid film or gas film is formed. However, it is known that in situations where the phase change is more intense, such as nucleate boiling, the interface is highly unstable because of the bubble formation and intermittent contact of the liquid phase with the solid particles. Here, it is proposed to extend that model to include such situations.

2.1. Heat transfers

Macroscopic energy conservation equations of the three phases were obtained by averaging the local energy conservation equations ([11], [15]). The complete set of closure problems was presented in [15]. However, the physical interpretation of the heat transfer terms was not straightforward. Here, we propose a new expression of the heat transfer terms where the physical meaning of each term can be clearly understood. The case SGL, where the gas wets the solid, is chosen as an example. The final formulation exhibits explicitly the thermal exchanges between gas and solid ($Q_{pg}$), and the three phase change terms ($Q_{gi}$), ($Q_{li}$) and ($Q_{pi}$). Two main volumetric exchange coefficients appear. The gas coefficient is $h_g^0 = \frac{12\lambda_g A^2}{\varepsilon^2 \alpha}$, where $\lambda_g$ is the gas conductivity, $A$ the specific surface, $\varepsilon$ the porosity and $\alpha$ the void fraction. The liquid coefficient is $h_l^0 = \frac{12\lambda_l A^2}{(1-\varepsilon)^2 \alpha}$. Another coefficient $h_g^1 = h_g^0 f(\alpha)$ is defined for the gas phase, where the function $f(\alpha)$ is:

$$f(\alpha) = (1 + 4(1 - \varepsilon)\lambda_g / 3\varepsilon\alpha\lambda_s)^{-1}$$

(1)

The function $f(\alpha)$ is almost equal to 1 except when $\alpha$ is close to zero. As an example, for a bed of spherical steel balls, $\lambda_g/\lambda_s \approx 0.002$ and $\varepsilon = 0.39$ which leads to the condition: $\alpha \gg 0.002$. With those notations and after some arithmetic transformations, the heat fluxes in the SGL configuration are:
\[ Q_{pg} = \frac{2}{3} h_{1g}^1 (T_s - T_g) \] (2)

\[ Q_{corr}^{pi} = \frac{2}{3} h_{1g}^1 (2T_g - T_s - T_{sat}) \] (3)

\[ Q_{li} = -h_{1g}^1 (T_l - T_{sat}) \] (4)

\[ Q_{gi} = -(h_{1g}^0 - \frac{1}{3} h_{1g}^1) (T_g - T_{sat}) \] (5)

\[ Q_{corr}^{gi} = \frac{4}{3} h_{1g}^1 (2T_g - T_s - T_{sat}) = 2Q_{corr}^{pi} \] (6)

One may note that \( Q_{corr}^{pi} \) and \( Q_{corr}^{gi} \) are close to zero if the gas temperature is close to its equilibrium value \( (T_{sat} + T_s)/2 \). Otherwise they act as corrective terms. Symmetrical expressions are obtained for the SLG configuration.

When superheated particles are considered, the modelling must also include other processes which involve a fast motion of the fluid phases and in particular the gas: nucleation and growth of bubbles along the solid surface, bubble motion and convective transfer with gas at high velocity. To take into account those processes, one of the difficulties of the analysis is that the pore-scale physics cannot be represented and solved using a quasi-steady configuration of the interface. However, the pore-scale physics may be represented by averaging over an interval of time the unstable and intermittent processes of bubble nucleation and departure or interface fast motion. We will introduce a geometrical relation and a time averaged closure relation in order to describe the bubble size and frequency of departure. Experimental measurements usually provide the heat flux extracted from the solid phase by nucleate boiling under the following form:

\[ Q_{nb}^{pi} = C_{nb} (T_s - T_{sat})^{m_{nb}} \] (7)

where the constant \( C_{nb} \) and the exponent \( m_{nb} \) depend on the fluid properties but also on the state and properties of the solid surface. Above the Leidenfrost temperature \( T_{mfs} \) (film boiling), a similar relation gives \( Q_{fb}^{pi} \) with a different constant \( C_{fb} \) and a different exponent \( m_{fb} \). In this paper we have chosen \( m_{nb} = 2 \) and \( m_{fb} = 0.75 \). The shape of the interface between water and steam depends on temperature conditions at the surface of the particles. The higher the temperature, the more likely the existence of a stable steam film around the particles. This is taken into account with the following function:

\[ \chi(T_s) = \left( \frac{T_s - T_{sat}}{T_{mfs} - T_{sat}} \right)^2 \] (8)

\[ Q_{pi} = (1 - \chi)Q_{nb}^{pi} + \chi Q_{fb}^{pi} + Q_{corr}^{pi} \] (9)

In addition, the following relation gives the size of the bubbles: \( d_b = (\sigma/(\rho_l - \rho_g) g)^{0.5} \). We assume that, for the regime of nucleate boiling, bubbles are generated at the saturation temperature and that the flux only contributes to evaporate water and create the bubbles (a negligible amount of heat is transferred to the gas or the liquid). When intense boiling occurs, one has to take into account the accumulation of steam within the pore space. The huge ratio between the liquid and vapor densities results in a fast increase of the vapor volume fraction. As an exemple, the bubble size is approximately 2.5mm for steam in water, at atmospheric pressure. More generally, we may state that there is an effect of the Bond number which is amplified by the reduced mobility of the gas phase at low void fraction, as expressed by the coefficient of relative permeability which remains close to zero up to relatively high values of the
void fraction (as an example, with a standard formulation of the relative permeability as $\alpha^3$, the relative permeability is less than 0.01 for $\alpha = 0.2$). Therefore, it is reasonable to consider that, during the quenching of a superheated porous medium, the combination of intense boiling and large drag force at low void fraction of the steam phase leads to a significant void fraction at the quench front (and also, obviously, downstream of the quench front). This means that the bubbly flow regime has a low probability of occurring, being replaced by a distribution of phases where pockets of steam occupy the pore space. Therefore, as the volume of vapor pockets increases, it is impossible for water to be in contact with all the surface of particles because the liquid film cannot become infinitely thin due to surface tension. Consequently, the fraction of particle surface in contact with the liquid must decrease when the void fraction increases. Without experimental observations of the flow, we just assume that a function $g(\alpha, Bo) = \frac{A_g}{A_p + A_l}$ gives the fraction of surface wetted by the gas. This is used to evaluate the heat transfers:

$$Q_{p\beta} = (1 - g(\alpha, Bo))Q_{p\beta}^{SLG} + g(\alpha, Bo)Q_{p\beta}^{SGL}$$

(10)

$Q_{p\beta}$ is also multiplied by $(1 - g(\alpha, Bo))$ since bubbles can only be generated where water is in contact with the particles. In the present study, we have chosen a very simple function: $g(\alpha, Bo) = \alpha$. Flow visualisations would be necessary to improve the definition of the geometrical function $g$.

To summarize, the overall combination of heat fluxes is illustrated schematically in Fig. 1(a) where the bubble generation may be simply seen as an additional contribution to the phase change rate and to the wall heat flux. Practically, it means that the bubbles are considered to be generated at the wall in all situations, and that they cross the liquid phase with a negligible influence on the average convection process. The quantitative effect on the total wall heat flux is represented in Fig. 1(b), where maximum and minimum values appear, as it is classically measured (Nukiyama-type curve).

The resulting macroscopic energy conservation equations are expressed as follows (valid for $SGL$ or $SLG$):
- gas phase:
\[
\frac{\partial (\alpha \varepsilon \rho_g h_g)}{\partial t} + \nabla \cdot (\alpha \varepsilon \rho_g \mathbf{v}_g h_g) = \nabla \cdot \left( K^*_g \nabla T_g \right) + \dot{m}_g h_g^{sat} + Q_{pg} + Q_{gi} + Q^{corr}_g \tag{11}
\]

- liquid phase:
\[
\frac{\partial ((1 - \alpha) \varepsilon \rho_l h_l)}{\partial t} + \nabla \cdot ((1 - \alpha) \varepsilon \rho_l \mathbf{v}_l h_l) = \nabla \cdot \left( K^*_l \nabla T_l \right) + \dot{m}_l h_l^{sat} + Q_{pl} + Q_{li} + Q^{corr}_l \tag{12}
\]

- solid phase:
\[
\frac{\partial ((1 - \varepsilon) \rho_s h_s)}{\partial t} = \nabla \cdot (K^*_s \nabla T_s) - Q_{pl} - Q_{pg} - Q_{pi} - Q^{corr}_s + \omega_s \tag{13}
\]

In these equations, \( h_\beta \) and \( T_\beta \) are the macroscopic enthalpy and the temperature of the \( \beta \)-phase respectively (\( \beta = g, l, s \) for the gas, the liquid and the solid phases respectively). \( K^*_\beta \) is the effective thermal diffusion tensor.

The phase change rate, which is obtained by adding the three phase equations and neglecting diffusion terms, is then given by the relation:
\[
\dot{m}_g = \frac{-Q_{pi} + Q^{corr}_{pi} + Q_{gi} + Q^{corr}_{gi} + Q_{li} + Q^{corr}_{li}}{h_g^{sat} - h_l^{sat}} \tag{14}
\]

### 2.2. Momentum balance equations

The friction forces on the fluid phases are taken into account by using the classical extension of Darcy’s law to two-phase flows. This means that viscous and inertial drag forces are calculated with relative permeabilities and passabilities coefficients, depending mainly on the void fraction.

When water is the wetting phase, the relative permeability and the relative passability for spherical particles have been chosen from the standard Brooks and Corey relation [16]. The exponents for the relative permeability and passability were chosen equal, as recommended by several authors [17, 18, 19, 20]. When the gas is the wetting phase [11] had proposed alternative relations for the relative permeabilities \( k_{rg}^{GGL} \) and \( k_{rl}^{GGL} \). Both relations are used here and combined with the parameter \( \chi \) to take into account the partial contact of each fluid phase with the particles: \( k_{rg} = (1 - \chi) k_{rg}^{GGL} + \chi k_{rg}^{GGL} \).

\[
\alpha \rho_g \left( \frac{\partial \mathbf{v}_g}{\partial t} + \mathbf{v}_g \nabla \mathbf{v}_g \right) = -\alpha \nabla p_g + \alpha \rho_g \mathbf{g} - \varepsilon \alpha^2 \left( \frac{\mu_g}{K_{kg}} \mathbf{v}_g + \varepsilon \alpha \frac{\rho_g}{\eta_{kg}} \mathbf{v}_g | \mathbf{v}_g | \right) \tag{15}
\]

\[
(1 - \alpha) \rho_l \left( \frac{\partial \mathbf{v}_l}{\partial t} + \mathbf{v}_l \nabla \mathbf{v}_l \right) = -(1 - \alpha) \nabla p_l + (1 - \alpha) \rho_l \mathbf{g} - \varepsilon (1 - \alpha)^2 \left( \frac{\mu_l}{K_{kl}} \mathbf{v}_l + \varepsilon (1 - \alpha) \frac{\rho_l}{\eta_{kl}} \mathbf{v}_l | \mathbf{v}_l | \right) \tag{16}
\]

In these equations, \( \rho_\beta \), \( \mu_\beta \) and \( \mathbf{v}_\beta \) are respectively the average pressure, density, dynamic viscosity and velocity of the \( \beta \)-phase (\( \beta = g, l \)). For uniform spherical particles, the intrinsic permeability and passability are correlated with the particle diameter \( d_p \) and the porosity \( \varepsilon \) by the Carman-Kozeny relation [21] and Ergun law [22]. The capillary pressure is negligible because of the relatively large size of the particles. Therefore capillary effects are not discussed further.

### 3. Applications to 1D reflooding from bottom

IRSN has set up the PRELUDE experimental facility to study debris bed reflooding and validate models. The debris bed (diameter 180 mm, height 200 mm and 24 kg of stainless steel spherical particles), is heated by means of an inductor. The debris bed is homogeneous, formed with 4, 2
or 1 mm diameter particles and porosity around 0.4 (see Fig. 2(a)). A non-heated bed of quartz particles is located below the bed of steel particles in order to support them, as it was not possible to use a metallic grid because of induction. 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 0.55 to 5.55 mm/s. Extensive series of experiments have provided a large amount of new data that significantly enhance the database of experimental results. This includes the prediction of 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. The velocity of the quench front is one of the key parameters to be validated in reflood analysis. The quench front velocity is identified from the determination of the elevation where temperature reaches the saturation value. It may be evaluated within the column for three different radii and five different elevations (see thermocouples positions in Fig. 2(a)). Calculations are made over a domain that covers the whole test section, including the bottom volume, the non-heated bed of quartz particles, the heated bed and the empty volume above. The meshing consists of 84 axial meshes (30 in the heated bed) and 5 radial meshes. That meshing may seem coarse but we verified that only limited differences were obtained with a finer meshing. The volumetric power is estimated before reflooding, at each thermocouple location, from the initial increase of temperature, just at the start of induction.

In Fig. 3, we can observe that the increase of injection velocity leads to a destabilization of the quench front, with a faster quenching velocity along the wall and a slower velocity at the center. For the lowest injection velocity (0.55 mm/s), all the thermocouples located at the same elevation are quenched at the same time. But for 1.38 mm/s, at the same elevation, the thermocouple located along the wall is quenched earlier than at the center. The difference is even larger for an injection velocity of 2.77 mm/s. This effect is well reproduced by the calculations and the values of the quenching velocities at different radial positions are quite well predicted. Looking at the steam production in Fig. 4, we see that there is a correlation with the destabilization of the quench front. For the lowest injection velocity (0.55 mm/s), the steam production is constant during the reflooding period, indicating a quasi steady-state propagation of the quench front. At higher injection velocities, there is a peak of steam production before the quasi steady-state propagation. The intensity of the peak increases with the injection velocity.
and the duration of the steady state propagation decreases. For the highest velocity \((2.77 \text{ mm/s})\), the experiment shows a sharp peak and almost no steady-state plateau. Obviously, the existence of the peak is related to the transient destabilization of the quench front. On the contrary, if the front is stable and one-dimensional, there is no peak. Again, the calculations predict quite well the steam production, with the correct value of the steady state plateau and an acceptable value of the peak. In conclusion, the model seems to be able to capture the main processes that govern the progression of water within the porous medium and the associated steam production. Of course, it is not possible to validate local values of void fraction and heat fluxes but the overall behaviour is correct, both in time and space.

Figure 3. Effect of injection velocity on the stability of the quench front

The analysis of calculations for different parameters that cannot be measured allows to draw additional conclusions. The thickness of the two-phase region is observed to be a few centimetres and appears to be almost constant during the propagation. As it was discussed previously, the void fraction at the location of maximum heat flux is observed to reach high values (0.7-0.9). The liquid flow velocity increases downstream of the quench front, however the maximum values are small (below 1 cm/s), which indicates that there are no inertial effects on the liquid friction. The axial profile of local pressure indicate a change of slope at the quench front location. If this result is confirmed by the future tests with local pressure measurements, this will constitute an additional, and possibly more reliable, criterion to identify the position of the quench front.

In Fig. 5(a), we present a summary of the measured quenching velocities for various experimental parameters. We can see that the most important parameters are the injection velocity and the initial temperature of the particles. This is not surprising as it corresponds to what we would expect by doing a simple energy balance. More interestingly, the diameter of the particles also has an effect but it is less important and, in particular, there is only a small difference between particles of 1 mm and 2 mm. This has not been completely explained at present. The calculated quenching velocities for all those cases are predicted within 30% accuracy, which is acceptable. Results are not presented here due to lack of space.
are larger for the cases with 1mm particles, indicating that a geometrical effect is not well accounted for in the model. Possibly it is the effect of Bond number, which was neglected in the function $g$.

Finally, in Fig. 5(b), we present a graph where the ratio of the quenching velocity along the wall to the quenching velocity at the center, as a function of the pressure gradient generated in the particle bed by the steam flow. The gradient is evaluated from the measured steam flow rate, using Darcy-Ergun relation. When a plateau value did not appear clearly, an uncertainty range was estimated for the steam production and the resulting uncertainty on the pressure gradient is indicated on the graph. The stable quench front corresponds to a velocity ratio close to 1. We can clearly see the correlation between stability and pressure gradient. From that graph, we may estimate that the front is 1D and stable if the pressure gradient is lower than $3\rho_l g$.
4. Conclusions
In this paper, we have presented a three-temperature model for two-phase flow in debris beds. This model is implemented in the ICARE/CATHARE code, developed by the French Institut de Radioprotection et de Sûreté Nucléaire (IRSN) to study severe accident scenarios in Pressurized Water Reactors. The model is based on two generalized Darcy momentum balance equations and three energy equations closed by semi-empirical relations. A particular attention is paid to deal with configurations where the liquid/gas interface is stable (films) or highly unstable (intense bubble generation). The model is assessed by comparing with an experiment conducted by [10] in a bed of overheated steel balls. Comparisons with experimental data show that the model is able to predict the quenching velocity and the steam production. For high flow rates or high temperatures, the front is destabilized and two-dimensional effects appear. This transition is also predicted by the model. An experimental criterion for the stability of the quench front seems to be if the pressure gradient created by the steam flow downstream of the quench front is lower than $3\rho g$.

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