Multi-dimensional approaches for severe accident modelling of LWRs

Florian Fichot, Olivier Marchand, Gaetan Guillard, Patrick Drai, Patrick Chatelard and Joelle Fleurot
Division of Major Accidents Prevention
Institut de Radioprotection et de Sûreté Nucléaire (IRSN)
13115 St Paul lez Durance - France
florian.fichot@irsn.fr

1. Abstract

Severe accidents in PWRs are characterized by a continuously changing geometry of the core due to chemical reactions, melting and mechanical failure of the rods and other structures. These local variations of the porosity and other parameters lead to multi-dimensional flows and heat transfers. In this paper, a comprehensive set of multi-dimensional models describing heat transfers, thermal-hydraulics and melt relocation in a reactor vessel is presented. Those models are suitable for the core description during a severe accident transient. A series of applications at the reactor scale shows the benefits of using such model.

Keywords: Severe accident, heat transfers, thermal hydraulics, melt progression, multi-dimensional, porous medium

2. Nomenclature

K	Conductivity tensor
H	Specific enthalpy
T	Temperature
ρ	Density
ε	Porosity or emissivity
v	Velocity
S	Saturation (relative volume fraction)
A	Surface density
d_p	characteristic diameter
P	Pressure
g	Gravity acceleration
μ	Kinematic viscosity
α	Void fraction
s,l,g	Index for solid, liquid or gas phase

3. Introduction

After the Three-Mile Island accident, in 1979, research programs about severe accidents in nuclear reactors were initiated in many countries. It consisted in experiments, code developments and reactor studies which have led to a better understanding of the important physical processes involved during an accident scenario. It has also helped to define a "typical" accident progression. A severe accident occurs when a loss of coolant event is long enough to cause the core uncovery and a substantial degradation or even melting of the core assemblies. Therefore, one of the characteristic features of a severe accident is the progressive loss of geometry of the core.

The causes of deformation or degradation of fuel rods are numerous. For a low pressure scenario, initial deformations may be caused by the creeping of Zircaloy claddings due to the internal pressure of the fuel rods. At higher temperatures (above 1300K), the claddings are oxidized by steam. This chemical reaction is highly exothermal which leads to a fast increase of temperature in the regions where oxidation occurs. When the temperature reaches the melting point of Zr, UO_2 pellets are partially dissolved by molten Zr. This has two effects on the geometry of the fuel rods : first, the pellets are no longer cylindrical and second, the molten (U-Zr-O) mixture relocates downwards, along the rods. All these mechanisms may progressively weaken the rods that may finally lose their mechanical strength and collapse into fragments. These fragments, with different size, shape and composition, form a debris bed, as it is usually called.

The average "particle" diameter is of the order of a few millimetres. Fig. 1 gives a qualitative idea of the degradation processes that may occur in the reactor core if it undergoes an accidental scenario leading to a temperature escalation. The temperature of severely damaged rods and fragments may finally reach the UO_2 melting point which leads to a complete liquefaction of the core materials and the formation of a massive molten pool.

The evolution and processes described above are mainly governed by the local temperature, often in a non-linear way (i.e. creeping, oxidation and dissolution all follow Arrhenius kinetic laws). Additionally, because of the non uniform burn-up along the fuel rods and across the core, the temperature field in the core, after uncovery, is not uniform. Differences of a few hundreds Kelvin may exist between the bottom of the core and the centre. This will obviously result in differences in the local state of degradation. Those differences are amplified by the non-linear kinetic laws. A simple example is to consider rods located in the middle plane, at different radii. At the center, when the temperature reaches 1800K, which is just prior to the fast temperature escalation caused by oxidation, the rods will reach the melting point of Zr and UO_2 will be dissolved within a few minutes, resulting in a highly damaged geometry. On the contrary, the external rods, which have a lower temperature may remain almost intact for a much longer time.

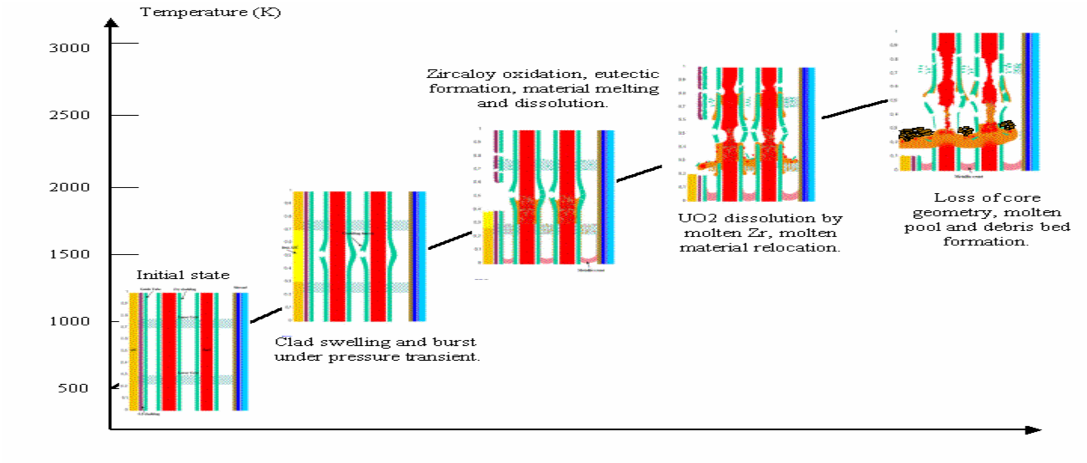

Fig. 1: Schematic view of a nuclear reactor core degradation scenario

The thermal hydraulics also induce non uniformities of the degradation. In particular, during oxidation, hydrogen is produced and accumulates downstream (i.e. at higher elevations). If steam is completely consumed, the local oxidation is stopped. This results in non uniform oxidation, even in the areas where the temperature is almost uniform.

Another cause of non-uniformities is the relocation of materials, either by melting or by collapse of the rods and other structures.

Therefore severe accidents are characterized by a continuous evolution of the geometry of the core, from an initially uniform but non-isotropic medium (parallel cylinders) to a more isotropic (because of the formation of debris) but non uniform medium. In a damaged core, the porosity may vary from zero in the areas where molten materials have been accumulated to one in the cavities where rods have collapsed.

The evolution towards a more isotropic medium implies that the modelling should be at least two-dimensional. Current codes all use a two-dimensional representation of the core or the vessel but not all of them actually model the heat transfers, the coolant flow and the melt progression in two dimensions. Such modelling requires the use of up scaling methods which allow representing a complex medium as a continuous one. In this case, it must be noticed that in most parts of the reactor core, except in the cavities, the randomness of the particle distribution and the small size of the particles compared to the size of the medium allows to use homogenization methods in order to treat the damaged core as continuous medium.

The purpose of this paper is to describe some models developed by the Institute of Radioprotection and Nuclear Safety (IRSN) in the last few years and integrated in the ICARE/CATHARE code in order to improve the accuracy of severe accident predictions.

Most severe accident experiments with real materials (i.e. UO_2 and Zr) were performed at a scale which is not large enough (usually 20 rods) to be able to show significant multi-dimensional effects. Although not so fundamental at such a very small scale, the importance of multi-dimensional effects was however highlighted during the assessment of the first major version of the ICARE/CATHARE code (V1). The details of this extensive assessment may be found in [1]. Indeed, keeping in mind that the ICARE/CATHARE V1 code, which already included a preliminary 2-D corium relocation model, could also deal with 2-D thermal hydraulics (for single phase gaseous flow only), concurrent simulations of various SFD experiments (early or late degradation phase experiments) were therefore performed with ICARE/CATHARE at that time to compare both 1-D and 2-D modelling responses.

Comparisons between 1-D and 2-D thermal hydraulics against experiments conducted under a gas atmosphere showed that, as soon as important rod ballooning or partial blockages appeared in the core, the radial heat transport by the fluid became important and a 1-D multi-channels model was no longer sufficient to evaluate correctly the temperatures all over the bundle. The importance of a 2-D description of the fluid flows was confirmed by the validation against both PHEBUS FPT1 rod-bundle test and PHEBUS FPT4 debris bed experiment. The FPT1 calculations showed in particular that the activation of the 2-D gaseous thermal hydraulics model allowed to better match the evolution of the cladding temperatures (and in particular the radial temperature gradient in the bundle) thanks to the correct redistribution of the steam flow from a channel to the others when a local blockage occurred. It is interesting

to note that such an improvement was obtained although the convective power represented less than 20\% of the nuclear power. For the FPT4 test, very good results of the thermal behaviour could be obtained only with the 2-D gaseous thermal hydraulics model.
As far as the movement and relocation of materials during the late phase of the degradation process are concerned, the simulations of the PHEBUS FPT4, ACRR-DC1, ACRR-MP1 and RASPLAV-AW-200-4 experiments [2][3] demonstrated that, differently from the original 1-D candling model, a 2-D corium relocation model was able to properly reproduce the progression of a solid/liquid corium inside a porous medium, as well as the formation and expansion of a molten pool. Even in the early phase of the degradation process, the results obtained against the CORA-2, CORA-5, PHEBUS FPT1 and LOFT-FP-2 tests showed the global ability of both the 1-D and 2-D models to calculate the main physical phenomena occurring during the flow down of a liquid film along a solid surface such as axial relocation, heat exchanges between the corium and the solid rods, solidification of the corium and melting-solidification processes. But, unlike the 2-D model, the 1-D model was found unable to simulate the radial spreading in case of presence of an axial obstacle (blockage, plate ...), making its application valid only to rod-like geometries.
Moreover, as far as the scale effect was concerned, it was noticed that the deviations observed with the 1-D modelling, which were generally reasonable for small test bundles (~20-30 rods like in PHEBUS or PBF), could become no longer acceptable for larger cores such as LOFT (~120 rods), making the extrapolation of the 1-D results to the reactor conditions highly uncertain. Conversely, very promising results were obtained against the LOFT FP-2 experimental data using the 2-D corium relocation model.

In summary, although a simple 1-D multi channels approach (for both melt thermal hydraulics and relocation) could sometimes appear sufficient (case of poorly degraded small bundles), unavoidable deviations between the code simulations and the experimental data were exhibited using such a 1-D modelling in case of either small bundles more severely damaged or larger cores whatever the degradation level. Indeed, the interpretation of available SFD experimental data allowed to conclude that, the higher the degradation level is, or the larger the core size is, the more important an adequate evaluation of the fluid circulation is.
So, the lack of a multi-dimensional two-phase thermal hydraulics model appeared to be prejudicial to the achievement of best-estimate reactor studies with ICARE/CATHARE V1 in case of large core blockages (no treatment of the cross-flows inside the bundle) and/or in case of a large cavity appearance (no treatment of the natural circulation).
In accordance, a full multi-dimensional modelling (covering both the fluid flow and the corium behaviour) was clearly required to be developed in the next ICARE/CATHARE versions in order to be able to perform best-estimate full scale safety analyses not excluding the case of severely damaged reactor cores, with a possible late reflooding.
Although the aim of this paper is to give an overview of multi-dimensional models which have been proposed to calculate severe accidents, all the examples will be taken from the ICARE/CATHARE V2 code, because they were developed by the authors and they are believed to be representative of other models developed by other teams (which will be mentioned in the text). ICARE/CATHARE is developed by IRSN to be used as a tool for severe accident analysis in IRSN and other foreign institutes. Its range of applicability covers all kinds of accident sequences, from the initial phases (for instance a break in the primary circuit) to the LOCA phase and eventually to the core degradation and melting, and possible vessel failure. For that purpose, it includes all the necessary models to deal with the different physical and chemical processes involved during an accident sequence.

In a first part, the modelling of heat transfers will be described, with an emphasis on radiation which is the dominant mode of heat transfer. In a second part, the modelling of melt progression, across the core or in the lower plenum, will be described. The modelling of thermal hydraulics is not addressed here, due to the limited size of this paper. However it is also important to model it accurately, in particular during the possible reflooding of the core where multi-dimensional effects have a strong impact.
Finally, an accident sequence in a French PWR 900 MW will be presented to illustrate the application of all models together in realistic conditions.
The conclusion will summarize the advantages and limitations of the multi-dimensional approach.
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4. Modelling of heat transfers

In severe accident codes, a lot of attention must be paid to the modelling of heat transfers in the core because all the other degradation processes (oxidation, melting, relocation, FP release, etc.) actually depend on the accurate estimate of temperature. As mentioned in the introduction, the evolution towards a more isotropic medium implies that the modelling should be at least two-dimensional. Current codes all use a two-dimensional representation of the core or the vessel but not all of them actually model the heat transfers in two dimensions. One of the simplifications made in most codes is the assumption that axial radiative heat transfers are negligible compared to radial heat transfers. However, it was shown in [4] that such an assumption is not valid in the late phase of the accident and even during the early phase in some cases. In a similar way, the radial convective transport of energy is neglected very often, because the coolant flow is assumed to be mainly 1D in the axial direction. This is also not verified in the late phase of the accident and it will be shown in the last section, presenting a complete accident scenario calculation.
The heat transfer model used in ICARE/CATHARE is two-dimensional and derived from a volume averaging

method, as it is explained for example in [5]. It consists in a set of energy conservation equations for the solid elements (either rods or debris), the corium melt, water and steam. For simplicity, only the equation for the corium melt is given here, under a relatively standard form:

$$\frac{\partial}{\partial t}\left(\varepsilon S_l \rho_l H_l\right) + \nabla \cdot \left(\rho_l \vec{v}_l H_l\right) = \nabla \cdot \left(K_e \nabla T_l\right)$$
$$+ h_{sl} A_{sl}\left(T_l - T_s\right) + h_{gl} A_{gl}\left(T_l - T_g\right) + \varepsilon S_l \gamma_g \Delta H_{ox} + \varepsilon S_l \rho_l q_l$$

(1)

Notations are provided in the nomenclature. K_e denotes the effective thermal conductivity h_{sl} and h_{gl} are the interstitial convection heat transfer coefficient "*solid matrix-liquid melt*" and "*liquid melt-coolant fluid*" respectively.

Of course, similar equations are verified for the other phases and similar coefficients must be determined as well.

As it will be shown below, the diffusion term, i.e. $\nabla \cdot \left(K_e \nabla T_l\right)$ includes the effects of both conduction and radiation. It has a significant influence on the multi-dimensional heat transfers. It takes into account the geometrical configuration and the temperature. The evaluation of K_e is described in the two following subsections.

4.1 Radiative heat transfers

In severe accident codes, simple homogeneous radiative heat transfer models have been used, such as the Net Radiation Enclosure (NRE) method [6] or Hottel's method [7]. For instance, the application of those models in SCDAP and ICARE2 codes can be found in [8].

Some limitations of those models have been identified. In particular, anisotropic radiation effects must be included in the models to obtain more accurate results. This is not surprising because homogeneous models are based on the assumption of independent scattering, and cannot model properly the multiple reflections which are characteristic of the radiative transfer in a dense particle medium. Anisotropic effects can be included in homogeneous models, but it makes the determination of the optical coefficients (or the mean view factors in the case of the NRE method) very complex. Another limitation of the NRE model is that the method used to obtain the mean view factors for intact rods (i.e. Hottel's crossed strings method applied to cylinders) cannot be extended to strongly damaged rods or debris particles because of the local 3D geometry. Finally, due to the integral nature of the radiation transport equation, it is very difficult to solve in a 2D or 3D domain.

Cell models are an interesting alternative in the case of dense particle beds and, in particular, the radiative conductivity model is very attractive and useful for engineering heat transfer calculations.

Compared to other approaches such as the NRE method, it has the major advantage of leading to a tridiagonal system (in each direction) that is quicker to solve, because only the neighbouring meshes are coupled numerically. Moreover, this allows a straightforward extension of the model to 3D calculations. This numerical advantage and the fact that the geometry of the medium can easily be taken into account in the derivation method of the radiative conductivity are serious arguments to favour the use of this model. Therefore, it was implemented in ICARE/CATHARE, as an alternative to the standard NRE model.

It is interesting to notice that in an earlier study for EPRI, Viskanta [9] had introduced the modelling of the core as a two-dimensional anisotropic porous medium made of parallel cylinders (rods) where radiative heat transfers were taken into account by introducing a two-dimensional effective conductivity. The scope of that study was limited to the early degradation phase and natural circulation effects in the core. A similar approach was later used by [10] in the DEBRIS code developed by SANDIA for the USNRC. The DEBRIS code was dedicated to the study of late phase degradation, representing the degraded core as a two-dimensional debris bed made of particles and molten materials. The ICARE/CATHARE model follows the lines explored in those earlier works and introduces a more general formulation of radiative heat transfers that is suitable for both the early and late phases of a reactor accident.

4.2 Radiative conductivity

We consider that, from the initial state of the structures to the most severely degraded state, the core can be regarded as a porous medium with an opaque solid phase and a fluid phase. The intact or moderately damaged regions can be approximated by an arrangement of cylinders with a given porosity and, according to the accident scenario, the geometry of the pores can evolve as illustrated in Fig. \ref{fidegrad}.

In the porous medium that we have to describe, we assume the optically thick limit to be valid because the arrangement of particles is rather compact and their size is much lower than the size of the core. Under this condition, the net radiative flux at a particular point in space does not depend on far field effects. The local flux is only a function of local conditions and the transport rate can be described by a diffusion model, similar to Fourier's law for conduction. This leads to write the radiative flux such as:

$$q_r = K_r \nabla T$$

where K_r is the radiative conductivity of the medium. The general form of the radiative conductivity proposed initially by Vortmeyer [11] was:

$$K_r = 4Fd_p \sigma T^3$$

where d_p is a characteristic size of the particles and F is called the radiative exchange factor. Several other formulations of F can be found in the literature.

For the geometries of interest in an intact or damaged core, the derivation of K_r is rather long and complex and the details are given in [12] and [13]. A general presentation of this model is also provided in [4].

In the model, the non - or little - damaged reactor core is regarded as an array of parallel cylinders.

Therefore, the radiative conductivity tensor K_r is determined using an appropriate axis system. Figure 2 shows the selected axis system in which K_r becomes diagonal and can be written:

$$\mathbf{K}r = \begin{bmatrix} Kr_{\perp} & 0 & 0 \\ 0 & Kr_{\perp} & 0 \\ 0 & 0 & Kr_{//} \end{bmatrix} \quad (2)$$

where $Kr_{\perp}$ and $Kr_{//}$ are the equivalent conductivities in the perpendicular and the parallel directions to the cylinders.

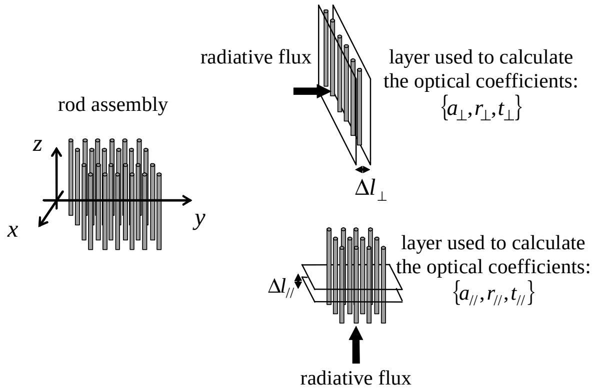


Fig. 2 Axis system, the rod assembly and the layers used to calculate the optical coefficients.

For a damaged core, modelled as a bed of spherical particles, the tensor K_r is isotropic $Kr_{\perp} = Kr_{//}$).

When the gas is assumed to be transparent, the radiative conductivity tensor is determined by its two main components:

$$\begin{cases} Kr_{\perp} = 4\left[\dfrac{2-(\hat{a}_{\perp}+2\hat{r}_{\perp})}{(\hat{a}_{\perp}+2\hat{r}_{\perp})}\right]\sigma T^3 d_{p\perp} \\ Kr_{//} = 4\left[\dfrac{2-(\hat{a}_{//}+2\hat{r}_{//})}{(\hat{a}_{//}+2\hat{r}_{//})}\right]\sigma T^3 d_{p//} \end{cases} \quad (3)$$

$\hat{a}$ and $\hat{r}$ are respectively the absorption and diffusion coefficients of the medium. Correlations were obtained by [12] for these optical coefficients, for an array of cylinders (intact core) and for an arrangement of spheres (debris bed). The general form is the following:

$$\hat{a} = \varepsilon_s n_s(p) C_a \quad (4)$$

$$\hat{r} = \varepsilon_s n_s(p) C_r \quad (5)$$

where ε_s is the particle emissivity, $n_s(p)$ is a geometrical factor representing the effective volume occupied by a particle in a representative cell, C_a and C_r are correction factors that account for the temperature variations on the solid surfaces and the presence of neighbouring particles. They depend on the shape of the particles (cylinders or spheres) and on the geometry of the arrangement. The details are given in [12] and [13].

4.3 Effective conductivity K_e

Although the radiative heat transfers are predominant most of the time, there are cases where the thermal conductivity through the solid particles (rods or fragments) must be taken into account. In particular, at low temperature or when the porosity is low, thermal conductivity becomes the dominant mode of heat transfer. If we consider that the thermal transfer inside the porous medium is completely characterized by the radiative and the thermal conductivity tensors (K_r and K_t respectively), an equivalent conductivity tensor K_e may be defined.

In many classical approaches, and in particular for continuous methods, both heat transfer modes are considered in parallel and the equivalent conductivity is expressed as:

$$K_e = K_t + K_r \quad (6)$$

We have chosen a cell method to take into account the interaction between radiative and conductive heat transfer inside a representative cell. The details of the derivation are given in [4]. A comparison was made with several existing models, in particular for beds of particles which have been studied extensively. It was shown that K_e obtained with the present model is comparable to the values predicted by those other models. Several experiments were selected for the assessment of the ICARE/CATHARE model, mostly for particle beds: ACRR-DC1 and DC2, RASPLAV-AW, ACRR-MP1 and MP2, RASPLAV-AW and PHEBUS FPT4. The details about the calculations and comparisons with DC1 experimental data can be found in [14], where a very good agreement was obtained. A good agreement was also found for ACRR-MP1 and MP2 [2], for PHEBUS-FPT4 and for RASPLAV-AW experiment [3]. For the assessment in rod geometry, Cox results [15] were found to be the only available reference. The calculations of Cox experiment with the present model may be found in [4].

4.4 Particular configurations: cavity and molten pool

During the evolution of core degradation, two singular configurations may appear.

The first singular configuration is the molten pool which results from a complete densification of the medium because of melting (the porosity is zero). In this case, the radiative conductivity vanishes and the thermal part only remains, governed by natural convection and turbulent diffusion. To properly take into account natural convection, a resolution of Navier-Stokes equations is necessary. However, this requires a very fine meshing, which is not compatible with the usual CPU time requirements for severe accident computer codes. This difficulty is usually treated by using correlations for turbulent diffusion in the molten pool, which provides the average heat transfers in the pool with a reasonable accuracy but cannot give details of the heat flux distribution along the boundaries of the pool. The turbulent thermal diffusion is introduced in the expression of K_t and the general formulation described above is still valid.

The second singular configuration is the large cavity which may be formed after the collapse or melting of rods (such as in TMI-2). In this case, the medium is mostly transparent and the porosity is equal to one, which means that thermal conduction is negligible and the radiative conductivity model cannot be applied. This configuration must be treated by a different model which identifies the boundaries of the cavity. This model is not described here.

5. Thermal Hydraulics

As it was mentioned in the introduction, many processes of the core degradation lead to multi-dimensional flows of the coolant. In particular, in the case of complete blockage of channels between the fuel rods. This has led to many studies about the coolability of a degraded core, in particular in case of reflooding.

The modelling of two-phase flow in the ICARE/CATHARE code is based on the two fluid model. The liquid and gas phases are described separately in terms of two sets of conservation equations governing the balance of mass, energy and momentum. The sets of equations are coupled by interaction terms which govern transfers of mass, energy and momentum.

The two-fluid model is solved numerically in two steps. First, the system of equations is discretized using a finite volume technique. In order to obtain numerical stability, the discretization is done on a staggered mesh. The second step is to solve the system of equations, at each point of the grid, in time, using Newton's method. The numerical scheme is semi-implicit.

Modelling two-phase flow in porous media such as a rod bundles or debris beds requires the use of specific equations for the momentum conservation, described in the following section.

5.1 Momentum Balance Equation

The momentum balance equation used to describe two-phase flow in a debris bed of porosity ε is a phenomenological extension of the one phase Darcy law, as it is explained in [5] or [16]. A generalized Darcy law is written separately for each phase. For the gas phase it is given by:

$$\alpha\rho_g\left[\frac{\partial\vec{v}_g}{\partial t}+\vec{v}_g\cdot\nabla\vec{v}_g\right]+\alpha\vec{\nabla}P_g=\alpha\rho_g\vec{g}$$
$$-\varepsilon\alpha^2\left[\frac{\mu_g}{KK_g}\vec{v}_g+\varepsilon\alpha\frac{\rho_g}{\eta\eta_g}\vec{v}_g\left|\vec{v}_g\right|\right]-\frac{1}{\varepsilon}\vec{F}_i \qquad (7)$$

where α is the gas phase volume fraction and $\vec{v}_g$, ρ_g, P_g and μ_g are the macroscopic velocity, density, pressure and the viscosity of the gas phase respectively. The first term on the left-hand side is the accumulation term while the second term is the gas pressure gradient. The first term on the right-hand side is the Darcy term for a two-phase-flow along with its Forchheimmer correction. The parameters K and η represent the permeability and passability of the medium. They depend on the characteristics of the porous medium, such as particle diameter and porosity, and are independent of the flow. The relative permeability and passability, K_g and η_g, are corrections to K and η which take into account the two-phase nature of the flow. K_g and η_g are functions of the local saturation $s=1-\alpha$ of the fluid. The equation simplifies to the classical one phase flow Darcy law if one of the phases is absent. The third term represents the interfacial friction between the liquid and the gas [17].

Similarly, the generalized Darcy's equation for the liquid phase is:

$$(1-\alpha)\rho_l\left[\frac{\partial\vec{v}_l}{\partial t}+\vec{v}_l\cdot\nabla\vec{v}_l\right]+(1-\alpha)\vec{\nabla}P_l=(1-\alpha)\rho_l\vec{g}$$
$$-\varepsilon(1-\alpha)^2\left[\frac{\mu_l}{KK_l}\vec{v}_l+\varepsilon(1-\alpha)\frac{\rho_l}{\eta\eta_l}\vec{v}_l\left|\vec{v}_l\right|\right]+\frac{1}{\varepsilon}\vec{F}_i$$

(8)

For a debris bed formed by mono-disperse spherical particles, the permeability and passability can be correlated to the particle diameter d_p and the porosity ε, [5][18][19][20][21]. The relative permeability and the relative passability for a spherical particles debris bed may be chosen as proposed in [5] or [21].

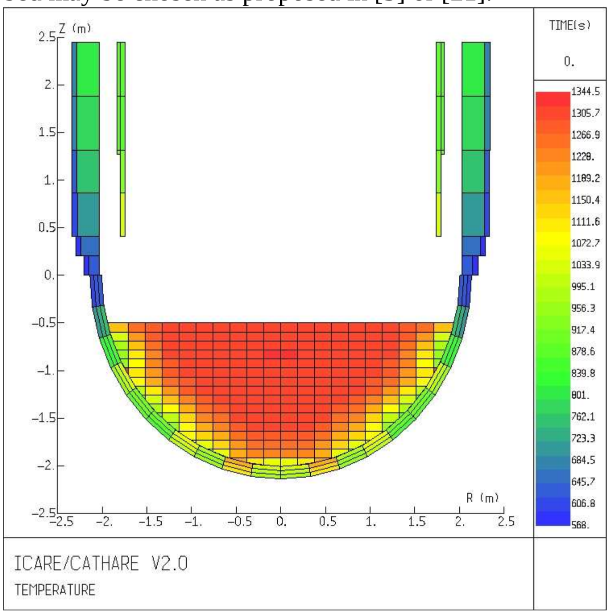


Fig. 3: View of the lower plenum filled with debris, before reflooding.

Relations for the relative permeabilities and passabilities have been widely used, with success, in the estimation of the dry out heat flux of an internally heated debris bed [19][21]. It is important to emphasize that they are valid when the liquid is the “wetting” phase. If the gas become the “wetting” phase, which may happen because of “calefaction” during the reflood of a debris bed at high temperature, the validity of these expressions is uncertain [22]. To our knowledge, there are no published correlations for closure laws of two-phase flow momentum conservation equations when steam is the wetting phase. This is most probably an essential issue in modeling debris bed reflooding.

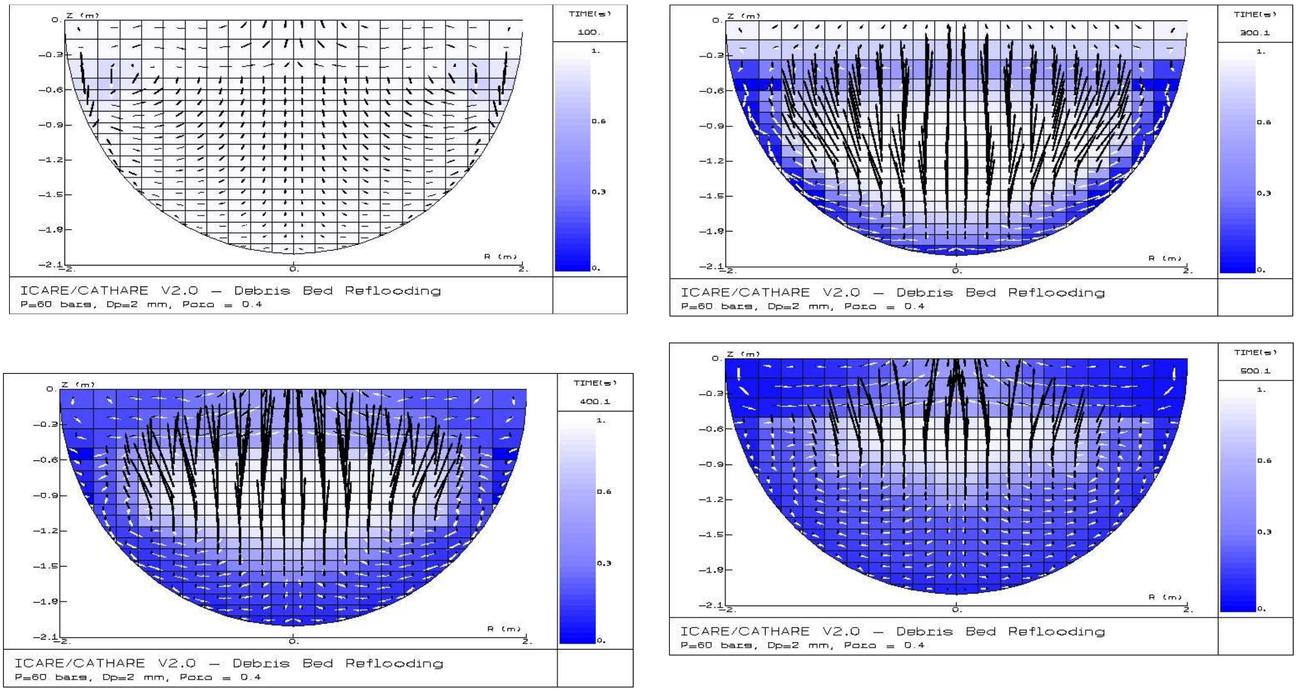


Fig. 4: Void fraction and velocity field during reflooding at 100s, 300s, 400s and 500s.

5.2 Application to the reflooding of debris bed

In this section, an example is shown for the reflooding of a debris bed made of 2mm particles, with a power of 200 W /kg of fuel and a porosity of 0.4. The pressure is 60 bar. The initial temperature is 1350K, which corresponds approximately to 800K above the saturation temperature. Water comes from a downcomer located above the lower plenum and the debris bed (see Fig. 3). The characteristic features of the transient flow are summarized below.

Because of the slope of the lower head, water can flow along the wall without any counter-current effect and steam escapes through the upper part of the debris bed. Moreover, the colder temperatures along the vessel wall favour a faster quenching of that region and, as it can be seen in Fig. 4, the main liquid flow path is located along the bottom wall. Penetration of water from the top of the bed is limited by the strong steam flow resulting from evaporation of water at the bottom. As a result, a liquid pool forms above the debris bed, and a dry "bubble" appears in the centre part of the bed, where the temperature keeps increasing. This bubble is progressively quenched by water, as water is continuously driven into the bed by hydrostatic pressure difference. The time of quenching strongly depends on the particle size, as expected.

As for 2D dryout, it appears that 2D reflooding is mainly driven by gravity and that the total quenching time depends on the maximum mass flow of water that can penetrate into the debris bed. Water penetration is not strongly limited by steam counter-current because steam is driven out of the debris bed far from the location of water penetration.

6. Modelling of melt relocation

The relocation of (U-Zr-O) mixtures along the rods, resulting from cladding failure and fuel dissolution, is an important step in an accident scenario. In the late phase, the massive relocation of molten fuel mixed with other materials across porous debris is also a key process leading to the molten pool formation. A good simulation of all these events is required for a proper description of the phenomena taking place during a severe accident.

The modelling of relocation of materials outside of cylindrical tubes (i.e. fuel and control rods) is usually one-dimensional whereas the relocation across particle debris beds has been modelled in two dimensions since a long time [23],[24]. Such works have opened a way to the elaboration of a general relocation model in ICARE/CATHARE for the flow of liquid mixture either along rods or through particles. Among the advantages of such a model is the single formulation for liquid mixture relocation either along the rods or in a porous debris bed, which simplifies the numerical resolution. Another improvement is the possibility to compute the radial spreading of corium across the rods.

The establishment of the conservation equations for the liquid mixture falling flow (momentum) in two directions (axial and radial-horizontal) is the main feature of this model for simulating the melt relocation. As for the thermal hydraulics model, the conservation equations are obtained with the volume averaging method. Details can be found in [25]. This method is especially interesting for such cases where the global interface between the fluid and the solid is complex, but may be reduced to a simple geometry when one considers a very small volume (i.e. one rod and the surrounding melt). The periodicity of the arrangement of rods or particles allows to define easily an elementary cell in which the momentum transfers can be calculated. The results of this local analysis are then used in the averaged form of the global conservation equations. The model is valid for both the rods and debris configurations (only the correlation used in the momentum equation change).

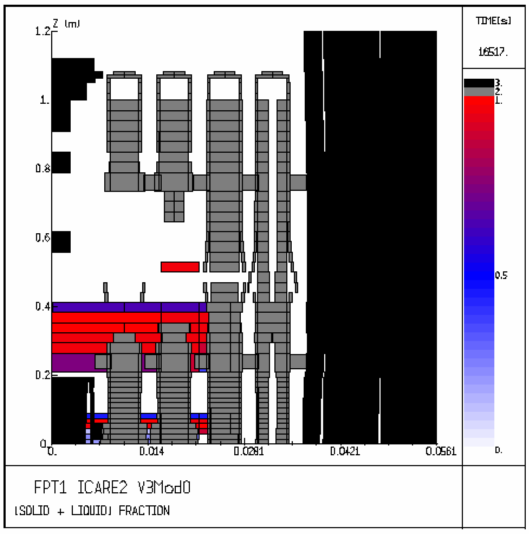


Fig. 5: Mass distribution of materials in PHEBUS FPT1 bundle at 16,500 s.

However, an additional modelling difficulty is introduced because of phase changes which may affect the corium as it relocates across the core. The first phase change is solidification due to changes of composition or temperature of the melt. The second phase change is the separation in two immiscible liquids when steel is present in the mixture. This results from a miscibility gap in the quaternary phase diagram (U-Zr-Fe-O).
The modelling of solidification is usually made in a simple way. Considering that the flowing mixture is convectively mixed and is homogeneous in composition and temperature, one may assume that solidification will occur as a distributed nucleation of crystals inside the mixture (i.e. precipitation). In such a case, it is usual to modify the apparent viscosity μ_{eff} of the melt to take into account the transport of solid particles. Several correlations are available to calculate μ_{eff} as a function of the solid fraction.. μ_{eff} is a also function of the temperature, which introduces a coupling between the energy and the momentum equations. This leads to implement an iterative method for the numerical resolution of the system.
The modelling of stratification is more complex and requires a coupled calculation of the thermo chemical equilibrium and the phase separation. Because of its relative complexity, it will not be described here, but details may be found in [26].

It is worth mentioning that the model treating the

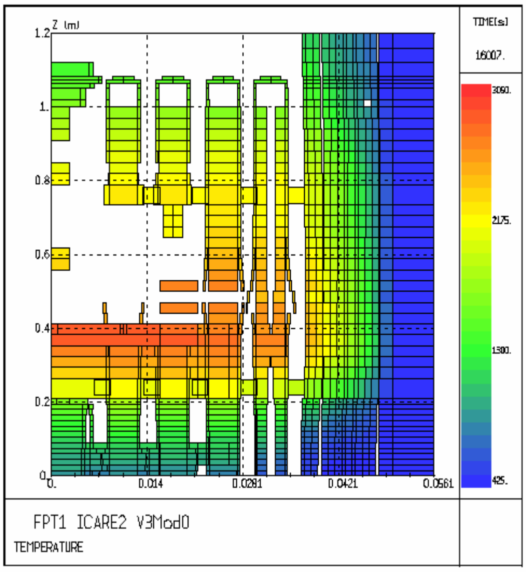


Fig. 6: Temperature of materials in PHEBUS FPT1 bundle at 16,500 s.

melting of debris and melt relocation (without stratification) was already assessed on several experiments such as PHEBUS-FPT4 or RASPLAV-AW-200-4 (see [3] for example) where it proved to be able to predict such processes quite accurately. An application of the relocation model to a rod bundle experiment (PHEBUS FPT1) has also shown the advantages brought by such a two-dimensional model [27]. This case is chosen as an example and shown on Figs. 5 and 6. In Fig. 5, the red color in several nodes of the inner rings at elevations over the lower grid indicates the presence of solid debris and molten materials filling the free volume between the remaining rods. The blue-red shaded nodes at the bottom of the bundle correspond to the relocation of metallic melt coming from the control rod (i.e., Ag-In-Cd material and Stainless Steel cladding). Due to its lower melting point, the metallic melt relocates to the elevations where the temperatures are low enough to cause it to freeze. This accumulation of materials causes the deviation of the gas flow towards the outer part of the bundle.
A molten pool has formed inside the debris bed. Since the solid relocation of fuel pellets has occurred, it has led to the displacement of the hottest point to the lower part of the bundle (Fig. 6).

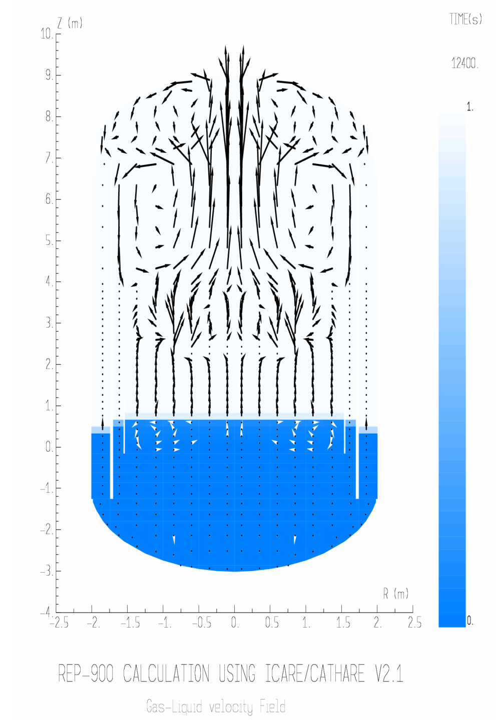
7. Application to a reactor case

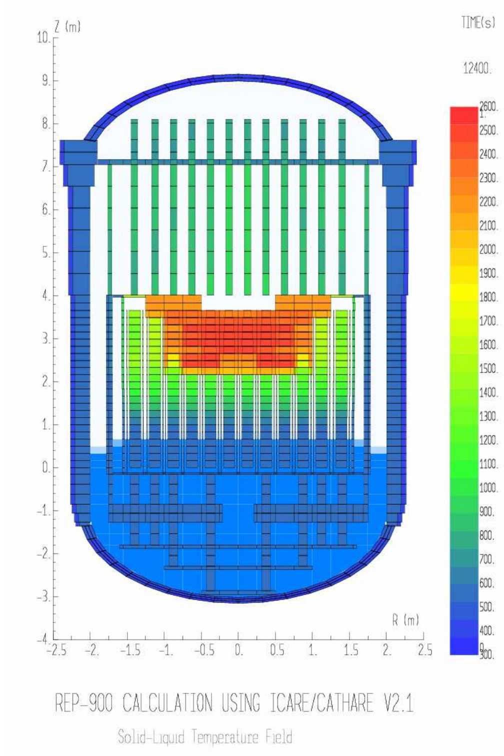
To better illustrate the use of all the models described in the previous section, a complete severe accident sequence in a French PWR (900 MWe) is presented. It corresponds to the rupture of two steam generator tubes (SGTR) leading to core melting and relocation down to the lower plenum. All models are activated and they are solved with a semi-implicit coupling, except for melt relocation which is calculated after the temperatures have been solved.
In order to define an accidental scenario which leads the reactor core to a severe situation, several assumptions regarding both safety systems availabilities and operating control have been defined. The main hypothesis are to suppose both the steam generator auxiliary feed-water system and the safety injection system (high and low pressure) unavailable.
This accidental transient can be divided into two characteristic phases.
In the first phase which occurs just after the rupture of two steam generator tubes, primary circuit is depressurised from 155 bar to the secondary pressure driven by GCTA valves (76 bar). During this phase, there is a mass flow rate from primary to secondary circuit induced by gradient of pressure, and a loss of mass from secondary to atmosphere induced by GCTA valves. The total mass of liquid in the reactor decreases and leads to an uncovering of the core (second phase or degradation phase).
In this second phase (10000s), the increase of the core temperatures following the core drain out leads to fuel cladding oxidation and later to a severe core degradation, with material melting and relocation (Figs. 7 and 8). During this phase, molten materials relocate down to the lower plenum (see Fig. 8).
The calculations clearly show the complex flow pattern resulting from the degradation in the upper part of the core and the upper plenum where two-dimensional recirculations are formed (Figs. 7 and 8). These recirculations actually occupy all the volume located above the water level. This has a strong impact on the steam temperature at the outlet of the core and thus in the hot leg, as it was already shown in [28]. It also has a strong impact on the total hydrogen production. The melt progression is obviously two-dimensional, as it starts from the center towards the external assemblies and finally flows along the core by-pass towards the lower plenum.

Since this accident sequence is just provided as an illustration, it will not be discussed further. Detailed comparisons of 1D and 2D calculations with different versions of ICARE/CATHARE (V1 and V2) are planned, in order to quantify the benefits of using 2D models. Preliminary conclusions have been presented in [29].

8. Conclusions

A severe accident in a PWR is characterized by an ever changing geometry of the core with local variations of





the porosity and other parameters which induce multi-dimensional flows and heat transfers. Although such effects are difficult to measure experimentally, the need for a multi-dimensional description has been widely recognized by the community of scientists in the field of severe accidents.
In this paper, a comprehensive set of multi-dimensional models describing heat transfers, thermal-hydraulics and

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