VETOR

Nuclear Meltdown Relocation and Core Catcher Analysis☆

Realocação do Núcleo do Reator Nuclear após Derretimento e Unidades de Contenção do Núcleo

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Abstract

Nuclear meltdown with the potential human and environmental harm is one of the major accident hazard (MAH) faced by nuclear power plants. Limiting (or entirely avoiding) criticality events are the main design strategies for reactors of generations 3½ and 4 (Gen3½ and Gen4). These include ensuring negative void and negative temperature coefficients (for both moderator and fuel) regardless of operational conditions, which provide a self-regulating mechanism that helps preventing accidents occurrence (*i.e.*, to address safety and reliability aspects of Gen4's goals). However, in severe accident scenarios (*e.g.* during loss-of-coolant, LOCA, events) where failure to extract heat from the reactor may lead to core degradation, strategies to mitigate reactor meltdown and relocation are critical in the design of safety protocols. This work aims to numerically investigate core relocation as an integrated multi-fluid and heat dynamics problem in which flow of melted materials (UO_2, Zircaloy and graphite) are modelled through interface capturing/tracking methods. Two interface tracking/capturing methods were compared, the level-set volume of fluid method (VOF) in Ansys Fluent, and the compressive advection method (CAM) in Fluidity/ICFERST. Both methods are in good agreement for the core relocation simulation. An in-vessel core catcher (IVCC) of tungsten alloy was also proposed to demonstrate core degradation control strategy through cooling of the melted multi-materials. The IVCC was simulated with a multifluid model in Ansys Fluent, in a specified applied heat flux model. The thickness of the IVCC is 0.20 m and the heat flux used is 600 $kW\,m^{-2}$. The tungsten material used was able to withstand both thermal and mechanical loads on the lower plenum by extracting decay heat from the corium.

Keywords

Nuclear reactor core • Meltdown relocation • Core Catcher • Lower plenum

Resumo

O derretimento nuclear, com potencial danos humanos e ambientais, é um dos principais acidentes graves em usinas nucleares. Limitar (ou mesmo evitar) eventos críticos são as principais estratégias no design de reatores das gerações 3½ e 4 (Gen3½ e Gen4). Isso inclui garantir coeficientes de reatividade (de temperatura e de vazio) negativos (para ambos, moderador e o combustível) independentemente das condições operacionais. Este é um mecanismo de autoregulação para prevenir a ocorrência de acidentes (ou seja, para abordar aspectos de segurança e confiabilidade dos objetivos do Gen4). No entanto, em cenários de acidentes graves (por exemplo, durante eventos de perda de fluido refrigerante, LOCA), onde a falha na extração de calor do reator pode levar à degradação do núcleo, estratégias para mitigar o derretimento e a realocação do reator são críticas na concepção de protocolos de segurança. Este trabalho visa investigar numericamente a realocação do núcleo como um problema integrado de dinâmica multifluido

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e térmica em que o fluxo de materiais derretidos (UO_2, Zircaloy e grafite) é modelado através de métodos de captura/rastreamento de interface. Dois métodos de rastreamento/captura de interface foram comparados, o método de volume de fluido (VOF, no CFD ANSYS Fluent) e o método de advecção compressiva (CAM, no CFD Fluidity/ICFERST). Ambos os métodos estão em bom acordo para o estudo de caso de realocação do núcleo. Também foi proposto uma unidade de contenção do núcleo (IVCC) composta de uma liga de tungstênio para demonstrar a estratégia de controle da degradação do núcleo através do resfriamento dos materiais. O IVCC foi simulado com um modelo multifluido com fluxo de calor especificado. A espessura do IVCC é de 0.20 m e o fluxo de calor utilizado é de 600 $kW\,m^{-2}$. O material de tungstênio utilizado foi capaz de suportar as cargas térmicas e mecânicas no plénum inferior extraindo o calor residual do corium.

Palavras-chave

Núcleo do reator nuclear • Realocação do Núcleo depois do Derretimento • Unidade de Contenção de Núcleo • Plenum inferior

1 Introduction

Safety is an important topic in all industry sectors, as it has a critical impact on human lives, environment protection and maintenance costs. This is no different in the nuclear industry where safety is at the forefront of every decision.

In a nuclear power plant, there is a number of events that may lead to major hazard accidents (MHA), but the biggest one is a nuclear core meltdown. There have been a number of those in the past, the most recent one being the accident at Fukushima Daichi power plant [1]. Events that leads to core meltdown may be summarised as [2]:

Stage 1: Some unspecified reason (usually electrical failure) impairs normal circulation of coolant in the core. This halts the removal of decay heat being produced and temperature starts raising.

Stage 2: The core is contained within the reactor pressure vessel (RPV) which has a design pressure of 100 – 150 atm. This allows for the coolant – usually water – to have a higher boiling point. This means that the coolant does not evaporate at low temperatures and that it can remove more heat than at atmospheric pressure. If the coolant is no longer circulating (*ie* it remains stagnant within the pressure vessel) temperature will rise to the boiling point leading to evaporation. At this point, no decay heat is removed and the temperature within the pressure vessel also raises.

Stage 3: The core is made of a number of solid materials, with very high melting temperatures (2000-3500°C). Once temperature increases, unless the coolant circulation is reinstated, the bulk temperature raises above materials' melting temperatures, leading to partial melt of the core.

Stage 4: Partial meltdown is initiated, and if there is no human intervention on the cooling system, full meltdown is likely to occur.

Stage 5: Once the core melting starts, it also begins to relocate to the lower levels of the reactor towards the lower plenum, where it accumulates. The molten material is then at very high temperature, with both convective and radiative heat transfer mechanisms playing significant role in the flow dynamics at the lower plenum. If no actions are taken, this would result in total meltdown and degradation of the vessel, and a consequent loss of containment.

Such sequence of events were investigated in a number of case studies of past nuclear accidents but also as postulated events to support design and optimisation of safety protocols in reactors. Coupled computational multi-fluid/fluid dynamics (CMFD and CFD) and neutron-radiation transport models have been used in the numerical investigation of each of the above stages. Some past work (*e.g.*, [3, 4]) have addressed similar events by considering a single phase system, comprised of two components: air and the nuclear core (composed of a single material with bulk properties). Furthermore, atmospheric conditions were assumed and the system was adiabatic. Here, we proposed to numerically investigate core relocation (Stage 5) during severe accidents. It considers a multiphase, multi-component system at reactor operational conditions. However, this study assumes constant heat flux from melted material, *i.e.*, it does not consider decay heat from neutron radiation calculations as it focuses only on the thermo-hydraulics (an example of coupled radiation and multi-fluid dynamics modelling for safety assessment in nuclear systems can be found in [5]). Numerical simulations of molten materials relocation are performed through interface tracking/capturing methods.

In Section 2, fluid governing equations are briefly outlined. Interface capturing and tracking methods are summarised in Section 3, including model validation. Numerical investigations of reactor core relocation and in-vessel core catcher are described in Sections 4-5. Finally, conclusions are drawn in Section 6

2 Fluids model

The multi-component fluids model is based in the interpenetrating continua (Eulerian approach) represented by a set of conservative equations with coupling terms. Volume fraction α of each of the n components is constraint to

$$\sum_{i=1}^{n} \alpha_i = 1, \tag{1}$$

and the continuity equation can be expressed as

$$\frac{\partial(\alpha_i \rho_i)}{\partial t} + \nabla \cdot (\alpha_i \rho_i \boldsymbol{u}) = Q_i, \tag{2}$$

where t and $\mathbf{u}$ are time and velocity, respectively. ρ_i and Q_i are density and mass source/sink terms of component i. Momentum balance is represented by

$$\frac{\partial(\alpha\rho)}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}\boldsymbol{u}) = -\nabla p + \nabla \boldsymbol{u}(\nabla \boldsymbol{u} + \nabla^T \boldsymbol{u}) - \nabla \frac{2}{3}\mu \nabla \cdot \boldsymbol{u} + \rho \boldsymbol{g_k}, \tag{3}$$

where p is pressure and g_k is gravity in the k direction. $\rho = \sum_{i=1}^{n} \alpha_i \rho_i$ and $\mu = \sum_{i=1}^{n} \alpha_i \mu_i$ are bulk density and dynamic viscosity, respectively. Finally, the thermal energy equation may expressed as

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \nabla \cdot (\boldsymbol{u} T) = \nabla \cdot (k \nabla T) + \mathrm{Y}, \tag{4}$$

where $C_p = \sum_{i=1}^{n} \alpha_i C_{p,i}$ and $k = \sum_{i=1}^{n} \alpha_i k_i$ are bulk heat capacity and thermal conductivity, respectively, whereas Y is the heat source/sink. The multi-component fluids model is fully described in [6] (see also [7].

3 Interface Models

3.1 Volume of Fluid based Interface Tracking Method

Interface tracking is a volume fraction capturing method [6] which uses the volume of fluid (VOF) method. This method [8] sets two phases, a primary and a secondary phase, in which there is just one primary phase and an arbitrary, n, number of secondary phases. The method is based on the introduction of a scalar field F which tracks the presence of any of the components (*i.e.*, phases/fluids)[1] in the control volume (here a finite volume method, FVM, based call). F_j is the scalar field of a certain phase j with values ranging from 0 to 1. If F_j is 0, then there is none of phase j in the cell, whereas if it is equal to 1, then the cell is filled with phase j. The scalar convective equation for the distribution of the volume fraction is

$$\frac{\partial F}{\partial t} + u \cdot \nabla F = 0. \tag{5}$$

Other variables, such as bulk density and dynamic viscosity are then derived through a linear relation with the volume fraction distribution (thus for 2 components i and j)

$$\Psi = (1 - F)\Psi_i + F\Psi_j, \tag{6}$$

where $\Psi = \{\rho, \mu\}$. VOF is a very reliable method for interface tracking of phases and has the advantage of being inherently mass conservative. It also assumes that the phases considered are not interpenetrating. In this study, it is coupled with the level set (LS) method [9], which provides a robust geometric reconstruction.

This method introduces its own continuous scalar function ϕ, which similarly to F, tracks the phases throughout the computational domain. In this case, $\phi > 0$ if phase i is in a cell k and $\phi < 0$ if phase j is in this cell. If an interface is present, then $\phi = 0$. The transport of ϕ can be expressed as

$$\frac{\partial \phi}{\partial t} + u \cdot \nabla \phi = 0. \tag{7}$$

Equation 7 is the linear advection equation of ϕ. Just like with the VOF method, the the bulk densities and dynamic viscosities can be defined as (based on Eqn. 6 with $\Psi = \{\rho, \mu\}$)

$$\Psi(\phi) = \Psi_l + \left(\Psi_l - \Psi_g\right) \mathcal{H}(\phi), \tag{8}$$

[1] For simplicity, in this manuscript, we will use the term phase to describe either a component, phase or fluid within a prescribed cell.

where subscripts l and g stand for liquid and gaseous phases and $\mathcal{H}$ is the Heaviside function.

Density and dynamic viscosity are then found

$$\rho(\phi) = \rho_l + (\rho_l - \rho_g)\mathcal{H}(\phi), \tag{9}$$

$$\mu(\phi) = \mu_l + (\mu_l - \mu_g)\mathcal{H}(\phi), \tag{10}$$

The level-set and VOF methods (CLSVOF) yields more robust simulations and a more accurate interface tracking.

3.2 Compressive Advection Method (Interface Capturing)

The interface capturing in Fluidity/ICFERST[2] is performed through the compressive advection method (for a full description of the method, see [7]) by the combination of a high-order accurate control volume finite element method formulation (CVFEM) and a new family of element types, such as the $P_1DG\text{-}P_2$ (linear and discontinuous discretisation of velocity with quadratic and continuous discretisation of the pressure).

In this method, pressure and velocity are discretised and solved in the finite element (FE) space to ensure computational accuracy whereas advected scalar (*eg* temperature, density, volume fraction etc) are discretised and solved in control volume (CV) space to ensure mass conservation. The velocity and pressure are also projected from the FE space to CV to be solved with the advected scalar, and then projected back to FE space. In addition to the conservation equations (Eqns. 2 -4), compressive-advection method is used in the formulation of the transport equation to advect the transport scalar quantity (volume fraction in this case) across the fluid interfaces.

For the CAM, the scalar ϕ_f can be amended by solving the advection and diffusion terms with Green's theorem. Flux-limiting schemes for both FE and CV spaces were applied to ensure computational efficiency and error minimization. Petrov-Galerkin method was applied [10] to derive a consistent residual-based discretisation with higher-order accurate and downwind biased. With the assumption of an isotropic diffussivity k_m, the transport equation with advection and diffussion terms for the advection of the scalar quantity is given as

$$\int_{V_e} M_e \left(\frac{\partial \phi}{\partial t} + \nabla \cdot u\phi - \nabla \cdot k_m \nabla \phi \right) dV = \int_{V_e} M_e \frac{\partial \phi}{\partial t} dV + \int_{\mathcal{F}_{v_e}} n \cdot u \left(\phi - \frac{n \cdot k_m \nabla \phi}{n \cdot u} \right) d\mathcal{F}, \tag{11}$$

where $\mathcal{F}$ is the outward normal control surface area of the control volume (CV), V is the elemental volume, u is the material velocity, M_e is the elemental mass and ϕ_f is the CV scalar field interface value that is transported. The interface value ϕ_f on the CV boundary (with normal n) is evaluated using finite element method (FEM) representation of the CV solution ϕ_{FEM}

$$\phi_f = \phi_{FEM} - \frac{n \cdot k_m \nabla \phi}{n \cdot u}, \tag{12}$$

which is the result of discretising

$$\nabla \cdot u\phi_f = \nabla \cdot u\phi_{FEM} - \nabla \cdot k_m \nabla \phi_{FEM}, \tag{13}$$

3.3 Model Validation: Collapse Water Column

Both interface models (CLSVOF and CAM) are initially validated against the classic CFD collapsing water column (CWC) test-case. Experimental data for the CWC is widely available in the literature and was used to validate the CAM [7] and it is used here to validate the CLSVOF.

The simulated domain is a 1×1 m square and the collapsing water is a 0.5×0.25 m column at the left=hand side of the domain; the remaining of the domain is assumed to contain just air. Properties of water and air at room conditions are used in this set of simulations. Also, non-slip boundary is imposed to all surfaces with a prescribed outlet pressure at the top surface

In the simulation performed with the CLSVOF model, a transitional turbulent regime was imposed. A second-order spatial discretisation coupled with the pressure-implicit with splitting of operators (PISO) numerical scheme is used. An adaptive time-step size method was used. The domain was discretised with 10000 rectangular cells and 10201 nodes. In the Fluidity/ICFERST model, a CVFEM formulation for the conservative and transport equations are used with adaptive time-step size (based on a modified Crank-Nicholson method [11]). The domain is discretised with 51120 elements. Figures 1 and 2 show snapshots of the collapsing water over 1 second using the CLSVOF and CAM formulations, respectively. Collapsing flow dynamics obtained from both formulations show good agreement. The main differences are more visible in the downward motion, where the CLSVOF model formulation has a more defined interface between the water and air.

[2] http://multifluids.github.io/

It is clear from the last two snapshots, where, once the downward descent is almost complete, a bubble of air is trapped in the water wave. This is then carried over and when the initial wall is reached again, a second one forms. Such behaviour is confirmed by experiments conducted by [8] and by Fluidity/ICFERST simulations [12].

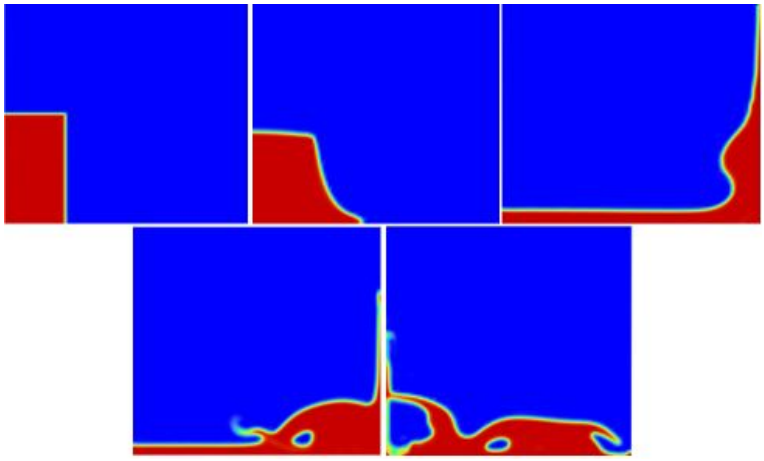

Figure 1: Volume fraction contour of the collapsing water column with the CLSVOF formulation. Snapshots taken at t = 0 s, t = 0.19 s, t = 0.5 s, t = 0.69 s and t = 1.0 s. Here, dark blue represents pure air whereas red represents pure water.

The descent is much slower in Fig. 2 with only one bubble forming at the end of the sequence. This is not in agreement with literature. This could be the result of a coarser mesh employed. Now that the two models have been validated, they can be employed in the analysis of a nuclear reactor meltdown and relocation.

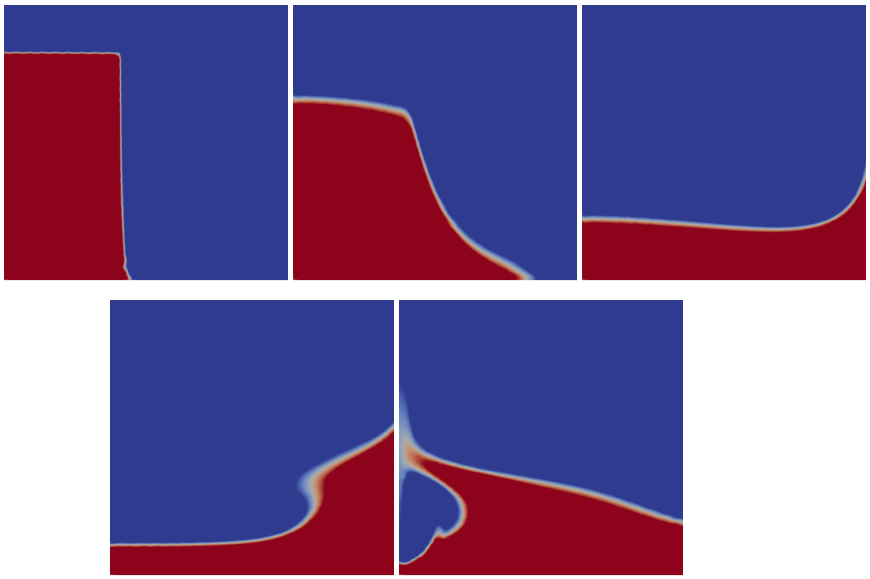

Figure 2: Collapsing water column volume fraction at different simulation time. Snapshots taken at t = 0.15 s, t = 0.25 s, t = 0.5 s, t = 0.75 s and t = 1.0 s. Here, dark red represents pure water whereas blue represents pure air

4 Nuclear relocation

For the simulations conducted in this section, the following assumptions were established:

- Reactor core materials are at liquid state, *i.e.*, they all melted and collapse simultaneously;
- Core material is assumed isothermal, *i.e.*, there is no heat generation due to nuclear criticality.

A reactor shape of height 1m and diameter 1m has been used for the 2D simulation. A core of size 0.3×0.5m has been placed at the centre of the reactor as shown below. The mesh is structured with 15088 triangular elements and 7775 nodes. A bias on the lower plenum is applied to save computational power in other less relevant areas. The core has been split into three equal parts which are made of three fluids: plutonium (light blue), uranium dioxide (yellow) and zirconium (red). These will be at a melted state, with the rest of the volume filled with air. The air is modelled with the compressible ideal gas model, whereas the liquid phase (melted fluid) is modelled with density and viscosity polynomials for the nuclear materials [13]. Contours of melted material volume fractions relocation using the CLSVOF model formulation is shown in Fig. 3.

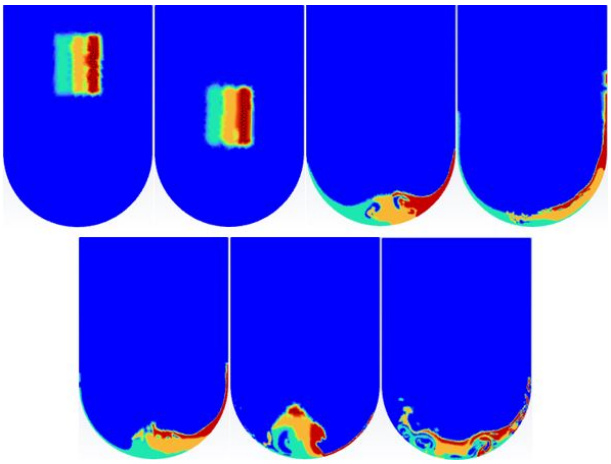

Figure 3: Core relocation through the interface tracking CLSVOF model formulation. Snapshots taken at t={0, 0.27, 0.51, 0.97, 1.13, 1.38, 1.75}s. PuO_2, UO_2, Zircaloy and air (and steam) are represented by light blue, yellow, red and dark blue, respectively.

Simulation of the reactor core relocation conducted with Fluidity/ICFERST model is shown in Fig. 4. The simulation was performed with a domain of similar dimension of Fig. 3. The domain is discretised with unstructured mesh containing 9908 triangular elements. The simulation presents 5 materials with the core split into 4: water (taken as material 1, coolant), UO_2 (material 2), Zircaloy (material 3) and graphite (material 4). Air (material 5) initially filled the containment. The simulation was conducted with similar boundary and initial conditions as used in the simulation shown in Fig. 3.

Core flow dynamics (in both simulations) show that the most affected area by the relocation is the lower plenum. There is a brief escalation towards the walls after the impact but that is temporary. The majority of the load is focusing in the lower plenum. The model also shows how materials interact with one another based on density and viscosity. It can be noted, for instance, in Fig. 3 that zirconium is flowing on top of the other two denser materials, whereas PuO_2 is mostly found at bottom. Also, the interface models shows the bubbles of air/steam being trapped by the liquid phase.

5 In Vessel Core Catcher

Nuclear meltdowns can lead to catastrophic events if not dealt with in time. During years, a number of solutions were developed either in-vessel or ex-vessel. In-vessel solutions [14] usually are made of systems that would protect the integrity of the RPV, so that the corium would not leak out, leading to a loss of containment. These solutions often include flooding the internal cavity with water, or cooling externally the walls of the RPV, relieving thermal loads that necessarily would act on it. Ex-vessel solutions [2] consist of a core catcher outside the RPV which aims at protecting the containment building once the corium has overcome the barrier posed by the RPV. Core catchers are structures which “catch” the core and try to cool it, finally stopping its progression.

Although these solutions have strong positive aspects on the core meltdown control, they also have negative aspects. For instance, an in-vessel retention strategy that would feature flooding the lower plenum could be detrimental if the rate of influx of the coolant is not correctly calculated. In fact, adding water at a lower rate than the

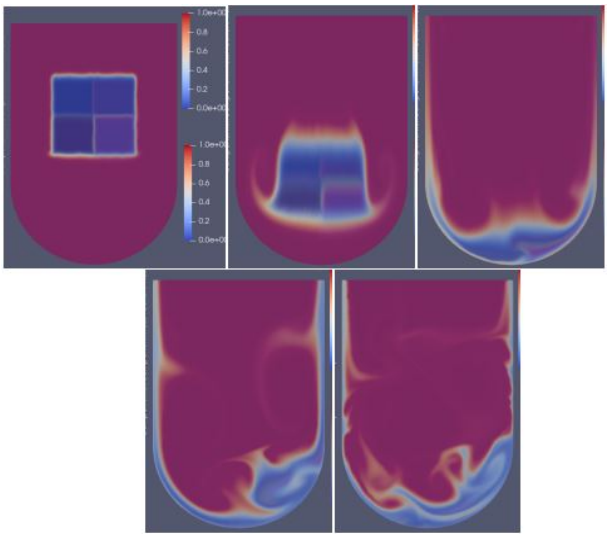

Figure 4: Core relocation through the interface capturing CAM model formulation. Snapshots taken at t = $\{0, 0.15, 0.25, 0.50, 0.75, 1.00\}$s. The dominated red colour at the simulation onset is Air, down left material is Water, top left is Uranium, top right is Zirconium and down right is Graphite.

minimum one required, could potentially lead to even further steam explosions, which could structurally affect the RPV, and generate more heat that would fuel further oxidation reactions. This would in turn generate even more hydrogen and potentially lead to explosions within the containment.

An ex-vessel retention strategy could be inherently dangerous if not properly handled, as this could lead to the loss of the containment building. This would also mean sacrificing a first layer of defence too easily, leaving only one between the threat of radioactivity to the environment. This section investigates an alternative strategy that could benefit from both in-vessel and ex-vessel strategies. In particular, an in-vessel core catcher (IVCC) that could be applied to the lower plenum level and would strengthen its structural and thermal stability. The core catcher would have a half sphere shape. It will be made of a material that has a very high melting point to withstand the extreme thermal loads. Also, it would be a material with a good thermal conductivity so that it could extract heat from the corium, allowing it to cool down. Since the system considered has a very high nuclear reactivity, the material selected should also be neutronically inert. Thus, tungsten [15] has been selected as it possess these thermophysical properties, although further studies on the result of high energy neutrons impacting on tungsten walls should be carried out. This is beyond the scope of this study.

The simulation carried out with the lower plenum of an RPV of 1 m diameter. This has been then filled with the three fluids considered and heat transfer modelled through a heat flux model in ANSYS Fluent. A no slip boundary condition has been set at the walls of thickness, 0.2 m. The temperature of the melted materials is initially at 1700 K with a heat flux of 600 kW/m^2 (heat removal [14]). Similarly to simulations performed in the previous section, it is assumed no heat generation. This is not actually realistic because, during and following a meltdown scenario, decay heat is still being produced due to criticality. The simulation was carried in 3D and the results are presented through the cross section of the core catcher and the temperature profile, at different times is shown in Fig. 5.

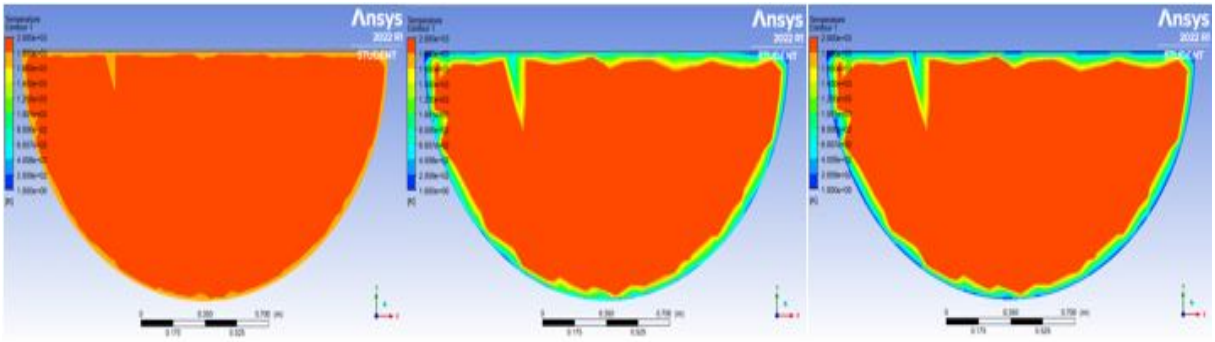

Figure 5: Temperature profile of the cross section, initialised at T = 2000 K at t = 0 s, t = 3 s and t = 6 s from left to right

The lower plenum is initially at the same temperature of the corium. As time progresses and heat is removed through the wall, corium's temperature gradually reduces, initially at the wall region then to the inner region. For this simulation, we assumed a constant heat flux from the wall to the boundaries. Further studies are necessary to take into account spatial- and time-dependent heat transfer due to convection and radiative mechanisms with potential phase change (vaporisation and solidification of materials). Also, an internal heat generation due to decay heat should also be considered in further studies.

6 Conclusion

A nuclear core meltdown is the biggest MHA that a nuclear power plant can experience. The melt formed from the nuclear fuels, coating and surrounding material is displaced to the lower plenum of the RPV, where an intense thermo-mechanical load is applied at the wall. The interface between fluids during the displacement of the corium were simulated with two methods: coupled level-set volume-of-fluid (CLSVOF) method and compressive-advection method (CAM). The model was initially validated against experiments and CAM (cross-code validation from previous publications). Simulations performed with both model formulations for core relocation indicated intense flow dynamics and material segregation. An in-vessel core catcher was proposed and applied on the lower plenum of 0.20 m thickness. The material proposed is a type of tungsten alloy which have not been initially applied for this purpose. The reason is to exploit the thermal properties of tungsten which would be neutronically inert, and more thermal stability to quench the hot melted material. The heat flux simulation carried has proven the effective cooling strategy.

In future studies, a non adiabatic and non-isothermal case will be considered for better understanding of the thermo-hydraulic behaviour of a reactor meltdown. Also, further parametric studies of the materials should be considered in the analysis for optimal performance investigation. For the core catcher analysis, a convective and radiative model should be used with internal heat generation. Further analysis into the material selection are required, as tungsten has great thermal properties, which might be affected by high energy neutrons.

References

[1] H. Madokoro and I. Sato, "Estimation of the core degradation and relocation at the fukushima daiichi nuclear power station unit 2 based on RELAP/SCDAPSIM analysis," *Nuclear Engineering and Design*, vol. 376, p. 111123, 2021. Available at: https://doi.org/10.1016/j.nucengdes.2021.111123

[2] B. Sehgal, *Nuclear Safety in Light Water Reactors: Severe Accident Phenomenology*. Elsevier Science & Technology Books, 2012. Available at: https://books.google.co.uk/books?id=Z_SmDAEACAAJ

[3] T. Feng, W. Tian, P. Song, J. Wang, M. Wang, L. Li, G. Su, and S. Qiu, "Spatial temperature distribution of fuel assembly pre-simulation for a new simple core degradation experiment," *Progress in Nuclear Energy*, vol. 111, pp. 174–182, 2019. Available at: https://doi.org/10.1016/j.pnucene.2018.11.004

[4] A. Nayak, P. Kulkarni, P. Pandey, and S. V. Prasad, *Advances of Computational Fluid Dynamics in Nuclear Reactor Design and Safety Assessment*. Woodhead Publisher, 2019, ch. Modelling of core melt scenarios in nuclear reactors, pp. 487–565.

[5] J. Gomes, C. Pain, M. Eaton, A. Goddard, M. Piggott, A. Ziver, C. de Oliveira, and Y. Yamane, "Investigation of nuclear criticality within a powder using coupled neutronics and thermofluids," *Annals of Nuclear Energy*, vol. 35, no. 11, pp. 2073–2092, 2008. Available at: https://doi.org/10.1016/j.anucene.2008.05.012

[6] ANSYS, *ANSYS Fluent Theory Guide 2021R1*, ANSYS, 2021.

[7] D. Pavlidis, J. Gomes, Z. Xie, J. Percival, C. Pain, and O. Matar, "Compressive advection and multi-component methods for interface-capturing," *International Journal for Numerical Methods in Fluids*, vol. 80, no. 4, pp. 256–282, 2016. Available at: https://doi.org/10.1002/fld.4078

[8] G. H. Yeoh and T. Barber, "Assessment of interface capturing methods in computational fluid dynamics (CFD) codes — a case study," *The Journal of Computational Multiphase Flows*, vol. 1, no. 2, pp. 201–215, 2009. Available at: https://doi.org/10.1260/175748209789563946

[9] N. D. Katopodes, "Chapter 13 - level set method," in *Free-Surface Flow*, N. D. Katopodes, Ed. Butterworth-Heinemann, 2019, pp. 804–828. Available at: https://doi.org/10.1016/B978-0-12-815485-4.00019-X

[10] A. N. Brooks and T. J. Hughes, "Streamline upwind/petrov-galerkin formulations for convection dominated flows with particular emphasis on the incompressible navier-stokes equations," *Computer Methods in Applied Mechanics and Engineering*, vol. 32, no. 1, pp. 199–259, 1982. Available at: https://doi.org/10.1016/0045-7825(82)90071-8

[11] J. Crank and P. Nicolson, "A practical method for numerical evaluation of solutions of partial differential equations of the heat-conduction type," *Mathematical Proceedings of the Cambridge Philosophical Society*, vol. 43, pp. 50–67, 1947. Available at: https://doi.org/10.1017/S0305004100023197

[12] D. Pavlidis, J. Gomes, Z. Xie, C. Pain, A. Tehrani, M. Moatamedi, P. Smith, A. Jones, and O. Matar, "Numerical modelling of melt behaviour in the lower vessel head of a nuclear reactor," *Procedia IUTAM*, vol. 15, pp. 72–77, 2015, iUTAM Symposium on Multiphase Flows with Phase Change: Challenges and Opportunities. Available at: https://doi.org/10.1016/j.piutam.2015.04.011

[13] *Thermophysical Properties of Materials for Nuclear Engineering: A Tutorial and Collection of Data*, ser. Non-serial Publications. Vienna: INTERNATIONAL ATOMIC ENERGY AGENCY, 2009. Available at: https://www.iaea.org/publications/7965/thermophysical-properties-of-materials-for-nuclear-engineering-a-tutorial-and-collection-of-data

[14] W. Ma, Y. Yuan, and B. R. Sehgal, "In-vessel melt retention of pressurized water reactors: Historical review and future research needs," *Engineering*, vol. 2, no. 1, pp. 103–111, 2016. Available at: https://doi.org/10.1016/J.ENG.2016.01.019

[15] P. Tolias, "Analytical expressions for thermophysical properties of solid and liquid tungsten relevant for fusion applications," *Nuclear Materials and Energy*, vol. 13, pp. 42–57, 2017. Available at: https://doi.org/10.1016/j.nme.2017.08.002