

LOCAL HEAT TRANSFER FROM THE CORIUM MELT POOL TO THE BOILING WATER REACTOR PRESSURE VESSEL WALL

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ABSTRACT

The present study considers in-vessel accident progression after core melt relocation to the lower head of a Boiling Water Reactor (BWR) and formation of a melt pool containing a forest of Control Rod Guide Tubes (CRGTs) cooled by purging flows. Descending streams of melt that flow along cooled surfaces of CRGT, and impinge on the bottom surface of the vessel wall can significantly increase local heat transfer. The area of enhanced heat transfer enlarges with decreasing of the melt Prandtl (Pr) number, while the peaking value of the heat transfer coefficient is a non-monotone function of Pr number. The melt Pr number depends on the melt composition (fractions of metallic and oxidic melt components) and thus is inherently uncertain parameter of the core melting and relocation scenarios. The effect of Pr number in the range of 1.02 - 0.03 on the local and integral thermal loads on the vessel wall is examined using Computational Fluid Dynamics (CFD). Heat transfer models obtained on the base of CFD simulations are implemented in the Phase-change Effective Convectivity Model (PECM) for simulation of reactor-scale accident progression heat transfer in real 3D geometry of the BWR lower plenum. We found that the influence of the low Pr number on the thermal loads in a big melt pool becomes more significant at later time, than rapid acceleration of the creep in the vessel wall. This result suggests that global vessel failure is insensitive to the melt composition in the considered 0.7 m deep melt pool configuration. However, it is not clear yet if the low Pr number effect has an influence on vessel failure mode in the other possible melt pool configurations.

KEYWORDS

Severe accident, melt pool, corium melt, fluid Prandtl number, local heat transfer, thermo-mechanical creep

1. INTRODUCTION

In this work we consider in-vessel stage of severe accident progression in an ABB-Atom design Nordic BWR. It is assumed that the core materials are melted, relocated, and quenched in the pool of water located in the lower head of the Reactor Pressure Vessel (RPV) in a postulated severe accident. In the process of reheating and remelting of the debris a large pool of molten corium can be formed. Thermal loads from the melt pool to the vessel wall define the mode and timing of the vessel failure and finally provide initial conditions for the ex-vessel accident

progression (e.g. Kudinov et al., 2010). Therefore the flow and heat transfer characteristics of volumetrically heated melt pool in the reactor lower plenum have been an important research subject for the last decades. Core relocation and remelting scenarios define melt composition and thus its thermo-physical properties are significant sources of uncertainties for the in-vessel accident phenomena.

During the 1970s, and in the 1990s, a number of experimental and analytical studies were focused on obtaining the heat transfer correlations for natural convection of internally heated fluid in different kinds of geometry, e.g. in fluid layers, rectangular, semi-circular and elliptical “slice-type” (torospherical) cavities, in cylindrical and hemispherical pools. A number of correlations were proposed based on the experimental data of Fiedler and Wille (cited by in Kulacki and Emara, 1977), Kulacki and Goldstein (1972), Jahn and Reineke (1974), Mayinger et al. (1976), Kulacki and Emara (1977), Steinberner-Reineke (1978), Gabor et al. (1980), COPO-I experiment (Kymalainen et al., 1994), mini-ACOPO (Theofanous et al., 1997), hemispherical pool (called bell jar) heat transfer experiments (Asfia et al., 1996), BALI tests (Bernaz et al., 1998), and ACOPO experiment (Theofanous and Angelini, 2000), etc. These correlations which were developed mostly experimentally are describing the dependency of the average Nusselt (Nu) number at the cooled surfaces.

In the experiments with simulant melt materials the fluid Pr number usually is about one order magnitude greater (e.g. water $Pr = 2.5-7$, Freon $Pr = 8-11$), than the prototypic Pr of the core melt ($Pr = 0.1-0.6$). Therefore it was not clear whether the heat transfer correlations obtained in the simulant material experiments are applicable to predictions of melt pool behavior in case of a severe accident conditions. The small-scale experiments using joule-heating of molten uranium oxide at Argonne National Laboratory (ANL) showed higher downward heat fluxes than those predicted on the basis of simulant material experimental data (Stein et al., 1979). The effect of the fluid’s low Prandtl number on its heat transfer characteristics in internally heated liquid pools was numerically studied by Nourgaliev et al. (1997). It was found that, as the Pr number is decreases, the heat transfer coefficients decrease (up to 20-30% for a low Pr number fluid) on the upward and sideward surfaces and increase on the downward surface. The effect was attributed to the ν -phenomenon which is related to low fluid viscosity and α -phenomenon which is related to high thermal conductivity. The effects of Prandtl number on Nu number at the bottom surface are found to be significant and they become larger with increasing of Rayleigh number. In a recent experimental study (Lee et al., 2004; Lee et al., 2007) the effect of fluid Pr on the downward heat transfer was confirmed.

So-called crud purge flow through the Control Rod Guide Tubes (CRGTs) is used in normal operation of a BWR. Cooled from inside CRGTs can be used as an element of Severe Accident Management (SAM) strategy for water injection into the reactor, and heat removal from a decay-heated debris bed (melt pool). Melt pool heat transfer in particular geometry of the BWR lower plenum with cooled CRGTs is simulated using the Computational Fluid Dynamics (CFD) tool (Tran et al., 2010). It was found that in the presence of the cooled CRGTs the heat transfer intensifies locally on the bottom surfaces connected to the vessel wall, in the vicinity of the CRGTs, results in a higher total heat flux imposed on the vessel wall. The reason for the local increase of heat transfer is the descending flow formed along the cooled surfaces of CRGTs that impinges on the bottom vessel wall. The effect of the corium melt Pr number on enhancement of the heat transfer is found to be significant. The local peak of downward heat transfer increases when Pr decreases. With the Pr in the range from 2 to 0.12, the dependency of the Nu number on Pr is found to be non-monotone (Tran and Kudinov, 2010). Enhancement of the local downward

heat flux leads to more intensive crust ablation at the bottom wall and causes the increase of the total heat flux imposed on the vessel wall. The question which we are considering in this work is, whether there is a possibility that the increased heat flux to the vessel wall can affect the timing of the creep failure of the vessel (e.g. Villanueva et al., 2010).

In the present study, a CFD method is used to perform numerical experiments for examination of the heat transfer and fluid flows in the specific geometry of BWR lower plenum. Corium melt with low Prandtl number is simulated. The paper structure is as follows. Section 2 describes the methodology for accident analysis in a BWR. The CFD method and study of flow characteristics and heat transfer are presented in Section 3. In Section 4, the PECM is applied for reactor-scale simulations to examine the influence of Pr number effect on integral heat transfer on the vessel wall and timing when such influence becomes important. Section 5 concludes the paper.

2. AN APPROACH TO ACCIDENT ANALYSIS FOR BOILING WATER REACTORS

The analysis of in-vessel accident progression in BWR is based on the approach which has been recently developed and used in Tran et al. (2010). The main idea of the approach is to employ the CFD methods as a tool for numerical experiments, to gain insights into flow physics and to develop effective and computationally efficient tools which in turn are employed for simulation of natural convection heat transfer of corium melt pools. The results obtained with high resolution CFD simulations are used as reliable data for validation of the new effective models, namely the Effective Convectivity Model (ECM) and Phase-change ECM (PECM) (Tran and Dinh, 2009a, 2009b). The developed models are then applied for melt pool heat transfer simulation in the BWR lower plenum.

In the ECM, the efficiency is achieved by eliminating the necessity in solving Navier-Stokes equations by employing the characteristic velocities to simulate transfer of the internal heat to cooled boundaries. The effectiveness is achieved by employing directional characteristic velocities which are determined using the Steinberner-Reineke correlations (Steinberner and Reineke, 1978):

$$Nu_{up} = 0.345Ra^{0.233} \quad (1)$$

$$Nu_{side} = 0.85Ra^{0.19} \quad (2)$$

$$Nu_{down} = 1.389Ra^{0.095} \quad (3)$$

where $Nu = \frac{q \cdot L}{k \cdot \Delta T}$ is the heat transfer coefficient, q is the heat flux ($W m^{-2}$), L is the characteristic length (m); ΔT is the temperature difference of the pool's maximum temperature and wall temperature (K); k is the thermal conductivity ($W m^{-1} K^{-1}$).

The PECM has been developed for resolving phase change heat transfer. In the PECM, the mushy characteristic velocities are used to describe heat transfer in a mushy zone. The ECM and PECM have been validated against experimental data and CFD simulated data, which cover a wide range of Rayleigh number and different physical phenomena involved in melt pool formation and heat transfer (Tran et al., 2010). The remained question is reduction and quantification of the uncertainty in application of the ECM/PECM to accident analysis. To

address this question, an approach to synergistic use of the CFD methods, experiments and ECM/PECM for reduction of uncertainty has been proposed (Tran and Kudinov, 2010). In this approach, the CFD is used to quantify the epistemic uncertainty related to scaling effect, and the modeling effect, while the ECM/PECM is used to quantify the experimental, parametric and scaling effects (Figure 1).

The main goal of the present study is to employ the CFD method to address the ECM/PECM modeling uncertainties related to local heat transfer in a homogeneous corium melt pool with different thermo-physical properties. Improved PECM models are used to examine the integral effects of local heat transfer enhancement on the time history of the vessel wall temperature and finally the creep development. The PECM simulated transient data are used for mechanical creep analysis with the ANSYS code.

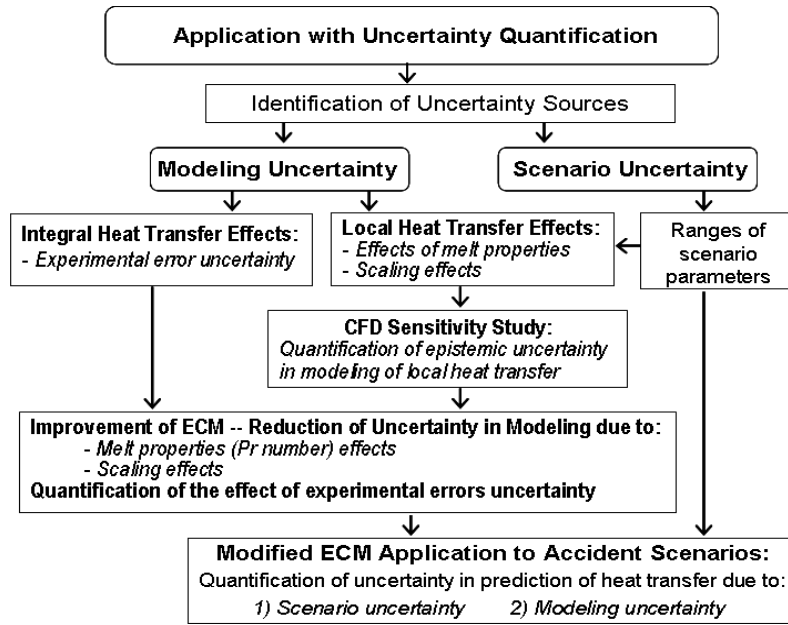


Figure 1: The uncertainty reduction methodology for analysis of in-vessel melt pool heat transfer in a BWR severe accident (Tran and Kudinov, 2010).

3. THE LOW PRANDTL NUMBER EFFECT OF CORIUM MELT

3.1. The Computational Fluid Dynamics method

Natural convection heat transfer with internal heat source is represented by the internal Rayleigh number Ra' , which quantifies the volumetric heat source (Q_v , W/m^3) and strength of the buoyancy. Natural convection phenomena can be scaled with the Grashof number (Gr), the Dammkohler number (Da), Prandtl number (Pr), and the heat source. The dimensionless numbers are as follows:

$$Gr = \frac{g\beta\Delta TL^3}{\nu^2}; \quad Pr = \frac{\nu}{\alpha}; \quad Da = \frac{Q_v L^2}{k\Delta T} \quad (4)$$

where α is the thermal diffusivity (m^2/s); ν is the kinematics viscosity (m^2/s); β is the thermal expansion (K^{-1}). The internal Rayleigh number Ra' is representing natural convection with internal heat source, and defined as:

$$Ra' = Gr Pr Da = \frac{g\beta Q_v L^5}{\alpha k \nu} \quad (5)$$

Prandtl number is the control parameter in the downward heat flux enhancement phenomenon. Clearly, depending on the accident scenario, the homogeneous corium melt may have different fractions of metallic components. Therefore, the corium Pr number can vary largely due to the difference between thermal conductivities of the metallic components and oxidic melts. Calculations of corium Pr number based on different fractions of metallic components indicate that corium Pr number can vary from the lower bound value of 0.1 to the higher bound value of 0.6 for the ABB-Atom BWR design. To examine the characteristics of the downward heat transfer coefficient and its non-monotone behavior in the peak value, in the present study, a wider Pr range from 0.03 to 1.02 is considered. To study the separate effect of Prandtl number on heat transfer, all considered cases are performed with the same Rayleigh number, $Ra' = 5.86 \times 10^{12}$.

The CFD method used for flow study is the Implicit Large Eddy Simulation (ILES) method, or “no model” LES. The ILES has been used for modeling of high Reynolds’ number flows and it combines computational efficiency and ease of implementation with high predictive capabilities and flexibility in application (Margolin et al., 2006). ILES solves Navier-Stokes equations using intrinsic, nonlinear and high-frequency filters built into the discretization and implicit SGS models. High-resolution grids are employed especially refined at the near-wall regions. The idea of ILES is that the numerical diffusion in an appropriately constructed numerical scheme is implicitly employed to simulate turbulent diffusion at sub-grid scale, thus no explicit sub-grid scale turbulence model is needed. An empirical selection of numerical schemes for ILES simulation of turbulent natural convection in internally-heated liquid pools has a root in Monotonically Integrated LES (or MILES) method (Boris et al, 1992). Validations of the ILES method have been performed against a different experiments (Dinh et al., 2004; Tran et al., 2010). In this work we follow recommendations for obtaining grid-independent solutions with ILES that have been well established in the previous works on validation of ILES.

We use realistic geometry of the ABB-Atom BWR lower plenum to examine the fluid flow characteristics in a melt pool enveloped with crust. We define Unit Volume (UV) as a rectangular cavity full of corium, containing a cooled CRGT in the center, and both top and bottom surfaces of the cavity are cooled (Figure 2). We assume that the fluid flow around a cooled CRGT is representative for studying of local melt pool convection and heat transfer. The initial and boundary conditions used for CFD simulation in a UV are defined as follows. The top, bottom and CRGT surfaces are isothermal at melting temperature of corium. On the other walls adiabatic, symmetrical conditions are imposed. The initial temperature of UV is about 2770K which is assumed to be liquidus temperature of homogeneous corium melt. The possible effect of changes in solidus/liquidus temperatures due to changes in the composition of the melt is beyond the scope of the present work. The volumetric heat source of corium is 1 MW/m^3 . Computational domain contains a quadrant of the UV, the number of cells in it is around one million.

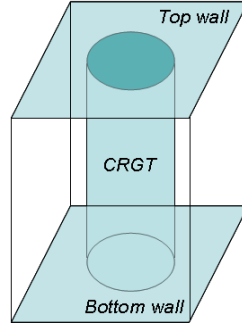


Figure 2: Unit volume of the BWR lower plenum.

In the next section, results of CFD ILES simulation and discussion on the flow characteristics and heat transfer are presented.

3.2. The local heat transfer effect of corium melt and flow characteristics

This section presents results of CFD simulation for different cases of low Pr fluid. Flow characteristics and heat transfer coefficients along the cooled boundaries are examined. Special focus of the analysis is the local effect of the heat transfer coefficient on the bottom wall. Local characteristics of heat transfer obtained in CFD are used then for improvement of modeling of downward heat transfer in the PECM.

Figure 3 presents respectively the heat transfer coefficients calculated along the top cooled surface (upward heat transfer coefficient) and along the cooled CRGT surface (sideward heat transfer coefficient) of the UV for fluids with different Pr numbers. The Steinberner-Reineke correlations (Eqs. 1-3) and (-15%) lower bounds are also shown in the figures. It can be seen that heat transfer coefficients (both upward and sideward) predicted by CFD are well fitted within the 15% uncertainty range of the correlations if Pr is in the range of 1.0 to 0.4. However, with decreasing of the Pr , the upward and sideward heat transfer coefficients are decreased significantly. At Pr of 0.03-0.06, the predicted upward and sideward heat transfer coefficients are 50% lower in comparison with the correlations. The decrease of the upward and sideward heat transfer coefficients with decrease of Pr number has been observed previously. This effect is explained by formation of a thicker boundary layers along the cooled surfaces (Nourgaliev et al., 1997; Lee et al., 2007). The dependencies of the upward and sideward Nu numbers on the Pr number can be described with the following relations, which provide the best fit to the calculated results:

$$Nu_{up} = 0.366 \cdot Ra^{0.233} \cdot Pr^{0.11} \quad (0.03 < Pr < 1.02) \quad (6)$$

$$Nu_{side} = 0.92 \cdot Ra^{0.19} \cdot Pr^{0.125} \quad (0.03 < Pr < 1.02) \quad (7)$$

Figure 4 shows the contours of the downward heat flux imposed on the bottom cooled surface, for 3 different Pr fluids. The enhancement of the heat flux in the vicinity of CRGT is due to the impingement of the flow descending along the cooled CRGT surface. The lower the Pr of the fluid, the broader is the area of enhanced heat flux. The local enhancement of heat flux to the bottom surface results in increase of the average downward heat flux as it is shown in Figure 5. The ratio of heat fluxes (q_{down}/q_{up}) is also increased as Pr decreases (Figure 5, right).

The downward heat transfer coefficients in all cases are quite close to each other and much higher (>100%) than the Nu calculated by the correlation at given Rayleigh number.

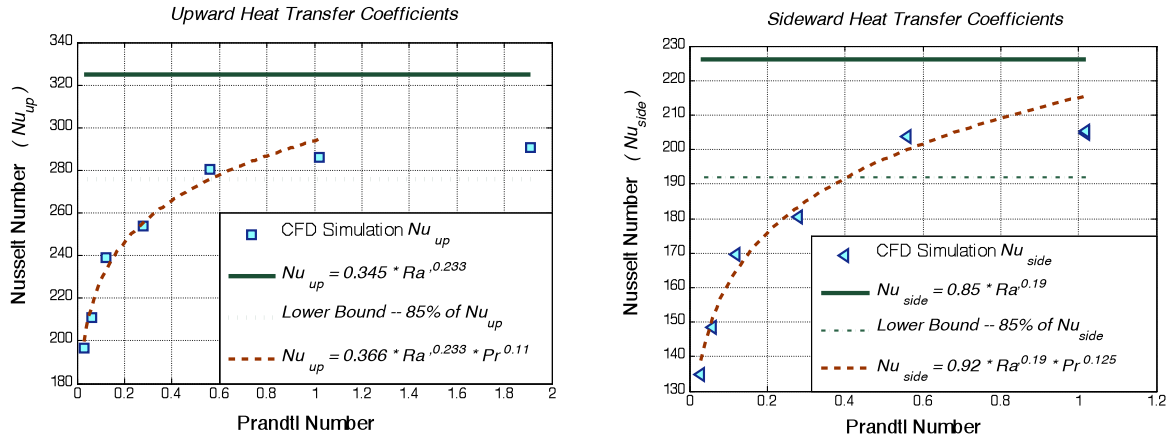


Figure 3: Upward heat transfer coefficients, Nu_{up} (left) and sideward heat transfer coefficients, Nu_{side} (right) as a function of Prandtl number at $Ra' = 5.86 \times 10^{12}$.

Radial distributions of the time averaged heat fluxes and downward heat transfer coefficients obtained at different Pr numbers are presented in Figures 6. It is worth noting that in the peripheral area, the CFD-simulated Nu is in good agreement with the Steinberger-Reineke correlation. Previously (Tran et al., 2010) it was found that the downward heat flux intensifies at lower Pr and has a peak value in the downward flow impingement area. In the present study we show that there is a non-monotone dependency of the maximum value of heat transfer coefficient on Pr . The maximum value of the local heat transfer is reached at Pr number in the range from 0.5 to 1.0, in the vicinity of CRGT surface, while the size of the area with enhanced heat transfer increases monotonically with decreasing of Pr (Figure 6). To explain this behavior, the flow characteristics are examined.

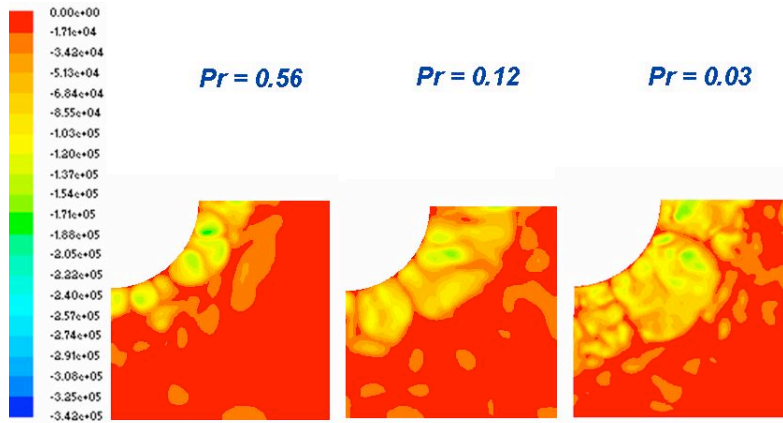


Figure 4: Contours of instantaneous heat flux distribution on the bottom wall.

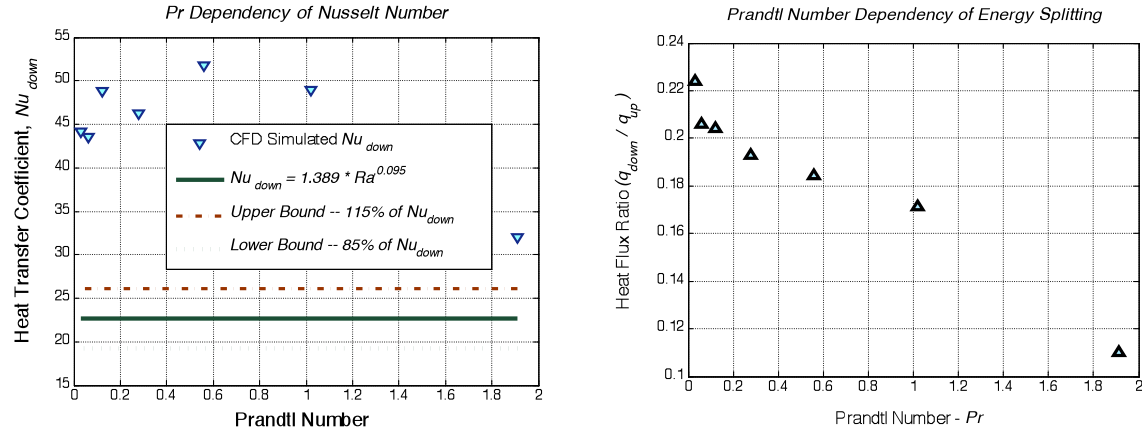


Figure 5: The average downward heat transfer coefficients (Nu_{down}) as a function of Prandtl number at $Ra = 5.86 \times 10^{12}$ (left), and ratio of heat fluxes (energy splitting) (right).

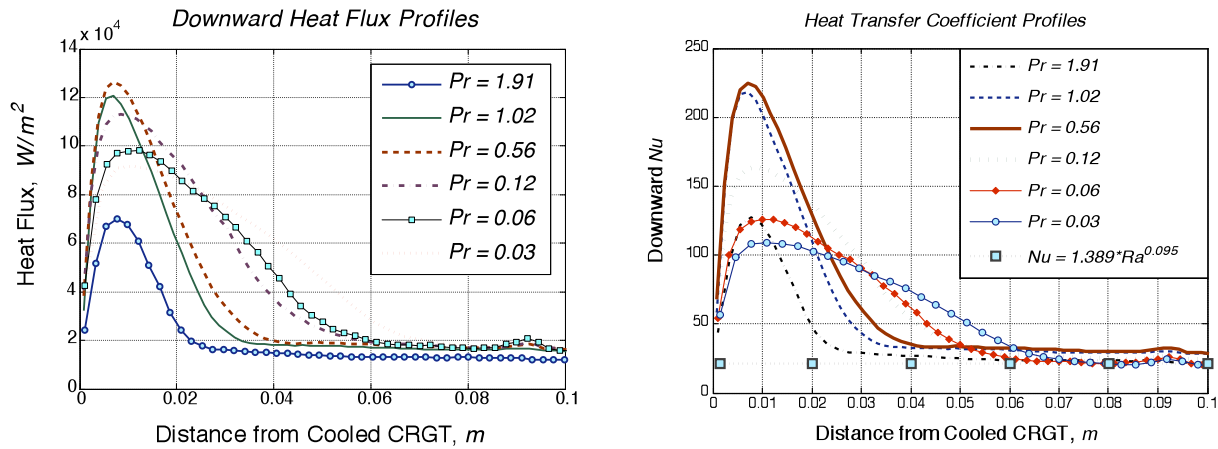


Figure 6: Profiles of the downward heat fluxes and corresponding downward heat transfer coefficients with different fluid Pr .

The following figures describe velocity and temperature distributions in the boundary layer on the bottom wall for different Pr numbers. Figure 7 presents vertical profiles of dimensionless radial velocities at 2 cm distance from the cooled CRGT surface. The maximum dimensionless radial velocity increases monotonically as the Pr number decreases. This is a result of so called v -phenomenon previously explained in (Nourgaliev et al., 1997). Namely as the Pr is decreased (e.g. viscosity ν is decreased), the fluid flowing downwards along cooled surfaces of CRGTs can penetrate easier into the conduction-dominated region at the bottom of the pool. This descending flow also entrains some hot fluid from the ambient pool and impinges on the bottom surface. The hot impinging flow causes the enhancement in heat transfer to the bottom surface.

Figure 8 shows the characteristics of the impinging flow spreading along the bottom surface (left), and temperature distribution in the vicinity of the bottom wall (right). With the lower Pr , the relative temperature in the impinged area decreases. As the Pr decreases the spreading area becomes larger because the descending flow becomes faster. Such effect has two main consequences. First, the area of enhanced heat transfer becomes larger. Second, with

decreasing Pr number the peak value of the downward heat transfer coefficient initially increases, and then, at $Pr < 0.5$ starts to decrease.

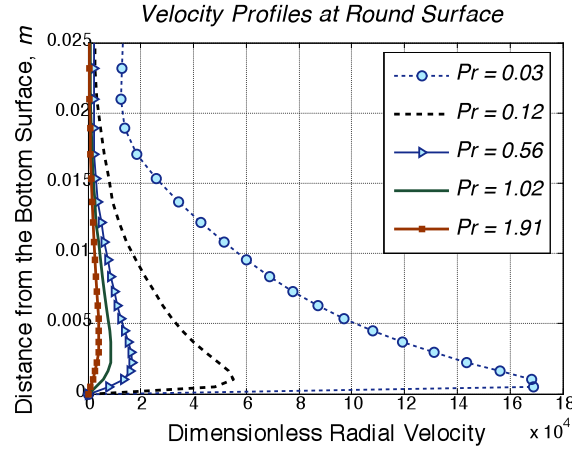


Figure 7: Vertical distribution of dimensionless radial velocity ($u L/v$) at 2 cm distance from the cooled CRGT surface for different Pr fluids.

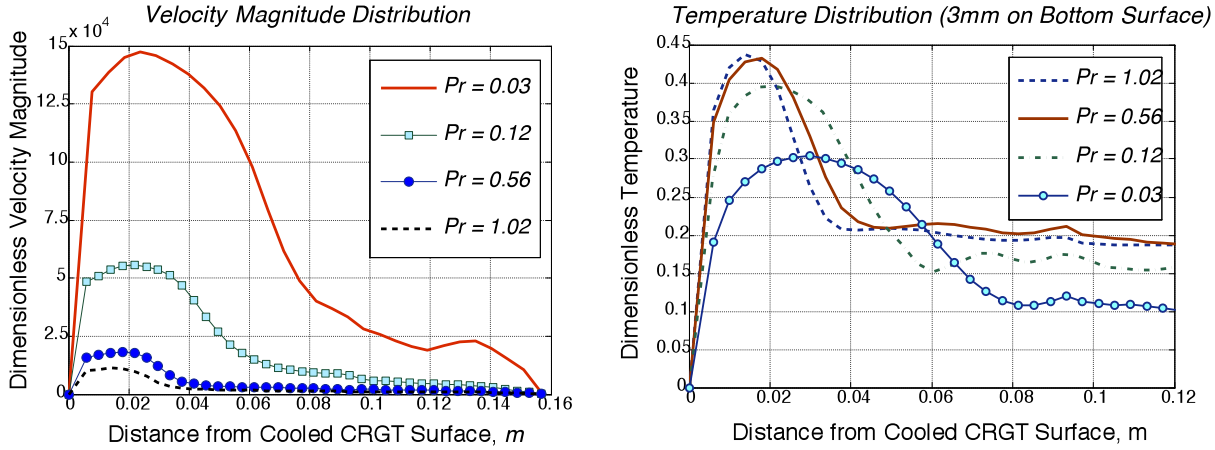


Figure 8: Distributions of time-average velocity magnitude and temperature $(T - T_{wall}) / (T_{max} - T_{wall})$ at 3mm above the bottom surface.

The non-monotone dependencies of the peak value of the heat flux (Figure 6) and average Nu_{down} number (Figure 5) on Pr number can be explained by an interplay between the ν -phenomenon (deeper penetration of the cold boundary layer flow into the bottom stratified layer) and the α -phenomenon (decrease of the bulk temperature due to increased thermal conductivity). The first effect (ν) generally helps to increase local heat transfer on the bottom surface, while the second effect (α) hinders heat transfer enhancement. These two phenomena are not completely decoupled because reduction of bulk temperature also reduces driving potential (buoyancy force) for the intensity of the descending boundary layer flow. Therefore, at certain values of Pr number, the negative effect of temperature difference reduction (α -phenomenon) prevails over the ν -phenomenon and causes reduction of the maximum local heat flux and resulting averaged Nu_{down} .

The profiles of the downward heat transfer coefficient obtained in the CFD simulations are implemented in the ECM and PECM for melt pool heat transfer simulation. Two improved profiles for Nu_{down} at $Pr=0.56$ and $Pr=0.03$ are used for describing the downward heat transfer

coefficient, instead of originally used Steinberner-Reineke correlation. The improved models for the downward Nu are as follows:

For $Pr = 0.56$:

$$\begin{aligned} Nu_{down}(r) &= 10.0 \cdot Nu_{SR} & \text{for } 0 \leq r \leq 0.01m \\ Nu_{down}(r) &= Nu_{SR} + 9.0 \cdot Nu_{SR} \cdot \left(\frac{0.035 - r}{0.025} \right) & \text{for } 0.01m \leq r \leq 0.035m \\ Nu_{down}(r) &= Nu_{SR} & \text{for } 0.035m < r \end{aligned} \quad (8)$$

For $Pr = 0.03$:

$$\begin{aligned} Nu_{down}(r) &= 6.5 \cdot Nu_{SR} & \text{for } 0 \leq r \leq 0.02m \\ Nu_{down}(r) &= Nu_{SR} + 5.5 \cdot Nu_{SR} \cdot \left(\frac{0.07 - r}{0.05} \right) & \text{for } 0.02m \leq r \leq 0.07m \\ Nu_{down}(r) &= Nu_{SR} & \text{for } 0.07m < r \end{aligned} \quad (9)$$

where Nu_{SR} is the Steinberner-Reineke correlation, Eq. (3), r is the radial distance from the vertical cooled surface. In the case of phase-change simulation, the cooled surface is the phase-change boundary. The improved PECM is used to simulate melt pool formation heat transfer. The PCM-simulated results are presented in the next section.

4. LOCAL HEAT TRANSFER ON THE BWR VESSEL WALL

4.1. PECM Unit Volume simulation

In this section the PECM heat transfer simulation of the UV with height of 0.7m is described. The UV is assumed to be a homogeneous decay-heated debris bed (or debris cake), initially at temperature of 450K in solid state. It is assumed that water is available atop of the debris bed and the top wall is isothermal at boiling temperature (383K) of water at 1.5-2 bars pressure. The CRGT wall is isothermal at 450K due to temperature drop in the CRGT wall. The bottom wall is connected with the steel vessel wall 0.2 m thick. The external surface of the vessel wall is covered with thermal insulation and a small heat flux (50W/m^2) is applied at the outer surface of the vessel. Other walls are adiabatic (or symmetrical). The debris bed heats-up and the process of remelting starts. Until the debris bed is in the solid phase, the conduction model is employed to simulate heat transfer between the debris bed and the vessel wall. As the debris bed is melted, the PECM is activated to describe natural convection heat transfer, including mushy zone heat transfer. Solidus and liquidus temperatures of the homogeneous debris are assumed to be 2750K and 2770K respectively. The decay heat is 1 MW/m^3 .

Figure 9 shows melt pool (red), crust (blue) and mushy zone (green) configuration at $t=15000$ sec (about 4.2h) for two cases of the downward heat transfer coefficient profile ($Pr=0.56$ and $Pr=0.03$). Clearly, using of different downward Nu profiles results in different phase-change boundary evolution. When the model described by Eq. (8) ($Pr=0.56$) is applied, the crust is eroded deeper in the region where the flow impinges, while for the model of Eq. (9) ($Pr=0.03$), the area of crust erosion is broader.

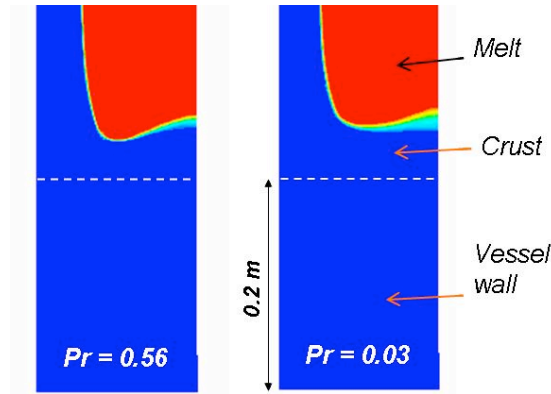


Figure 9: Evolution of the crust boundaries after 4.2h (liquid fraction in red).

Due to local crust erosion, the minimum crust thickness in these two cases is considerably thinner compared with the case where uniform, correlation based profile is used for downward Nu . Such erosion of the crust results in a higher heat flux to the vessel wall and in higher vessel temperature (Figure 10). Steady-state temperature of the vessel wall of two cases with improved Nu_{down} is increased for more than a hundred degrees in comparison with the case calculated using the original Steinberner-Reineke correlation. Note that the heat fluxes and vessel wall temperature of these two cases with improved Nu_{down} are different. However, the difference is insignificant.

In the next section, the integral effect of the local heat transfer due to fluid low Prandtl number is examined using the slice geometry of BWR.

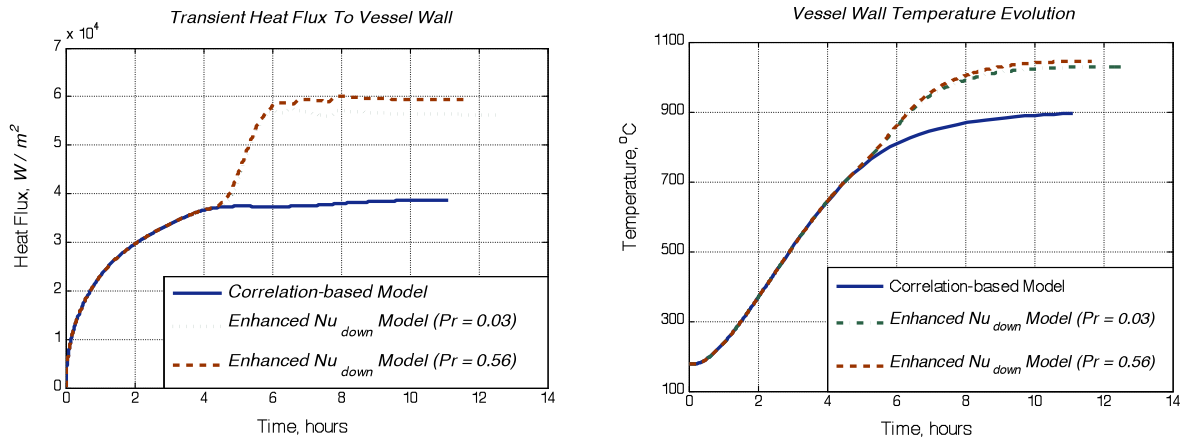


Figure 10: PECM simulation, transient heat flux to the vessel wall (left) and evolution of the vessel wall maximum temperature with different models of Nu number (right).

4.2. Integral heat transfer effect on the pressure vessel wall of BWR

To examine the integral effect of the new models for the local downward heat transfer at low Pr numbers on the vessel wall temperature we apply profiles of Nu_{down} based on results of CFD study for analysis of a BWR slice geometry (Figure 11). The BWR slice geometry is a segment of the BWR lower plenum containing a decay-heated debris bed, 6 cooled penetrated

CRGTs and the vessel wall. The depth of the debris bed is 0.7m. The top surface of the debris bed is assumed to be isothermal (383K) in contact with water available atop of the bed. The CRGT walls are isothermal (450K), the debris bed is thermally coupled with the vessel wall from below. The external surface of vessel wall has a layer of thermal insulation, therefore, 50W/m² heat flux is applied. Due to a small gap available between the CRGTs and vessel wall, the lower parts of CRGTs are specified to radiation heat transfer boundary condition. The debris bed is heated-up from 450K, remelted and a large melt pool is formed. Heat transfer from the corium molten pool to the cooled top surface, CRGTs, and the vessel wall is simulated by the PECM.

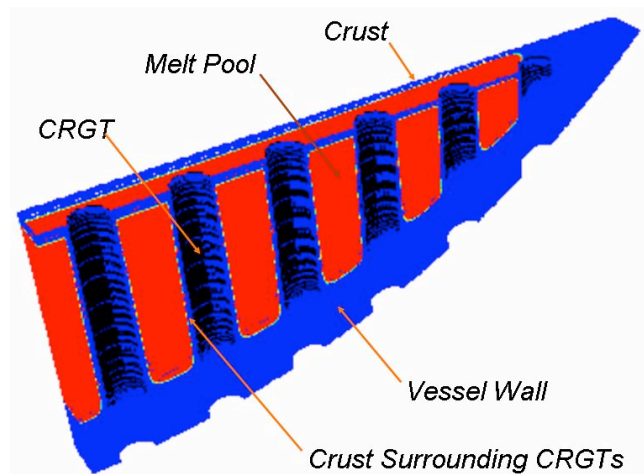


Figure 11: Slice of BWR used for PECM simulation.

The coupled thermo-mechanical creep analysis was previously performed using one way coupled PECM with ANSYS code (Villanueva et al. 2010). Transient temperature of the inner surface of the vessel predicted by PECM is used as boundary conditions for transient thermo-structural analysis of the vessel wall with ANSYS code. The study demonstrates that the effect of molten corium *Pr* number on the vessel wall displacement is observed only in about 5.5 hours. On the other hand, the acceleration of the creep and vessel failure is initiated early (about 4.5 hours), when only a small fraction of the melt is liquefied. Therefore the local heat transfer effect of low *Pr* corium melt has no significant influence on the vessel wall failure process for 0.7 m and deeper beds. Thus the uncertainty in modeling of global vessel failure mode due to melt composition effect can be significantly reduced. However, it is not clear at the moment if the low Prandtl number effect can affect vessel failure in case of smaller melt pools (less than 0.7 m deep). Also it is important to address the question about the influence of changes in solidus/liquidus temperatures for the melts with different compositions (e.g. fraction of metallic components) on the phenomena and timing of the debris remelting and thermo-mechanical load on the vessel wall.

5. CONCLUDING REMARKS

The present study demonstrates an approach for uncertainty reduction in accident analysis for Boiling Water Reactors (BWRs). The approach suggests a synergistic use of the Computational Fluid Dynamics (CFD) method, experiments and the Effective Convectivity Model (ECM) and Phase-change ECM (PECM). The effect of low fluid Prandtl number on heat

transfer from a melt pool to the BWR vessel wall has been examined using numerical experiments performed with reliable CFD tool. The local heat transfer effect due to corium melt low Prandtl number (Pr) on the downward heat transfer coefficient has found to be significant. The local downward heat transfer coefficient is a function of Pr , as the Pr is decreased, the local effect is enlarged to a broader area. However, the Pr number dependency of the Nu local peak value is non-monotone.

The data produced in CFD analysis about local heat transfer behavior at different melt Pr numbers is used for modification of the PECM heat transfer models. PECM is employed then for examination of integral effect of melt pool heat transfer on the vessel wall.

The integral effect of the local heat transfer enhancement is found to be significant, and the vessel wall temperature is considerably increased. However, we also found that this effect takes place at later timing than rapid acceleration of vessel thermal creep starts, at least in considered case of 0.7 m deep melt pool. Thus global vessel failure is not sensitive to the local heat transfer enhancement caused by fluid low Pr number. Further work is needed to examine systematically the timing of heat transfer and thermo-mechanical creep effects in different relevant configurations of the melt pool including different values of solidus/liquidus temperatures.

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