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Comparison of PTS analyses of RPVs based on 3D-CFD and RELAP5

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HIGHLIGHTS

- RPV fracture mechanics model based on RELAP5.
- RPV fracture mechanics model based on CFD.
- Comparison of models based on RELAP5 and CFD for fracture mechanics.

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ABSTRACT

The integrity of a reactor pressure vessel related to pressurized thermal shocks is one of the most important issues for the assessment of life time extension of a nuclear power plant. The most critical scenario occurs during cold water injection through the cold leg due to a Loss-Of-Coolant Accident (LOCA). Due to the difficulties associated with the crack modeling with the three-dimensional finite element method (FEM), simple geometries and crack configurations are usually employed.

In the present study, a hypothetical medium break LOCA is assumed in one of the hot legs for an adopted reference design of a two-loop pressurized water reactor. The boundary conditions obtained from RELAP5 calculations are used as input for the three-dimensional computational fluid dynamics simulations in order to provide three-dimensional temperature distribution for the structural mechanics analysis in which submodeling and eXtended FEM (XFEM) are applied. The results from these three-dimensional computations are compared with those from simplified axisymmetric models based on reference data temperatures.

1. Introduction

The structural integrity of a Reactor Pressure Vessel (RPV) is usually considered as a limiting factor for the operation time of a nuclear power plant, as it contains the reactor core and the reactor coolant, is crucial for the safe confinement of the radioactive fuel inventory, and is regarded as non-replaceable. Furthermore, RPV of nuclear power plants are exposed to neutron irradiation, which causes embrittlement of the ferritic steels and makes the material susceptible to brittle fracture (Odette and Lucas, 1986).

One potential risk for the integrity of a RPV is the brittle failure due to a Pressurized Thermal Shock (PTS), which occurs in case of an emergency cooling of the core, as a Loss-Of-Coolant Accident (LOCA). This is typically associated with a depressurization which, in the worst case, can be followed by a re-pressurization. Pressurized thermal shocks are produced by a number of events and accidents like a pipe break in the primary pressure circuit, a stuck-open valve in the primary circuit that later re-closes, or a break in the main steam line.

The most severe conditions for PTS take place when cold Emergency Core Cooling (ECC) water is injected inside the cold legs filled initially with hotter primary water and/or steam. The cold plume will flow into the downcomer and cool the RPV walls causing large temperature gradients. Pressurized thermal shock transients lead to high tensile circumferential and axial stresses in the RPV walls, these high stress states may produce crack initiation, propagation and, in the worst case, even brittle failure. As a consequence, the RPV has to be assessed against cleavage fracture (Keim et al., 2001; Qian and Niffenegger, 2013a,b, 2014; Shum et al., 1994).

Accurate prediction of the temperature distributions is necessary for determination of the stresses resulting from these thermal loads and for assessment of failure probability of the RPV due to crack propagation at critical locations (Smith, 2010; Boyd, 2012). However the one-dimensional models, used in thermal hydraulic analysis softwares such as RELAP5 or TRACE, cannot realistically represent the complex mixing phenomena in the downcomer.

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Nomenclature

RPV	Reactor Pressure Vessel
PTS	Pressurized Thermal Shock
LOCA	Loss-Of-Coolant Accident
CFD	Computational Fluid Dynamics
FEM	Finite Element Method
XFEM	eXtended Finite Element Method
LEFM	Linear Elastic Fracture Mechanics
SIF	Stress Intensity Factor
PWR	Pressurized Water Reactor
MLOCA	Medium Loss-Of-Coolant Accident
BPG	Best Practice Guidelines
FM	Fracture Mechanics
RCP	Reactor Coolant Pumps
SIP	Safety Injection Pumps
FE	Finite Element
a	semielliptical crack depth [mm]
c	semielliptical crack length [mm]
E	elastic modulus [MPa]
h	height of modeled RPV geometry or simplified RPV geometry [m]
K_I	mode I linear elastic stress intensity factor [$\text{MPa m}^{0.5}$]
R_i	inner radius of the modeled RPV geometry [m]
t	thickness of RPV wall [mm]

Computational Fluid Dynamics (CFD), on the other hand, is able to take into account the details of geometry and to predict multi-dimensional features of the mixing process between the ECC subcooled water and the primary hot water or two-phase mixture present in the cold legs and the downcomer. However CFD models are usually very time consuming from the computational point of view. Therefore, simplified models with an axisymmetric thermal hydraulic approximation are used for the PTS temperature evolution during the transient instead of using the three-dimensional plume information.

The mechanical model for RPV analysis is also very often reduced to a three-dimensional axisymmetric model (or even to a two-dimensional model) containing only the characteristic properties of the wall, due to the difficulties associated to a complete realistic three-dimensional modeling. Furthermore, these simplified models are usually assumed as over-conservative (Qian and Niffenegger, 2013b, 2014; González-Albuixech et al., 2014a,b). However, if more detailed temperature information is used, it is not clear if such simplifications and symmetry assumptions are valid.

The numerical structural integrity analysis of the RPV usually relies on the modeling of the RPV and the crack within the Finite Element Method (FEM) framework. The necessity of a mesh that adapts to the geometry of the RPV and also to the crack topology imposes some limitations, which simplified models entail. However, some new techniques have been recently developed that allow more comprehensive analysis of the RPV, like the eXtended Finite Element Method (XFEM; Duflot, 2006; Gravouil et al., 2002; Moës et al., 1999, 2002; Sukumar et al., 2000). Furthermore, XFEM was recently implemented in the commercial finite element code ABAQUS, Hibbitt et al. (2013) and already successfully applied to study a simplified RPV model (González-Albuixech et al., 2014a,b). A submodel analysis technique is linked to the complete three-dimensional RPV model study, as a complete detailed structural integrity analysis is not feasible due to the mesh refinement required for studying local effects as cracks.

The integrity analysis of RPVs is mostly based on the comparison of the mode I stress intensity factor (SIF) of postulated or detected flaws with the fracture toughness, K_{IC}, for the whole PTS. Calculation of the mode I SIF, K_I, is generally based on the Linear Elastic Fracture Mechanics (LEFM) theory. Moreover, the fracture toughness testing standards use highly constrained specimens and consequently the application of the LEFM framework can yield to over-conservative results. However, these results are still of great benefit for determining the RPV structural integrity for a given crack geometry (Keim et al., 2001; Qian and Niffenegger, 2013b, 2014; Shum et al., 1994; Zhu and Joyce, 2012).

In the present work a fracture mechanic analysis of a realistic RPV for a reference Pressurized Water Reactor (PWR) is performed. A Medium size LOCA (MLOCA) scenario according to a 70 cm^2 leak in the hot leg is chosen because it results in very rapid cooling in addition to high system pressure loads on the RPV and corresponds to the worst situation for the RPV structural integrity analysis. After defining the initial and boundary conditions from the RELAP5 system code calculations, the CFD analysis of PTS is performed with state-of-the-art computational methods and following as close as possible the Best Practice Guidelines (BPG) for the application of CFD in nuclear safety analysis (Mahaffy et al., 2007). The obtained transient results for the three-dimensional temperature distributions are then extracted from CFD for the subsequent Fracture Mechanics (FM) analysis. The fracture mechanic analysis relies on submodeling and XFEM allowing the analysis of different crack geometries and locations without complicated remeshing techniques. The same analysis is repeated for the same PTS transient using the temperature distribution obtained from reference data on a simplified mechanical model with axisymmetric load conditions.

The calculated SIFs are compared to those resulting from simplified models showing that the core region simplified model with homogeneous cooling yields to non-conservative results. Consequently if only a simplified model and boundary conditions are used the results cannot be considered as over-conservative as the transient effect is underestimated, thus for structural integrity analysis a three-dimensional model as realistic as possible should be used.

2. Computational fluid dynamics model

The RELAP5 (SCIENTECH Inc., 1999) system code was used to investigate different LOCA transient scenarios assuming breaks with varying sizes in each test for the cold and hot legs. In the current study, the RELAP5 results for a break size of 70 cm^2 in the hot leg are used to extract the reference initial and boundary conditions for the CFD calculations. A hypothetical break in the hot leg is more severe for PTS than a break in cold leg, because in the latter case part of the ECC water would flow out of the break and will not reach the downcomer. After the break, the system pressure decreases quickly and the Reactor Coolant Pumps (RCP) are postulated to be tripped with the actuation of a pressure signal. The high pressure safety injection water is injected in each cold leg from the Safety Injection Pumps (SIP) at a temperature of 30 °C. The pressure then reaches a value of 6.9 MPa at which additional safety water is injected from two accumulators connecting the cold legs at different lines before the system pressure continues to decrease again. In the current study, only the accumulator connected to loop B (see Fig. 1) is assumed operational which leads to asymmetric cooling conditions. This was found to create larger thermal loads than in case of symmetric injection conditions (Sharabi et al., 2014).

At the start of the ECC injection, the flow in the loops was almost stagnant. The ECC from SIP reaches a value of 80 kg/s in each loop and it remains constant for a long period of time. The flow rate from the accumulator has an average value of 200 kg/s and the temperature of the injected water was assumed to be 10 °C. In order to save computation time, the CFD calculations were launched at the