PRESSURE THERMAL SHOCK ANALYSIS FOR NUCLEAR REACTOR PRESSURE VESSEL

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1. Introduction

The reactor pressure vessel is considered the most reliable component of pressurised water reactors. The target of concurrent research is the extension of operating life of existing power plants end their components. The condition of the reactor pressure vessel is a major limiting factor for the operating life of a power plant. The pressure vessel is exposed to thermo-hydraulic transients and the embrittlement effect caused by hard radiation. The coupled impact of these effects increases the risk of structural damage to the pressure vessel during high transients by pressure thermal shock (PTS). Thermal shock damage within solid materials represents high risk of structural weakening or in severe cases total structural failure and its elimination represents a significant engineering challenge.

2. Pressure thermal shock phenomenon

Loss of coolant accidents create highly transient processes within the reactor pressure vessel. The two properties that influence the vessel wall are pressure and temperature, both experience rapid changes during evaporation of the working fluid [1]. Pressure thermal shock is the combined effect of thermal shock damage induced by temperature gradients and the structural load created by internal pressure of the fluids within the reactor pressure vessel. The combined stress from pressure thermal shock can cause crack formation or in severe cases the total structural failure of the reactor pressure vessel [2]. Thermal shock occurs as a reaction of solid materials to dynamic temperature changes. A basic example is an object at an initially uniform temperature which is suddenly exposed to higher or lower external temperatures. The resulting diffusion of thermal energy creates a rapidly changing temperature gradient, which can induce severe internal thermal stresses in the material[3,4].

3. PTS analysis methodology and evaluation methods

A pressure thermal shock as a transient event in a reactor pressure vessel is a highly complex multi-physical process. The analysis of such a process needs to be divided into multiple stages with different methods and models. Our approach is based on the UNIPI methodology [5]. The methodology and stages required for the evaluation of the process are shown in Fig. 1.

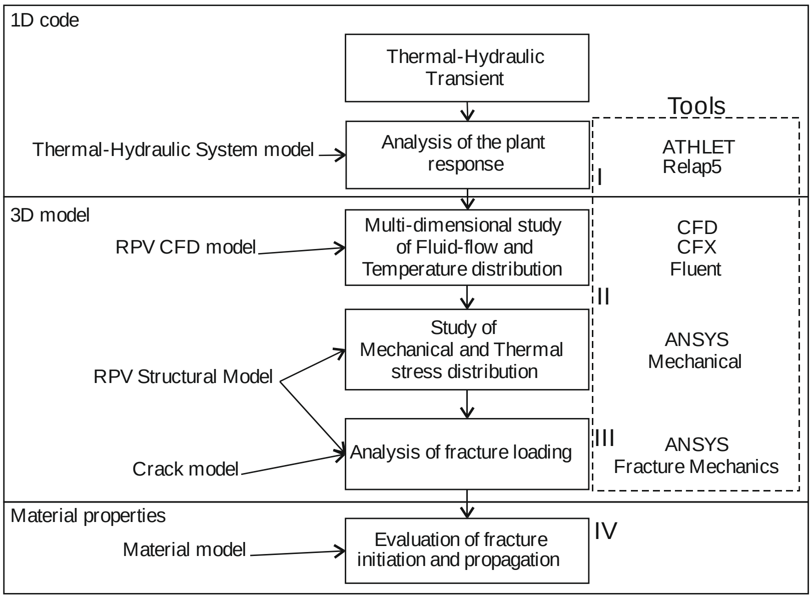

Fig. 1 Methodology for PTS analysis

The methodology starts with the simulation of a PTS in the primary circuit via 1D system thermo-hydraulic code to determine the response of the primary circuit to the transient loading (Fig. 1 I). The acquired response is used as a load for the analyses on 3D CFD and FEM models to determine the spatial and time distribution of investigated values (Fig. 1 II). Fracture states are examined for different time points and different pre crack geometries (Fig. 1 III). Finally the acquired fracture states are evaluated for the possibility of crack formation and propagation based on available material model data.

High temperature gradients during transients can induce severe internal stresses in the material. Fracture and crack formation occurs when internal stresses exceed the ultimate strength of the material. Depending on the mutual orientation of the fracture and the acting thermal stresses, there are three modes of fracture formation as described in Fig. 2.

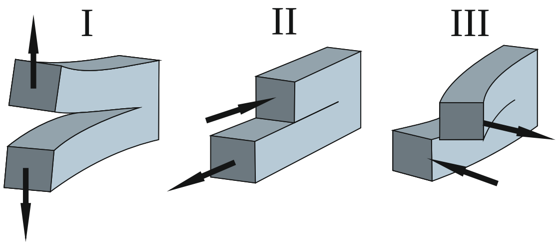

Fig. 2 Fracture modes (I-Opening, II-Sliding, III-Tearing)

Single mode fractures are rare in real structures, usually fracture formation occurs by the simultaneous loading of multiple modes.

SIF - The stress intensity factor K is used to describe the stress intensity at the crack tip for a given load. The stress intensity factor´s analytical equation form is highly dependent on crack geometry and location. Fracture propagation criterion (G-criterion) can be determined by stress intensity factors for all three fracture modes as

$$K_{Ic}{}^2 = K_I{}^2 + K_{II}{}^2 + \frac{E'}{2G} K_{III}{}^2 \qquad (1)$$

where K_{Ic} is the critical stress intensity factor, K is the stress intensity factor with subscripts indicating fracture mode component, E' is the Young´s modulus for given material and G is shear modulus. The critical stress intensity factor K_{Ic} determines a pre-cracked materials resistance against further crack growth via brittle fracture [6].

J-integral - J-integral represents the strain energy release rate per unit of fracture surface area. It is a path-independent integral of accumulated strain energy for linear-elastic deformations. In a material with plastic deformation only a path sufficiently close to the crack tip will give a correct energy release rate. The path of J-integral in the case of ductile fracture is shown in Fig.3.

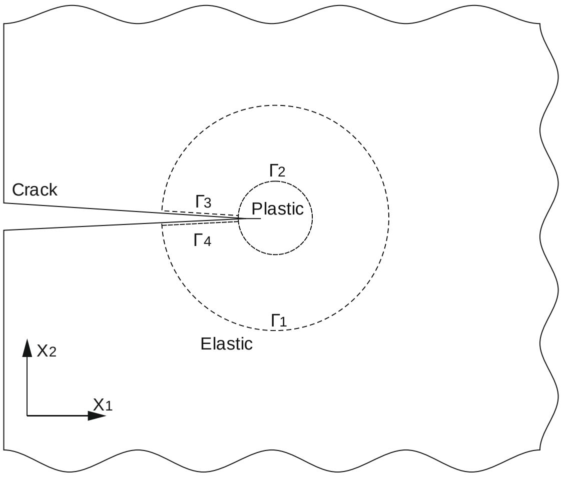

Fig. 3 J-integral integration path

J-integral method can be used to determine J_{Ic} an analogous value to K_{Ic}. J_{Ic} represents the resistance against ductile fracture propagation in materials.

4. Detailed CFD analysis

The methodology described above requires multiple different numerical models and analyses to successfully simulate and evaluate a pressure thermal shock event. The detailed CFD analysis (Fig.1 II) is required to simulate fluid flow and mixing with sufficient fidelity and detail.

4.1. CFD model

The CFD model represents the fluid domain within a primary circuit cold-leg with ECC injection nozzle as shown in Fig. 4a. Cold-legs of coolant loops 2, 3 and 5 are identical and contain the nozzle of a high pressure coolant injection pump as shown in Fig. 4b. Fig. 4c shows the model detail around the ECC injection nozzle.

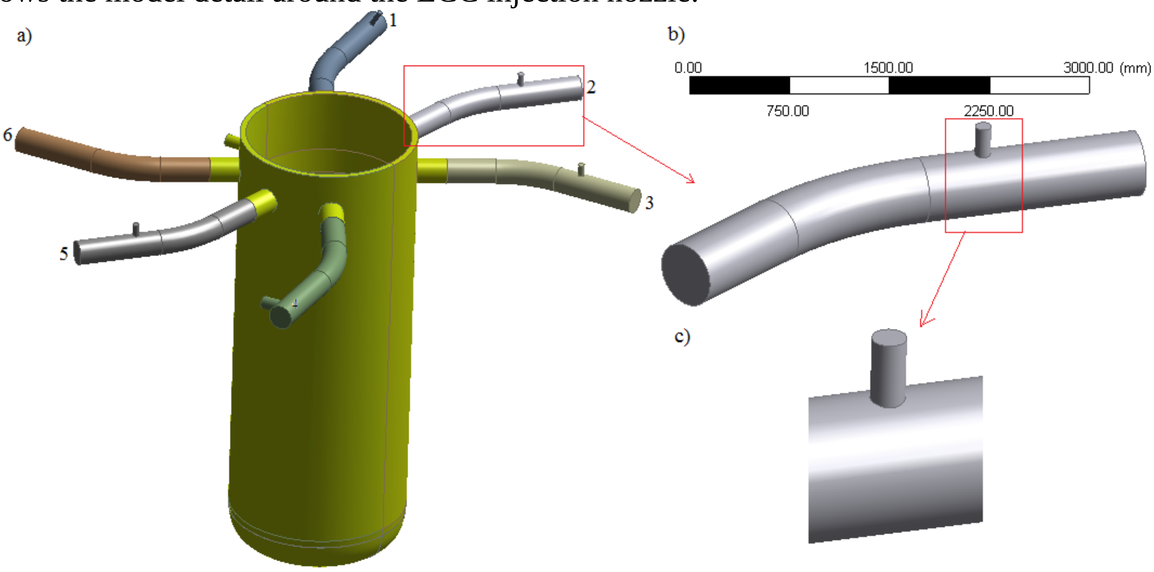

Fig. 4 Model for detailed CFD analysis

4.2. CFD Transient analysis

The transient analysis simulates the initiation of high pressure coolant injection into the primary circuit cold leg. In the beginning of the simulation, the primary circuit is in nominal operational state. Water is pumped through the cold leg into the downcomer region by the main circulatory pump. Cold water injection is initiated by the decrease in pressure at the beginning of the simulation caused by a small leak LOCA. Specific parameters are listed in Tab.1.

Tab. 1 Initial and Boundary Conditions

Primary Coolant Temperature	265.6	°C
Primary coolant Pressure	11.97	MPa
Primary coolant Mass flow rate	1400	kg/s
ECC injected coolant Temperature	60	°C
ECC injected coolant Mass flow rate	10	kg/s
Total simulation time	5	s

The total simulation time was chosen to achieve a steady state at the end of the simulation. Mass flow rates were determined based on pump characteristics and coolant pressure and temperature states. The resulting steady-state temperature distribution is shown in Fig. 5.

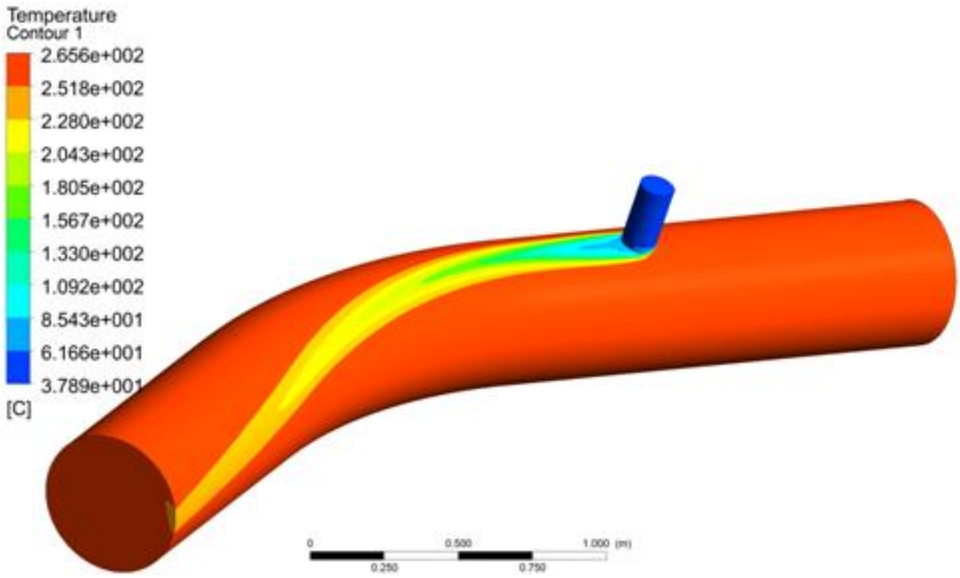

Fig. 5 Temperature distribution

Fig. 5 shows the temperature distribution created by coolant mixing on the internal surface of the pipe wall. The lowest temperatures are expected at the injection nozzle, located downstream.

5. Conclusion

The appearance of structural weaknesses within the reactor pressure vessel or its structural failure caused by crack formation during pressure thermal shock processes pose as a severe environmental hazard. Coolant mixing during ECC cold water injection was simulated in a detailed CFD analysis. The temperature distribution acting on the pipe wall internal surface was calculated. Although, the results show the formation of high temperature differences and intense gradients, an additional structural analysis is required to determine the possibility of structural damage from PTS. Such an analysis will be the subject of follow-up research.

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