



Features of heat and deformation behavior of a VVER-600 reactor pressure vessel under conditions of inverse stratification of corium pool and worsened external vessel cooling during the severe accident. Part 1. The effect of the inverse melt stratification and in-vessel top cooling of corium pool on the thermal loads acting on VVER-600's reactor pressure vessel during a severe accident

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ABSTRACT

The problems touched on in this work are closely associated with the realization of in-vessel melt retention strategy through the external reactor vessel cooling and cooling of the molten corium pool inside the medium-power reactor VVER-600 (thermal power is ~ 1600 MW) in the course of the SA. The general objective of the research was to determine a thermal state in two- and inverse three-layer molten corium pools, which can be formed in the reactor vessel during the SA. The second task was to estimate the efficiency of the top water flooding of corium pool for its cooling in SA by comparing the new results with those obtained in the previous investigation of the authors. Compositions and mass of the corium pools for the two-layer and inverse three-layer pool structures are analyzed and presented in the paper. Simulation of heat transfer in the molten pool was performed for time values 10, 24 and 72 h from the initiating event (IE) in the SA. To estimate the influence of decay heat generation in the bottom metallic layer of the inverse molten pool on the thermal state of molten pool, a series of model SA scenarios was considered in the work. To simplify the simulations the computation domain was bounded by only the pool with taking corresponding boundary conditions. Simulations of thermal state of the molten pool were carried out by means of the NARAL/FEM computer code in which the turbulent convection at the high-Rayleigh numbers was used through the use of the effective heat conduction properties of the corium materials. The numerical results obtained for two-layer corium pool brought out a series of features: (a) the top water flooding of the melt pool resulted in temperature decrease by ~ 150 K only in the upper melt steel layer and had no effect on an essential temperature change in the oxide phase of the corium; (b) top flooding of the corium results in an essential decrease (by more than 40%) of maximal values of heat flux acting on the reactor vessel in the region of contact of the vessel wall with steel melt layer. Thus, the top water flooding of the pool surface yields an essential drop of the heat flux peak acting on the vessel wall from 1.65 to ~ 1.2 MW/m² in case at 24 h after IE; (c) the heat flux peaks acting on the vessel decrease from ~ 1.65 MW/m² (at 24 h after IE) to ~ 1.15 MW/m² (at 72 h) in case when the top flooding of the corium pool is absent, and decrease from 1.2 (24 h) to ~ 0.6 MW/m² (at 72 h) when using the top flooding. In the case of the inverse corium pool, the top water flooding essentially decreases (by more than 50%) the maximal value of heat flux in upper layer of steel melt; (d) in the case of melt inversion and redistribution of total decay heat generation in the corium pool between oxide and bottom metallic layers of the pool (parameter $K_{Oxide} = Q_{Oxide}/(Q_{Oxide} + Q_{Bot.Me})$, the dependence of maximal values of thermal load on the lateral surface of the pool depending on K_{Oxide} value is observed. Thus, the increase of power of heat generation in the bottom metallic layer of the melt from 0.2 to 0.45 (the decrease of K_{Oxide} from 0.8 to 0.55) causes the increase of heat flux value in the bottom layer by ~ 1.5 times. Taking into account the fact that in this region of RPV lower head the CHF has low values ($\sim 0.3 \dots 0.45$ MW/m²), the probability of superheat and premature failure of the vessel bottom in this field increases. The maximal values of heat flux in the oxide phase and bottom heavy metal layer of the pool are observed near the boundary separating these layers. In this region of the VVER lower head, the heat flux attains the values that may

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Nomenclature

BC	boundary condition
BHM	bottom heavy metallic layer
CFD	computational fluid dynamics
CHF	critical heat flux
DHG	decay heat generation
ERV	external reactor vessel cooling
HFD	heat flux density
HTC	heat transfer coefficient
IE	initiating event
IVR	in-vessel retention
IVMR	in-vessel melt retention
K_{oxide}	the ratio of value of decay volumetric heat generation rate in oxide phase to the total decay volumetric heat generation rate
LH	lower head
NPP	nuclear power plant
RI	reactor internals
RP	reactor plant
RPV	reactor pressure vessel
SA	severe accident
VVER	water-water energetic reactor
c_p	specific heat capacity
H_0	height of corium pool
h_{met}	thickness of bottom heavy metallic layer

h_{ox}	thickness of oxide layer of the corium
h_p	vertical coordinate
h_{stl}	thickness of upper metallic layer
L	latent heat of melting
Q_{dec}	total decay volumetric heat generation rate in corium pool
Q_{oxide}	decay volumetric heat generation rate in oxide phase
q	heat flux density
q_{chf}	critical heat flux density
q_{max}	maximal values of heat flux density
q_{top}	heat flux density on the top surface of the pool
q_{wall}	heat flux density on inner wall surface of RPV
R_0	radius of corium pool
r_{ves}	radial coordinate of the inner surface of the RPV wall
T_{liq}	melting temperature
T_{sur}	surrounding temperature
ΔT_{sub}	water subcooling to the saturation temperature

Greek letters

β	coefficient of volume expansion
ε_{st}	emissivity at the top surface of upper melt steel layer
φ	slope angle of the external surface of RPV
λ	thermal conductivity
μ	viscosity
ρ	density

exceed the corresponding values of CHF. Because of this, there is a high probability of superheat and the reactor vessel premature failure due to worsened heat transfer and cooling conditions on the external surface of the vessel wall. This fact should be necessarily taken into account when acting on the RPV lower head the thermal loads of moderate intensity ($\sim 0.5\ldots 0.7 \text{ MW/m}^2$) that may cause superheat and premature failure of the reactor vessel in the case of inverse molten pool formation during the SA in VVERs.

1. Introduction

The present manuscript is devoted to the urgent problem of providing the in-vessel retention of molten corium in the VVER-600 during the severe accident (SA). The problems touched on in this work are closely associated with the realization of well-known in-vessel melt retention (IVR, IVMR) strategy through the external reactor vessel cooling (ERV) and cooling of the molten corium pool inside the VVER-600's reactor pressure vessel (RPV) in the course of the SA. For more than 30-year period of active studies on IVR-ERV strategy, the knowledge of highest value and understanding the features of complex, thermal-physical, thermochemical, and thermal-mechanical processes have been obtained at this stage of the SA *** (Asmolov et al., 2000, 2001, 2004; Bakouta et al., 2015; Bechta et al., 2008; Bernaz et al., 2001; Esmaili and Khatib-Rahbar, 2005; Fukasawa and Tamura, 2007; Fukasawa et al., 2008; Gaus-Liu et al., 2010; Henry and Fauske, 1993; Kang et al., 2014; Knudson et al., 2004; Kolev, 1996, 2001, 2009; Koundy et al., 2005a; Koundy and Corneau, 2005b; Kymalainen et al., 1994, 1997; Le Tellier et al., 2015; Miassoedov et al., 2007, 2008; Nicolas et al., 2003; Nieminen, 2013; Park and Bang, 2013; Park et al., 2015; Rempe et al., 1993, 2004; Rouge, 1997; Sehgal et al., 2002, 2005, 2006; Sehgal, 2006; Seiler et al., 2003, 2007; Theofanous et al., 1996, 1997a,b; Theofanous and Angelini, 2001; Tran et al., 2010; Villanueva et al., 2012; Willschütz et al., 2001; Willschütz, 2004; Zhang et al., 2011). As applied to the VVER reactors that differ from those of foreign design in geometry and a set of structure features, the problems on IVR-ERV were in focus of attention in a series of papers (Asmolov et al., 2000, 2004, 2007, 2008; Dombrovskii et al., 1998, 2005, 2006; Gencheva et al., 2016; Granovskii et al., 1994, 1995; Kochetov et al.,

2015; Likhachev et al., 1994; Loktionov et al., 1999, 2003, 2005, 2011; Loktionov, 2007; Loktionov and Mukhtarov, 2016; Matejovic et al., 2014, 2017; Rassokhin et al., 2006; Rogov et al., 1996; Tarabelli et al., 2009; Tsurikov et al., 2009; Zvonarev et al., 2011, 2014). Of course, the above references to papers and studies cannot fully cover the whole range and amount of investigations already performed and those being carried out nowadays concerning the subject discussed here as well as those who perform this research and make a contribution to the solution of IVR-ERV problem and strengthening the safety of NPP.

The analysis of events taken place at NPP "Fukushima Daiichi" in 2011 showed that it is reasonable to consider a wider range of probable SAs and conditions accompanying such accidents. For instance, it is worthwhile studying the scenarios of SAs, in which a sufficiently high level of overpressure in the RPV (up to 8 MPa) is preserved for tens of hours (Jianfeng et al., 2016; Mao et al., 2016). The research concerning the realization of IVR-ERV strategy remains its relevance nowadays. This fact is confirmed by the level and content of recent investigation (Fuller et al., 2016; Kim et al., 2016; Lim et al., 2016; Miassoedov et al., 2016; Zhang et al., 2016a,b,c; Carénini et al., 2017).

Turning to the IVR problem, it is necessary to confirm again the known fact that thermal and hydrodynamic processes occurring in the molten corium pool determine the value and distribution of thermal load acting onto the RPV wall in the SA. Whereas both thermal load from the molten corium pool acting onto the RPV wall and the conditions of its external cooling influence largely on the kinetics of the reactor vessel deformation and the model of its failure during the SA (Gencheva et al., 2016; Koundy et al., 2005a; Koundy and Corneau, 2005b; Likhachev et al., 1994; Loktionov et al., 1999, 2005, 2011; Loktionov, 2007; Matejovic et al., 2014, 2017; Nicolas et al., 2003;

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