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Boundary identification between LBLOCA and SBLOCA based on stratification and temperature gradient in two-phase PTS

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ABSTRACT

Temperature gradient on the thick Reactor Pressure Vessel (RPV), caused by sudden overcooling events, especially in the downcomer, would intensify the propagation of structural defects. This situation known as Pressurized Thermal Shock (PTS) could be created in case of Emergency Core Cooling System (ECCS) actuation which leads to injection of cold water into the cold leg of the primary loop in some accidents, e.g. Loss Of Coolant Accident (LOCA). Prediction of Plant response to LOCA and water temperature gradient in the downcomer are performed in thermal-hydraulic section of PTS analysis. Employment of system codes is one of the proposed procedures in literature to obtain plant response and flow condition in the cold leg during LOCA. Also the results of these codes would be used to find the flow regime in the cold leg with some limitations. In this paper simulation of different break sizes in Bushehr Nuclear Power Plant as VVER-1000 reactor is performed by RELAP system code to find the temperature gradient and flow regime in the cold leg according to different criteria. Due to some limitations of system codes, CFX code is employed to evaluate turbulence characteristics at the interface for identification of flow regime. The comparison between results of different LOCA scenarios reveals a sharp reduction of water temperature in downcomer for large breaks which would be used for classification of LOCA. Also the flow regime in the cold leg during ECCS injection changes from stable stratified flow to wavy flow when the break size increases beyond a certain value. Therefore, the difference of temperature gradient in downcomer and flow regime in cold leg will be proposed as a new definition of Small Break LOCA (SBLOCA) and Large Break LOCA (LBLOCA) relevant to PTS analysis.

1. Introduction

The neutron radiation has a detrimental effect on the mechanical properties of the RPV material such as hardening (or embrittlement) while neutrons are absorbed by RPV material (Araneo and D'Auria, 2012). A major concern in embrittled RPVs is propagation of critical flaw which may cause through-wall cracks. Some transients leading to overcooling of RPV intensify the propagation of the cracks, as a result of thermal load on RPV, known as PTS. A complete analysis of PTS has three main steps including PSA, TH analysis and fracture mechanics analysis. Identification of the overcooling events and estimation of their occurrence frequency should be carried out in PSA part. The results of the researches of PSA part accomplished in literature show that different sizes of LOCA dominate the most severe condition in PTS (EricksonKirk et al., 2007; Kirk, 2013). Therefore, LOCA is considered as the main initial event in PTS analysis. The objectives of TH step of PTS analysis are the prediction of Plant response to LOCA and production necessary data for fracture mechanics analysis (IAEA, 2010).

As a consequence of LOCA, decrease of primary side coolant is compensated by ECCS which injects cold water into the cold leg (or hot leg) of the primary side. Two- phase PTS will occur for medium and large break sizes and needs more attention for related complex phenomena (Bestion et al., 2006). In this condition, two-phase stratified flow propagates in the cold leg by means of density difference between water and steam. Water moves along the

Abbreviations: BNPP, Bushehr Nuclear Power Plant; CFD, Computational Fluid Dynamics; DCC, Direct Contact Condensation; ECCS, Emergency Core Cooling System; FSAR, Final Safety Analysis Report; HPIS, High Pressure Injection System; LBLOCA, Large Break Loss OF Coolant Accident; LOCA, Loss Of Coolant Accident; LPIS, Low Pressure Injection System; MSIV, Main Steam Isolation Valve; PSA, Probabilistic Safety Assessment; PSD, Pulse Safety Device; PTS, Pressurized Thermal Shock; PWR, Pressurized Water Reactor; RCP, Reactor Circulation Pump; RPV, Reactor Pressure Vessel; SBLOCA, Small Break Loss Of Coolant Accident; SG, Steam Generator; TGSV, Turbine Generator Stop Valve; TH, Thermal-Hydraulics.

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Nomenclature

D	Hydraulic diameter of test section
g	Gravity acceleration
h	Phase height
P	Pressure
t	Time
v	Velocity
α	Volume fraction
ρ	Density
σ	Surface tension
τ	Shear stress

Subscript and superscript

b	Bubble
g	Gas phase
m	Mixture of water and steam
l	Liquid phase
t	Turbulence
w	Wall

bottom of the cold leg and quasi steady condition remains for low gas velocity. As the gas velocity increases, the local pressure drops and generation of new lift force lead to upward movement of the interface. The direction of this force is opposite of gravity as a stability factor at the interface. For a particular velocity, the suction effect overcomes the gravity effect and amplifies the wavy flow (Andritsos and Hanratty, 1987). So the flow regime of the cold leg changes to wavy or slug flow. The new flow of steam and water dictates a considerable temperature gradient on RPV wall and leads to a thermal load on it.

The maturity of system codes such as RELAP is sufficient to obtain the plant response to LOCA. On the other hand, the second objective of TH analysis (production necessary data for fracture mechanics analysis) would include 3D effects and local phenomena which are outside the capabilities of system codes. In stratified flow zone (downstream of injection point), the proposed models at the interface of water and steam depend on initial condition and specially flow regime during the injection of ECCS water (Lucas et al., 2007). Calculation of mass, momentum and energy transfer at the steam/water interface depends on flow characteristics of any kind of interface shape (Höhne and Lucas, 2011; Kim et al., 1985; Lim et al., 1984), and should be done by consideration of flow regime (Bestion, 2010). Based on SRT (Higbie, 1935), condensation of steam in the cold leg as important heat source is controlled by turbulence eddy motion. The evaluation of turbulence parameters (e.g. turbulence kinetic energy and dissipation rate) strongly depends on identification of flow regime and some stratification criteria are defined based on these parameters (Bestion and Serre, 2012; Brocchini and Peregrine, 2001). Also, pressure drop in the cold leg affecting water flow rate, water layer thickness and natural circulation in primary side is a function of flow regime and interfacial flow characteristics (Fabre et al., 1987; Mouza et al., 2001). Therefore, the prediction of flow regime in the cold leg should be accomplished for employment of different models in CFD part. Depending on the leak size, its location and operation conditions of the plant after LOCA, the flow regime in the cold leg will change. The increasing of break size (transition from SBLOCA to LBLOCA) results in further reduction of pressure and increasing of steam quality in the cold leg. As a result of this transition, the dictated temperature gradient in downcomer increases (Arcieri et al., 2006), and the flow regime changes from stable stratified flow to wavy flow. From the point of view of PTS, these variations would be used for classification of different scenarios of LOCA. Based on this method, the breaks leading to unstable and transient stratified flow in the cold leg and high temperature drop in the downcomer are known as large breaks. Also, small breaks result in stable stratified flow and lower temperature drop. As a result, the selection of CFD models for simulation of interfacial phenomena and primary estimation of temperature drop in downcomer will be obtained by the identification of the break type.

In this paper, RELAP5/3.3 is used for simulation of different break sizes of LOCA in BNPP as VVER-1000 and identification of a boundary between SBLOCA and LBCOLA based on two-phase PTS consequences. For this purpose, the illustration of flow regime criteria will be done based on viscous Kelvin-Helmholtz instability and propagation of bubbly flow at the interface in Section 2. Due to some limitations of system codes for evaluation of turbulence variables (Bestion, 1990), CFD simulation of stratified flow is used to approximate some turbulence variables relevant to flow regime prediction. In Section 3, The RELAP model of BNPP is described and results of different scenarios of LOCA are employed for evaluation of temperature drop in the downcomer. In Section 4, flow regime of different locations in the cold leg is identified by means of introduced criteria, and classification of LOCA scenarios will be done.

2. Flow regime prediction in the cold leg

After LOCA, the new mixture of water and steam propagates in the cold leg. For low velocity of steam, stratified flow is established due to high different density between water and steam. In this condition, gravity force is high enough to overcome the other force (e.g. lift force). As the gas velocity increases, the lift force due to pressure reduction acts as a destabilizing factor and unstable waves will grow (Lamb, 1932; Milne-Thompson, 1968). The evaluation of unstable stratified flow is done by Kelvin-Helmholtz instability theory. Based on different interfacial force consideration, two types of this theory have been introduced in literature (Bestion and Micaelli, 1987). In the first type known as viscous Kelvin-Helmholtz instability, all forces (especially viscous force) are taken into account in full two-fluid model and numerical solution of the momentum equations is the main strategy to find the transition criteria (Lin and Hanratty, 1986; Wallis, 1969). In the other type, the shear stresses are neglected due to low viscosity between two fluids (Ishii, 1980; Taitel and Dukler, 1976). By this assumption, gravity and inertial forces dominate the flow condition. The effect of each mentioned force would be evaluated by calculation of non-dimensional modified Froude number as follows:

$$Fr' = \frac{\rho_g \rho_l (v_g - v_l)^2}{\rho_m g D (\rho_l - \rho_g)} \quad (1)$$

If the value of Fr' is more than one, no stratified flow is possible and all waves at the interface become unstable. When this value is less than one, full stratified flow and transition region would occur based on flow condition. Wallis and Dodson (1973) experimentally showed that the transition from stratified to slug or plug flow in a horizontal rectangular channel occurs at 0.5 of Eq. (1). The difference between two criteria would be explained by the effect of shear stress at the interface neglected in inviscid theory. Some numerical and experimental results in literature show that the