IYNC 2008
Interlaken, Switzerland, 20 – 26 September 2008
Paper No. 192

Numerical Analysis on Transient of Steam-gas Pressurizer

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ABSTRACT

In nuclear reactors, various pressurizers are adopted to satisfy their characteristics and uses. The additional active systems such as heater, pressurizer cooler, spray and insulator are essential for a steam or a gas pressurizer. With a steam-gas pressurizer, additional systems are not required due to the use of steam and noncondensable gas as pressure-buffering materials. The steam-gas pressurizer in integrated small reactors experiences very complicated thermal-hydraulic phenomena. To ensure the integrity of this pressurizer type, the analysis on the transient behavior of the steam-gas pressure is indispensable. For this purpose, the steam-gas pressurizer model is introduced to predict the accurate system pressure. The proposed model includes bulk flashing, rainout, inter-region heat and mass transfer and wall condensation with noncondensable gas. However, the ideal gas law is not applied because of significant interaction at high pressure between steam and noncondensable gas. The results obtained from this proposed model agree with those from pressurizer tests.

1 INTRODUCTION

A number of issues will be considered in an increasingly competitive and regional energy market such as enhancing reactor safety, minimizing environmental impact, improving nuclear power generation economics and resource utilization. RERI (Regional Energy Research Institute for Next Generation) in Korea has been developing a small-scale electric power system with an integrated transmission/distribution/load powered by an environmentally-friendly and stable small nuclear reactor, REX-10 (Regional Energy rX – 10MW$_{th}$) [1]. Since this regional energy reactor will be located relatively close to a residential area such as an apartment complex and an island, highly enhanced safety features are required compared with current commercial nuclear power plants. The REX-10 reactor system is designed based on SMART (System-integrated Modular Advanced ReacTor) [2] and its system pressure and capacity are determined properly for a regional energy reactor. For high safety, the integral type reactor concepts with natural circulation, pool-type vessel and low operation pressure are introduced. Figure 1 shows the schematic diagram of REX-10. To satisfy these integral reactor concepts, the entire primary systems such as core, pumps, main heat exchangers (steam generators) and pressurizer are arranged in a single pressure vessel. REX-10 is designed to remove the heat from nuclear fuel by natural circulation and to be operated with low system parameters compared with traditional pressurized water reactor. REX-10 operates with full power natural circulation cooling at all power levels so that primary circulating pumps can be eliminated. In order to increase the natural circulation capacity, there is a long riser in the upper part of the core. The steam generator is a type of helical-coiled tube bundle, and the integral type of helical-coiled steam generator is also considered as an alternative. Moreover, the thorium fuel cycle with a 20-year lifetime is considered for non-proliferation and the economical efficiency is ensured by the unmanned automatic control.

From the viewpoint of pressurizer, various pressurizers are used according to their characteristics and purposes. One of the basic concepts of this small integrated reactor is the built-in steam-gas pressurizer which operates in a way of self-pressurization because REX-10 adopts a passive system for enhanced safety. Since the steam-gas and gas pressurizers have a characteristic of self-pressurization, additional active systems such as an electrical heater and a spray for pressure control are not required by using steam and noncondensable gas as a pressure-buffering material. In addition, the gas pressurizer based on low-temperature concept has additional devices to minimize the steam partial pressure such as a pressurizer cooler and a wet thermal insulator, which makes the structure of pressurizer system complex.

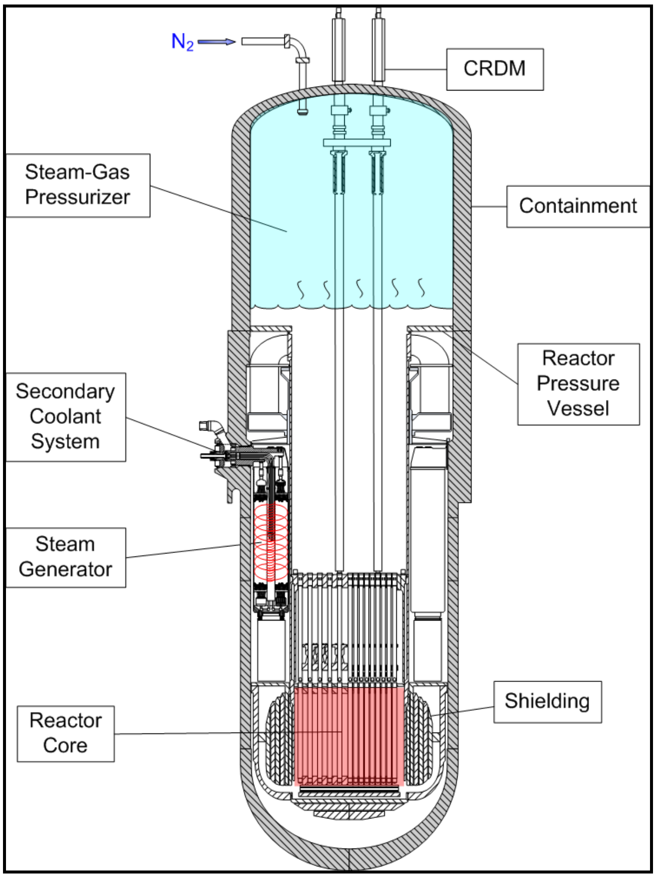

Figure 1: Schematic diagram of REX-10.

As shown in Fig. 1, the structure of a steam-gas pressurizer is simple. It is allowed for the core exit temperature and the pressurizer temperature to be the same. Therefore, the primary system is pressurized by the partial pressures of steam and noncondensable gas. The built-in steam-gas pressurizer has been mainly used in the nuclear reactor with enhanced safety such as AST-500, ATS-150, NHR-200 [3,4], etc. However, there have been few investigations and reports on the steam-gas pressurizer compared with the steam pressurizer. In Russia Federation, the steady-state analysis code for built-in steam-gas pressurizer, GARRIC, was developed to investigate the characteristics of steam-gas pressurizer and the distribution of the noncondensable gas in the pressurizer volume [5]. In GARRIC, four kinds of noncondensable gases such as hydrogen, helium, nitrogen, and oxygen are considered and the steam-gas mixture is treated as a Gibbs-Dalton mixture. Basically, the ideal gas law is used for determining the thermodynamic state of noncondensable gas. However, the available information on development of steam-gas pressurizer and analysis code is very restrictive and few data are not opened to the public.

Recently, Kim et al. [6] developed the steam-gas pressurizer model based on the two-region nonequilibrium concept using RETRAN-3D/INT code. To investigate thermal–hydraulic characteristics of a steam–gas pressurizer in the integral type reactor, the steam–gas pressurizer model based on the two-region nonequilibrium concept was developed and implemented into RETRAN-3D/INT code. The model includes an explicit solution method for the one-dimensional governing equations and the equation of the state solution method to determine the thermal–hydraulic state of the steam–gas pressurizer volume. RETRAN-3D/INT code employed the ideal gas law for the thermodynamic state for noncondensable gas. However, steam and noncondensable gas undergo significant interaction at high pressure, resulting in deviation of the gas thermal properties from the ideal gas law [7]. The compressibility is 0.9852 at 0.1 MPa and 0.8865 at 2.0 MPa which is the operation pressure of REX-10. Thus, the ideal gas law underestimates the density of steam and noncondensable gas. This causes an inaccurate prediction of the heat and mass transfer in the gas mixture volume.

In this study, a steam-gas pressurizer model is newly proposed to estimate the pressure transient of the steam-gas pressurizer without using the ideal gas law. This proposed model is validated with a set of experiments on the pressurizer insurge transient performed in MIT and analysis results from RETRAN-3D/INT by Kim.

2 STEAM-GAS PRESSURIZER MODEL

The volume inside the steam-gas pressurizer is divided into two independent volume, liquid and gas mixture, separated with an interface. The schematic diagram of the steam-gas pressurizer volume is shown in Fig. 2.

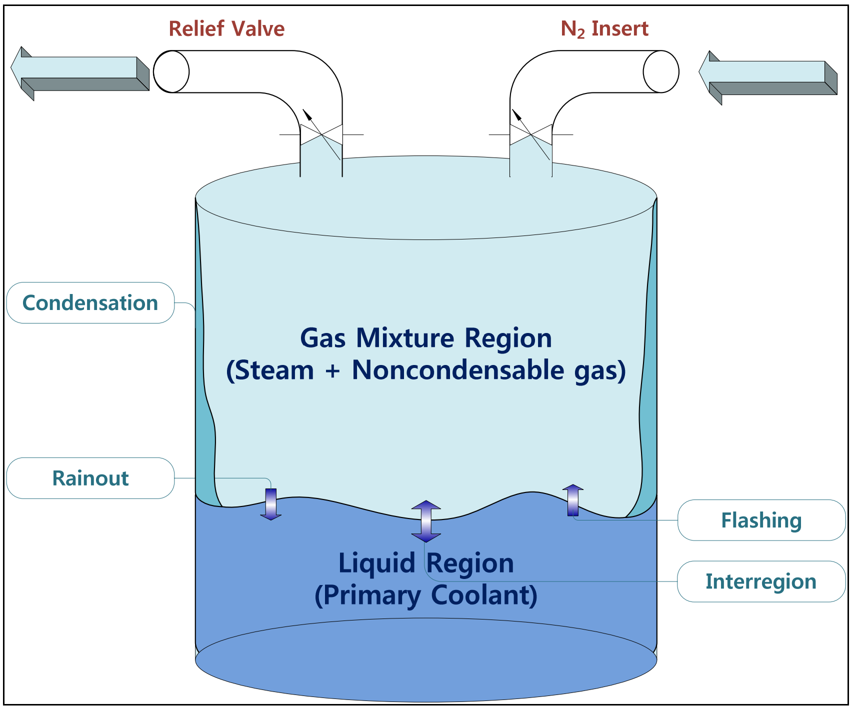

Figure 2: Schematic diagram of the steam-gas pressurizer volume.

The several researches [8,9,10] have carried out the simulation of the nonequilibrium steam pressurizer using separated mass and energy equations for each thermodynamic region. In this steam-gas pressurizer model, those models are modified by considering the noncondensable gas to mass and energy equations in gas mixture volume not based on the ideal gas law.

As shown in Fig. 2, the liquid region describes the primary coolant of the integral reactor. The gas mixture region consists of steam and noncondensable gas (nitrogen gas). It is assumed that the noncondensable gas is in mechanical and thermal equilibrium state with steam. Thus, the steam and noncondensable gas share the same temperature, and the gas and liquid regions are at same pressure. In addition, the gas mixture is treated as Gibbs–Dalton mixture. Therefore, the total pressure consists of the partial pressures of the steam and noncondensable gas.

The heat and mass transfer process in the steam-gas pressurizer volume is also considered. The rainout, flashing and inter-region heat and mass transfer models are introduced in this steam-gas pressurizer model as well as the steam pressurizer model. However, since the steam-gas pressurizer does not have a spray system, the heat and mass transfer due to spray is not considered unlike the previous steam pressurizer analysis model. In addition, the condensation heat transfer model is modified considering the effect of noncondensable gas. The presence of noncondensable gas has been reported to decrease substantially the condensation heat transfer [11]. Moreover, several researchers have performed experiments and investigated the effect of system pressure on natural convection condition. It was found that the heat transfer rates increase with increasing system pressure because the density of the gas components increases with an increase of pressure. In this model, the empirical heat transfer correlation derived by Seoul National University experiment [12] which can be applied under high pressure condition is used. The critical flow model including the effect of noncondensable gas has not been determined yet. The detail model and correlation will be explained in Section. 2.5.

2.1 Mass Conservation

The mass conservation equation for each region can be expressed as follows.

1) Liquid region

$$\dot{M}_{\mathrm{liquid}} = \dot{M}_{\mathrm{insurge}} + \dot{M}_{\mathrm{rainout}} - \dot{M}_{\mathrm{flashing}} - \dot{M}_{\mathrm{interregion}} + \dot{M}_{\mathrm{condensation}} \tag{1}$$

2) Gas mixture region

$$\dot{M}_{\mathrm{gas}} = \dot{M}_{\mathrm{steam}} + \dot{M}_{\mathrm{N_2}} \tag{2}$$

$$\dot{M}_{\mathrm{steam}} = \dot{M}_{\mathrm{flashing}} - \dot{M}_{\mathrm{rainout}} + \dot{M}_{\mathrm{interregion}} - \dot{M}_{\mathrm{condensation}} - \dot{M}_{\mathrm{relief_{steam}}} \tag{3}$$

$$\dot{M}_{\mathrm{N_2}} = -\dot{M}_{\mathrm{relief_{N_2}}} + \dot{M}_{\mathrm{insert_{N_2}}} \tag{4}$$

$$\dot{M}_{\mathrm{gas}} = \dot{M}_{\mathrm{flashing}} - \dot{M}_{\mathrm{rainout}} + \dot{M}_{\mathrm{interregion}} - \dot{M}_{\mathrm{condensation}} - \dot{M}_{\mathrm{relief_{steam}}} - \dot{M}_{\mathrm{relief_{N_2}}} + \dot{M}_{\mathrm{insert_{N_2}}} \tag{5}$$

where $\dot{M}$ is mass flow rate and each subscript means the heat and mass transfer process such as insurge, rainout, flashing, inter-region heat and mass transfer, wall condensation, insertion of nitrogen gas and release gas mixture through relief valve.

2.2 Energy Conservation

The energy balance equations for liquid and gas mixture regions can be obtained as following procedure.

1) Liquid region

The following basic definition about enthalpy is used.

$$M_{\text{liquid}} \cdot h_{\text{liquid}} = U_{\text{liquid}} + P_{\text{total}} \cdot V_{\text{liquid}} \tag{6}$$

By taking the derivative of Eq. (6)

$$\dot{U}_{\text{liquid}} = M_{\text{liquid}} \cdot \dot{h}_{\text{liquid}} + \dot{M}_{\text{liquid}} \cdot h_{\text{liquid}} - P_{\text{total}} \cdot \dot{V}_{\text{liquid}} - \dot{P}_{\text{total}} \cdot V_{\text{liquid}} \tag{7}$$

The energy balance equation for liquid region is expressed as,

$$\begin{aligned}\dot{U}_{\text{liquid}} = {} & \dot{M}_{\text{insurge}} \cdot h_{\text{insurge}} + \dot{M}_{\text{rainout}} \cdot h_{\text{rainout}} - \dot{M}_{\text{flashing}} \cdot h_{\text{flashing}} - \dot{M}_{\text{interregion}} \cdot h_{\text{interregion}} \\ & + \dot{M}_{\text{condensation}} \cdot h_{\text{condensation}} + \dot{Q}_{\text{h}} - P_{\text{total}} \cdot \dot{V}_{\text{liquid}}\end{aligned} \tag{8}$$

If Eqs. (7) and (8) are equated, the following equation can be obtained.

$$\begin{aligned}M_{\text{liquid}} \cdot \dot{h}_{\text{liquid}} + \dot{M}_{\text{liquid}} \cdot h_{\text{liquid}} = {} & \dot{M}_{\text{insurge}} \cdot h_{\text{insurge}} + \dot{M}_{\text{rainout}} \cdot h_{\text{rainout}} - \dot{M}_{\text{flashing}} \cdot h_{\text{flashing}} \\ & - \dot{M}_{\text{interregion}} \cdot h_{\text{interregion}} + \dot{M}_{\text{condensation}} \cdot h_{\text{condensation}} + \dot{Q}_{\text{h}} + \dot{P}_{\text{total}} \cdot V_{\text{liquid}}\end{aligned} \tag{9}$$

In addition, an equation for liquid enthalpy ($\dot{h}_{\text{liquid}}$) can be determined from Eq. (9).

$$\dot{h}_{\text{liquid}} = \frac{1}{M_{\text{liquid}}} \begin{bmatrix} \dot{M}_{\text{insurge}} \cdot h_{\text{insurge}} + \dot{M}_{\text{rainout}} \cdot h_{\text{rainout}} - \dot{M}_{\text{flashing}} \cdot h_{\text{flashing}} - \dot{M}_{\text{interregion}} \cdot h_{\text{interregion}} \\ + \dot{M}_{\text{condensation}} \cdot h_{\text{condensation}} - \dot{M}_{\text{liquid}} \cdot h_{\text{liquid}} + \dot{Q}_{\text{h}} + \dot{P}_{\text{total}} \cdot V_{\text{liquid}} \end{bmatrix} \tag{10}$$

2) Gas mixture region

In case of gas mixture region, the equations start from the enthalpy definitions.

$$M_{\text{gas}} \cdot h_{\text{gas}} = U_{\text{gas}} + P_{\text{total}} \cdot V_{\text{gas}} \tag{11}$$

Since the two components of steam and noncondensable gas (nitrogen gas) occupy the steam-gas pressurizer volume, it is needed to consider the contribution of each component to energy balance. As it was mentioned before, steam and gas occupy the same space, the subscript of gas mixture can be standardized to “gas”.

$$M_{\text{steam}} \cdot h_{\text{steam}} = U_{\text{steam}} + P_{\text{steam}} \cdot V_{\text{gas}} \tag{12}$$

$$M_{N_2} \cdot h_{N_2} = U_{N_2} + P_{N_2} \cdot V_{\text{gas}} \tag{13}$$

From the Eqs. (11) ~ (13), the following equation can be derived.

$$M_{\text{gas}} \cdot h_{\text{gas}} = M_{\text{steam}} \cdot h_{\text{steam}} + M_{\text{N}_2} \cdot h_{\text{N}_2} \tag{14}$$

From the viewpoint of the internal energy of each gas by taking the derivative of Eqs. (12) and (13), the Eqs. (15) and (16) can be obtained.

$$\dot{U}_{\text{steam}} = M_{\text{steam}} \cdot \dot{h}_{\text{steam}} + \dot{M}_{\text{steam}} \cdot h_{\text{steam}} - P_{\text{steam}} \cdot \dot{V}_{\text{gas}} - \dot{P}_{\text{steam}} \cdot V_{\text{gas}} \tag{15}$$

$$\dot{U}_{\text{N}_2} = M_{\text{N}_2} \cdot \dot{h}_{\text{N}_2} + \dot{M}_{\text{N}_2} \cdot h_{\text{N}_2} - P_{\text{N}_2} \cdot \dot{V}_{\text{gas}} - \dot{P}_{\text{N}_2} \cdot V_{\text{gas}} \tag{16}$$

The energy equations for gas mixture are shown in Eqs. (17) and (18).

$$\begin{aligned} \dot{U}_{\text{steam}} &= \dot{M}_{\text{flashing}} \cdot h_{\text{flashing}} - \dot{M}_{\text{rainout}} \cdot h_{\text{rainout}} + \dot{M}_{\text{interregion}} \cdot h_{\text{interregion}} \\ &\quad - \dot{M}_{\text{condensation}} \cdot h_{\text{condensation}} - \dot{M}_{\text{relief}_{\text{steam}}} \cdot h_{\text{relief}_{\text{steam}}} - P_{\text{steam}} \cdot \dot{V}_{\text{gas}} \end{aligned} \tag{17}$$

$$\dot{U}_{\text{N}_2} = \dot{M}_{\text{insert}_{\text{N}_2}} \cdot h_{\text{insert}_{\text{N}_2}} - \dot{M}_{\text{relief}_{\text{N}_2}} \cdot h_{\text{relief}_{\text{N}_2}} - P_{\text{N}_2} \cdot \dot{V}_{\text{gas}} \tag{18}$$

If Eqs. (15) and (17), (16) and (18) are equated, the result are ;

$$\begin{aligned} M_{\text{steam}} \cdot \dot{h}_{\text{steam}} + \dot{M}_{\text{steam}} \cdot h_{\text{steam}} &= \dot{M}_{\text{flashing}} \cdot h_{\text{flashing}} - \dot{M}_{\text{rainout}} \cdot h_{\text{rainout}} + \dot{M}_{\text{interregion}} \cdot h_{\text{interregion}} \\ &\quad - \dot{M}_{\text{condensation}} \cdot h_{\text{condensation}} - \dot{M}_{\text{relief}_{\text{steam}}} \cdot h_{\text{relief}_{\text{steam}}} + \dot{P}_{\text{steam}} \cdot V_{\text{gas}} \end{aligned} \tag{19}$$

$$M_{\text{N}_2} \cdot \dot{h}_{\text{N}_2} + \dot{M}_{\text{N}_2} \cdot h_{\text{N}_2} = \dot{M}_{\text{insert}_{\text{N}_2}} \cdot h_{\text{insert}_{\text{N}_2}} - \dot{M}_{\text{relief}_{\text{N}_2}} \cdot h_{\text{relief}_{\text{N}_2}} + \dot{P}_{\text{N}_2} \cdot V_{\text{gas}} \tag{20}$$

In addition, the terms of the left side of the Eqs. (19) and (20) are summed, the following equations can be obtained.

$$\begin{aligned} M_{\text{steam}} \cdot \dot{h}_{\text{steam}} + \dot{M}_{\text{steam}} \cdot h_{\text{steam}} + M_{\text{N}_2} \cdot \dot{h}_{\text{N}_2} + \dot{M}_{\text{N}_2} \cdot h_{\text{N}_2} &= \left(M_{\text{steam}} \cdot h_{\text{steam}} + M_{\text{N}_2} \cdot h_{\text{N}_2} \right)' \\ &= \left(M_{\text{gas}} \cdot h_{\text{gas}} \right)' = M_{\text{gas}} \cdot \dot{h}_{\text{gas}} + \dot{M}_{\text{gas}} \cdot h_{\text{gas}} \end{aligned} \tag{21}$$

$$\begin{aligned} M_{\text{gas}} \cdot \dot{h}_{\text{gas}} + \dot{M}_{\text{gas}} \cdot h_{\text{gas}} &= \dot{M}_{\text{flashing}} \cdot h_{\text{flashing}} - \dot{M}_{\text{rainout}} \cdot h_{\text{rainout}} + \dot{M}_{\text{interregion}} \cdot h_{\text{interregion}} \\ &\quad - \dot{M}_{\text{condensation}} \cdot h_{\text{condensation}} - \dot{M}_{\text{relief}_{\text{steam}}} \cdot h_{\text{relief}_{\text{steam}}} \\ &\quad + \dot{M}_{\text{insert}_{\text{N}_2}} \cdot h_{\text{insert}_{\text{N}_2}} - \dot{M}_{\text{relief}_{\text{N}_2}} \cdot h_{\text{relief}_{\text{N}_2}} + \dot{P}_{\text{N}_2} \cdot V_{\text{gas}} + \dot{P}_{\text{steam}} \cdot V_{\text{gas}} \end{aligned} \tag{22}$$

$$\dot{h}_{\text{gas}} = \frac{1}{M_{\text{gas}}} \begin{bmatrix} \dot{M}_{\text{flashing}} \cdot h_{\text{flashing}} - \dot{M}_{\text{rainout}} \cdot h_{\text{rainout}} + \dot{M}_{\text{interregion}} \cdot h_{\text{interregion}} \\ - \dot{M}_{\text{condensation}} \cdot h_{\text{condensation}} - \dot{M}_{\text{relief}_{\text{steam}}} \cdot h_{\text{relief}_{\text{steam}}} \\ + \dot{M}_{\text{insert}_{\text{N}_2}} \cdot h_{\text{insert}_{\text{N}_2}} - \dot{M}_{\text{relief}_{\text{N}_2}} \cdot h_{\text{relief}_{\text{N}_2}} - \dot{M}_{\text{gas}} \cdot h_{\text{gas}} + \dot{P}_{\text{Total}} \cdot V_{\text{gas}} \end{bmatrix} \tag{23}$$

Similar to Eq. (23), the changes in enthalpies of steam and nitrogen gas can be obtained as shown in Eqs. (24) and (25).

$$\dot{h}_{\text{steam}} = \frac{1}{M_{\text{steam}}} \begin{bmatrix} \dot{M}_{\text{flashing}} \cdot h_{\text{flashing}} - \dot{M}_{\text{rainout}} \cdot h_{\text{rainout}} + \dot{M}_{\text{interregion}} \cdot h_{\text{interregion}} \\ -\dot{M}_{\text{condensation}} \cdot h_{\text{condensation}} - \dot{M}_{\text{relief}_{\text{steam}}} \cdot h_{\text{relief}_{\text{steam}}} - \dot{M}_{\text{steam}} \cdot h_{\text{steam}} + \dot{P}_{\text{steam}} \cdot V_{\text{gas}} \end{bmatrix} \tag{24}$$

$$\dot{h}_{\text{N}_2} = \frac{1}{M_{\text{N}_2}} \left[\dot{M}_{\text{insert}_{\text{N}_2}} \cdot h_{\text{insert}_{\text{N}_2}} - \dot{M}_{\text{relief}_{\text{N}_2}} \cdot h_{\text{relief}_{\text{N}_2}} - \dot{M}_{\text{N}_2} \cdot h_{\text{N}_2} + \dot{P}_{\text{N}_2} \cdot V_{\text{gas}} \right] \tag{25}$$

2.3 Volume Relation

The following definitions for each component are used.

$$V_{\text{gas}} = M_{\text{gas}} \cdot v_{\text{gas}} = M_{\text{steam}} \cdot v_{\text{steam}} = M_{\text{N}_2} \cdot v_{\text{N}_2} \tag{26}$$

$$V_{\text{liquid}} = M_{\text{liquid}} \cdot v_{\text{liquid}} \tag{27}$$

$$V_{\text{total}} = V_{\text{liquid}} + V_{\text{gas}} \tag{28}$$

An additional expression for total volume, liquid and gas volumes can be obtained by taking the derivative of Eq. (28).

$$\dot{V}_{\text{total}} = \dot{V}_{\text{liquid}} + \dot{V}_{\text{gas}} = 0 \tag{29}$$

Taking the derivative of Eqs. (27), the Eq. (30) is obtained.

$$\dot{V}_{\text{liquid}} = \dot{M}_{\text{liquid}} \cdot v_{\text{liquid}} + M_{\text{liquid}} \cdot \dot{v}_{\text{liquid}} \tag{30}$$

And, the equation of state is as follows.

$$v_{\text{liquid}} = v_{\text{liquid}} \left(h_{\text{liquid}}, P_{\text{total}} \right) \tag{31}$$

Thus, the partial derivative can be derived.

$$\dot{v}_{\text{liquid}} = \frac{\partial v_{\text{liquid}}}{\partial h_{\text{liquid}}} \dot{h}_{\text{liquid}} + \frac{\partial v_{\text{liquid}}}{\partial P_{\text{total}}} \dot{P}_{\text{total}} \tag{32}$$

The eq. (32) can be substituted into the Eq. (30) and the result is as follows.

$$\dot{V}_{\text{liquid}} = \dot{M}_{\text{liquid}} \cdot v_{\text{liquid}} + M_{\text{liquid}} \left(\frac{\partial v_{\text{liquid}}}{\partial h_{\text{liquid}}} \dot{h}_{\text{liquid}} + \frac{\partial v_{\text{liquid}}}{\partial P_{\text{total}}} \dot{P}_{\text{total}} \right) \tag{33}$$

Contrary to the liquid volume, the gas mixture volume is treated more complexly. The two components coexist and react mutually in the same gas mixture volume. In addition, the steam and noncondensable gas undergo significant interaction at high pressure, resulting in deviation of the gas thermal properties from the ideal gas law. The compressibility is 0.9852 at 0.1 MPa and 0.8865 at 2.0 MPa which is the operation pressure of REX-10. Thus, the equation for gas mixture volume is not based on the ideal gas law. From the Eq. (26), the Eq. (35) can be obtained by taking the derivative.

$$V_{\text{gas}} = \dot{M}_{\text{N}_2} \cdot v_{\text{N}_2} + M_{\text{N}_2} \cdot \dot{v}_{\text{N}_2} \tag{34}$$

Similar with the procedure to find the change in the volume of liquid region,

$$v_{\text{N}_2} = v_{\text{N}_2}\left(f\left(h_{\text{N}_2}, P_{\text{N}_2}\right)\right) = v_{\text{N}_2}\left(h_{\text{steam}}, P_{\text{total}}\right) \tag{35}$$

The specific volume of nitrogen gas (v_{N_2}) is expressed as a function of the total pressure and the enthalpy of steam. Because the partial pressures of steam and nitrogen gas can be determined by enthalpy of steam and total pressure ,the temperature of gas mixture also can be obtained by enthalpy of steam due to thermal equilibrium state.

$$\dot{v}_{\text{N}_2} = \frac{\partial v_{\text{N}_2}}{\partial h_{\text{steam}}}\dot{h}_{\text{steam}} + \frac{\partial v_{\text{N}_2}}{\partial P_{\text{total}}}\dot{P}_{\text{total}} \tag{36}$$

Equation (36) can be substituted into Eq. (34) and the result is as follows.

$$\dot{V}_{\text{gas}} = \dot{M}_{\text{N}_2} \cdot v_{\text{N}_2} + M_{\text{N}_2} \cdot \left(\frac{\partial v_{\text{N}_2}}{\partial h_{\text{steam}}}\dot{h}_{\text{steam}} + \frac{\partial v_{\text{N}_2}}{\partial P_{\text{total}}}\dot{P}_{\text{total}} \right) \tag{37}$$

2.4 Determination of the Total Pressure

An expression containing change in pressure term can be obtained by substituting Eqs. (10), (23), (24) and (25), substituting the results into Eq. (31), and solving for change in pressure. The final form of the differential equation for the pressure is shown in Eqs. (38) and (39).

$$\begin{aligned}
&\dot{M}_{\text{liquid}} \cdot v_{\text{liquid}} + \dot{M}_{\text{N}_2} \cdot v_{\text{N}_2} + M_{\text{liquid}} \frac{\partial v_{\text{liquid}}}{\partial P_{\text{total}}}\dot{P}_{\text{total}} + M_{\text{N}_2}\frac{\partial v_{\text{N}_2}}{\partial P_{\text{total}}}\dot{P}_{\text{total}} \\
&+\frac{\partial v_{\text{liquid}}}{\partial h_{\text{liquid}}}\begin{bmatrix} \dot{M}_{\text{insurge}} \cdot h_{\text{insurge}} + \dot{M}_{\text{rainout}} \cdot h_{\text{rainout}} - \dot{M}_{\text{flashing}} \cdot h_{\text{flashing}} - \dot{M}_{\text{interregion}} \cdot h_{\text{interregion}} \\ +\dot{M}_{\text{condensation}} \cdot h_{\text{condensation}} - \dot{M}_{\text{liquid}} \cdot h_{\text{liquid}} + \dot{Q}_{\text{h}} + \dot{P}_{\text{total}} \cdot V_{\text{liquid}} \end{bmatrix} \\
&+\frac{M_{\text{N}_2}}{M_{\text{steam}}}\frac{\partial v_{\text{N}_2}}{\partial h_{\text{steam}}}\begin{bmatrix} \dot{M}_{\text{flashing}} \cdot h_{\text{flashing}} - \dot{M}_{\text{rainout}} \cdot h_{\text{rainout}} + \dot{M}_{\text{interregion}} \cdot h_{\text{interregion}} \\ -\dot{M}_{\text{condensation}} \cdot h_{\text{condensation}} - \dot{M}_{\text{relief}_{\text{steam}}} \cdot h_{\text{relief}_{\text{steam}}} - \dot{M}_{\text{steam}} \cdot h_{\text{steam}} + \dot{P}_{\text{steam}} \cdot V_{\text{gas}} \end{bmatrix} = 0
\end{aligned} \tag{38}$$

$$\left(M_{\text{liquid}} \frac{\partial v_{\text{liquid}}}{\partial P_{\text{total}}} + M_{\text{N}_2} \frac{\partial v_{\text{N}_2}}{\partial P_{\text{total}}} + \frac{\partial v_{\text{liquid}}}{\partial h_{\text{liquid}}} \cdot V_{\text{liquid}} \right) \dot{P}_{\text{total}}$$

$$= -\left\{ \begin{array}{l} \dot{M}_{\text{liquid}} \cdot v_{\text{liquid}} + \dot{M}_{\text{N}_2} \cdot v_{\text{N}_2} \\ + \dfrac{\partial v_{\text{liquid}}}{\partial h_{\text{liquid}}} \left[\begin{array}{l} \dot{M}_{\text{insurge}} \cdot h_{\text{insurge}} + \dot{M}_{\text{rainout}} \cdot h_{\text{rainout}} - \dot{M}_{\text{flashing}} \cdot h_{\text{flashing}} - \dot{M}_{\text{interregion}} \cdot h_{\text{interregion}} \\ + \dot{M}_{\text{condensation}} \cdot h_{\text{condensation}} - \dot{M}_{\text{liquid}} \cdot h_{\text{liquid}} + \dot{Q}_{\text{h}} \end{array} \right] \\ + \dfrac{M_{\text{N}_2}}{M_{\text{steam}}} \dfrac{\partial v_{\text{N}_2}}{\partial h_{\text{steam}}} \left[\begin{array}{l} \dot{M}_{\text{flashing}} \cdot h_{\text{flashing}} - \dot{M}_{\text{rainout}} \cdot h_{\text{rainout}} + \dot{M}_{\text{interregion}} \cdot h_{\text{interregion}} \\ - \dot{M}_{\text{condensation}} \cdot h_{\text{condensation}} - \dot{M}_{\text{relief}_{\text{steam}}} \cdot h_{\text{relief}_{\text{steam}}} - \dot{M}_{\text{steam}} \cdot h_{\text{steam}} + \dot{P}_{\text{steam}} \cdot V_{\text{gas}} \end{array} \right] \end{array} \right\} \tag{39}$$

Finally, the change in the total pressure at unit time can be expressed as following equation.

$$\dot{P}_{\text{total}} = -\frac{\left\{ \begin{array}{l} \dot{M}_{\text{liquid}} \cdot v_{\text{liquid}} + \dot{M}_{\text{N}_2} \cdot v_{\text{N}_2} \\ + \dfrac{\partial v_{\text{liquid}}}{\partial h_{\text{liquid}}} \left[\begin{array}{l} \dot{M}_{\text{insurge}} \cdot h_{\text{insurge}} + \dot{M}_{\text{rainout}} \cdot h_{\text{rainout}} - \dot{M}_{\text{flashing}} \cdot h_{\text{flashing}} - \dot{M}_{\text{interregion}} \cdot h_{\text{interregion}} \\ + \dot{M}_{\text{condensation}} \cdot h_{\text{condensation}} - \dot{M}_{\text{liquid}} \cdot h_{\text{liquid}} + \dot{Q}_{\text{h}} \end{array} \right] \\ + \dfrac{M_{\text{N}_2}}{M_{\text{steam}}} \dfrac{\partial v_{\text{N}_2}}{\partial h_{\text{steam}}} \left[\begin{array}{l} \dot{M}_{\text{flashing}} \cdot h_{\text{flashing}} - \dot{M}_{\text{rainout}} \cdot h_{\text{rainout}} + \\ \dot{M}_{\text{interregion}} \cdot h_{\text{interregion}} - \dot{M}_{\text{condensation}} \cdot h_{\text{condensation}} \\ - \dot{M}_{\text{relief}_{\text{steam}}} \cdot h_{\text{relief}_{\text{steam}}} - \dot{M}_{\text{steam}} \cdot h_{\text{steam}} + \dot{P}_{\text{steam}} \cdot V_{\text{gas}} \end{array} \right] \end{array} \right\}}{\left(M_{\text{liquid}} \dfrac{\partial v_{\text{liquid}}}{\partial P_{\text{total}}} + M_{\text{N}_2} \dfrac{\partial v_{\text{N}_2}}{\partial P_{\text{total}}} + \dfrac{\partial v_{\text{liquid}}}{\partial h_{\text{liquid}}} \cdot V_{\text{liquid}} \right)} \tag{40}$$

As shown in Eq. (40), the change in the total pressure is a function of the change in the steam partial pressure. Also, the change in the steam partial pressure is related to that in the total pressure as shown in Eq. (41).

$$\dot{P}_{\text{total}} = \dot{P}_{\text{steam}} + \dot{P}_{\text{N}_2} \tag{41}$$

Thus, this coupled equation can be solved by using the following procedure. As $\dot{P}_{\text{steam}}$ is guessed initially, $\dot{P}_{\text{N}_2}$ and $\dot{P}_{\text{total}}$ can be determined, respectively. Then, the changes in the internal energy and enthalpy of nitrogen gas can be obtained and the temperature of the nitrogen gas can be updated. Due to the thermal equilibrium between steam and nitrogen gas, the temperature of steam is updated, too. As the temperature of steam is changed, the value of $\dot{P}_{\text{steam}}$ is updated. Finally, $\dot{P}_{\text{steam}}$ can be determined through this iteration procedure. Figure 3 shows the flow chart for the determination of the total pressure.

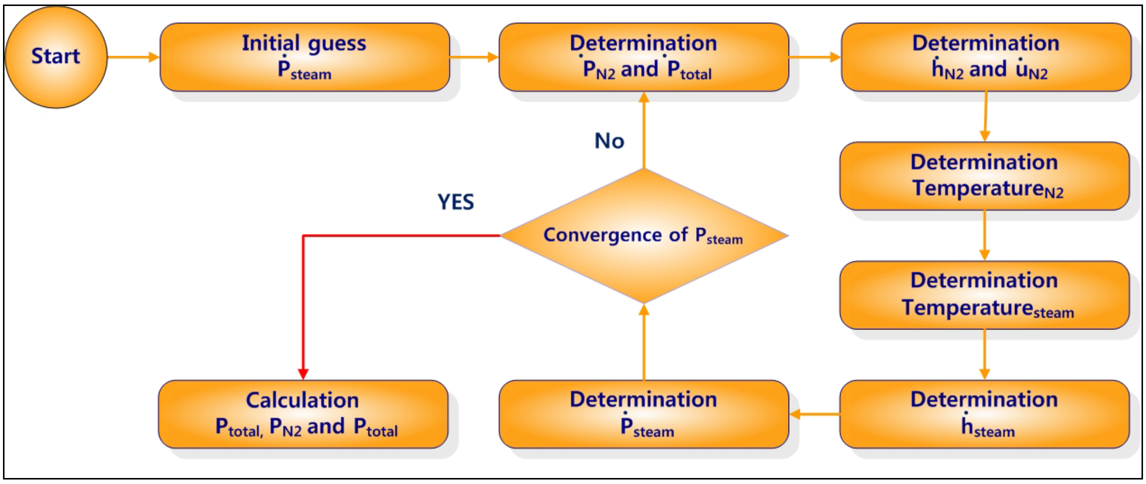

Figure 3: Flow chart for the determination of the total pressure.

2.5 Mass and Energy Transfer Model in the Steam-gas Pressurizer Model

1) Rainout and flashing models

The rainout of liquid droplets from the vapor to the liquid region is modelled in the pressurizer model. The rainout mass flow rate is calculated as follows :

$$\dot{M}_{\text{rainout}} = v_{\text{rainout}} A(1-\alpha)\rho_f \qquad (42)$$

In addition, the mass flow rate due to the flashing can be determined from the following relation.

$$\dot{M}_{\text{flashing}} = v_{\text{b}} A\alpha\rho_g g \qquad (43)$$

2) Inter-region heat and mass transfer

The heat and mass transfer at the interface between liquid and gas mixture can be accounted for in the pressurizer model. The mass flow rate can be obtained as follows [5].

$$\dot{M}_{\text{interregion}} \left(h_{steam} - h_{liquid}\right) = Nu\frac{k}{L}\left(T_{liquid} - T_{gas}\right) \qquad (44)$$

3) Wall condensation (with noncondensable gas at high pressure)

Although the structure of the steam-gas pressurizer is simple, the thermal-hydraulic phenomena are very complex. Especially, the effect of condensation heat transfer in the presence of noncondensable gas under a natural convection is important to evaluate the pressurizer behavior. The steam generated from primary coolant is mixed with nitrogen gas which is pre-filled to control the pressure. The film condensate is formed on the cold wall of the steam-gas pressurizer and falls down to the coolant. Thus, the condensation heat transfer would be a dominant heat transfer mechanism to ensure the pressure sustainability in the steam-gas pressurizer. At low pressure, the previous condensation model and empirical correlation could be applied. Kim et al. [12] have already performed the condensation heat transfer experiment with noncondensable gas at high pressure and developed the empirical correlation for condensation heat transfer coefficient given in Eq. (45). The mass flow rate due to the wall condensation can be also obtained by applying the heat and mass transfer analogy.

$$h = 740 + 23000 \cdot \exp\left(-\frac{7.7}{P^{0.52}} \cdot \left(\frac{w}{1-w} \right)^{0.42} \right) \left(T_{mix} - T_w \right)^{-0.25} \tag{45}$$

where
$$0.1 \text{ MPa} < P < 2.0 \text{ MPa}$$
$$20^{\circ}\text{C} < T_{mix} - T_w < 80^{\circ}\text{C}$$
$$0.01 < w < 0.7$$

3 MIT INSURGE EXPERIMENT

The proposed steam-gas pressurizer model in this study is verified with the pressurizer insurge transient experiment performed in MIT. The series of tests were carried out to estimate the pressure transient with noncondensable gases such as nitrogen gas, argon gas and helium gas. The schematic diagram of the experimental apparatus is shown in Fig. 4.

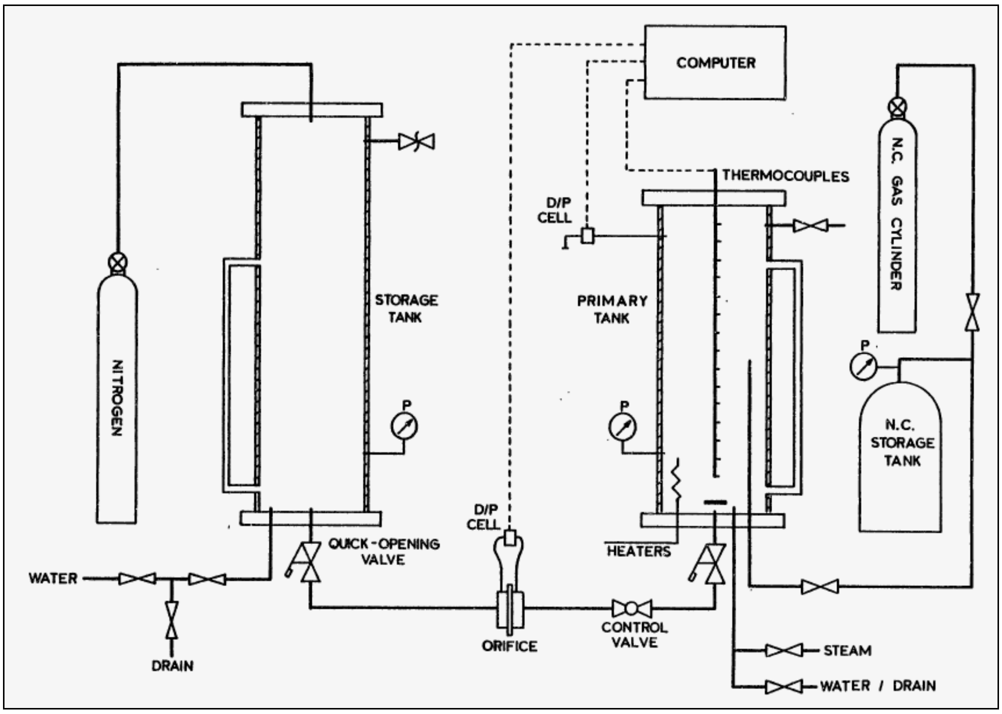

Figure 4: Flow chart for the determination of the total pressure.

The experimental system consists of the two stainless steel tanks. One simulates the pressurizer volume and the other serves as a reservoir for cold injection water. The primary tank which simulates the pressurizer volume is an 8” inner diameter pipe, 45” in height. It has the electric heaters of 9 kW to make the initial condition. The storage tank is filled with the 70℉ water. The noncondensable gas injection system is connected to the bottom of the primary tank and the end of the nozzle is located above the initial water level in the tank.

The water was filled to the initial water level of 0.431 m. The remained gas in the tank was removed by heating the water and releasing the gas mixture containing the air through a gas ventilation valve. Then, the noncondensable gas was injected to meet the experimental condition. After the heaters were turned off, the system pressure rose above the operating pressure. Therefore, the insurge transient was initiated when the system pressure was returned to the operating pressure. The insurge was initiated by opening the quick-opening valve at the bottom of the primary tank. The insurge was terminated when the liquid level was reached to 0.864 m. In addition, it was found that the amount of the heat loss to the surroundings was consistently 1.3 kW in this experiment.

Table 1 shows the test matrix for verification in case that the noncondensable gas is nitrogen gas.

Table 1: Test matrix for verification

Case	Noncondensable gas	Initial mass fraction (%)
N2-1	Nitrogen gas	9.7
N2-2		20.1

The insurge mass flow rate is approximately 0.4309 kg/sec from 0 sec to 35 ~ 40 second. Then, the analysis is continued until 60 second.

4 RESULTS AND DISCUSSIONS

Figures 5 and 6 show the results of case N2-1 and N2-2, respectively. From these results, it is found that the trend on the pressure behavior from the proposed model is in good agreement with that from MIT insurge experiment and analysis by RETRAN-3D/INT. As shown in Figs. 5 and 6, the total pressure increases as the gas mixture volume decreases due to the insurge flow. Thus, the peak pressure appeared on the time when the insurge was ended. In addition, the peak pressure from case N2-2 is higher than that from case N2-1. This is due to the characteristic of condensation heat transfer in the presence of noncondensable gas that the heat transfer coefficient decreases with increasing mass fraction of noncondensable gas. To evaluate the effect of noncondensable gas on the condensation heat transfer in detail, the pressure history of base case from MIT experiment was compared as shown in Fig. 7. The peak pressure is about 0.64 MPa in base case whereas the peak pressure in the case with noncondensable gas is higher than 0.64 MPa. The difference in peak pressure is caused by the degradation of condensation heat transfer due to the noncondensable gas. As shown in Fig. 8, it is certified by the experimental data and empirical correlation of the condensation heat transfer coefficient at high pressure performed in Seoul National University. After the insurge flow, the gas mixture volume becomes stagnant and the pressure goes to a certain converged value due to the condensation heat transfer and heat loss. Consequently, it is concluded that the condensation heat transfer is a dominant factor to govern the pressure behavior at the transient in the steam-gas pressurizer. Moreover, the difference between the experimental data and the analysis result can be found. This is caused by application of the heat and mass transfer model. For the accurate prediction, the sensitivity test of the heat and mass transfer model is needed.

In addition, the following content is expected from above results. If the steam-gas pressurizer volume is over-heated, the wall condensation heat transfer prevents the steam-gas pressurizer volume from over-pressurization with reducing the partial pressure of steam. That is, the condensation heat transfer will play a role to ensure the integrity of the reactor.

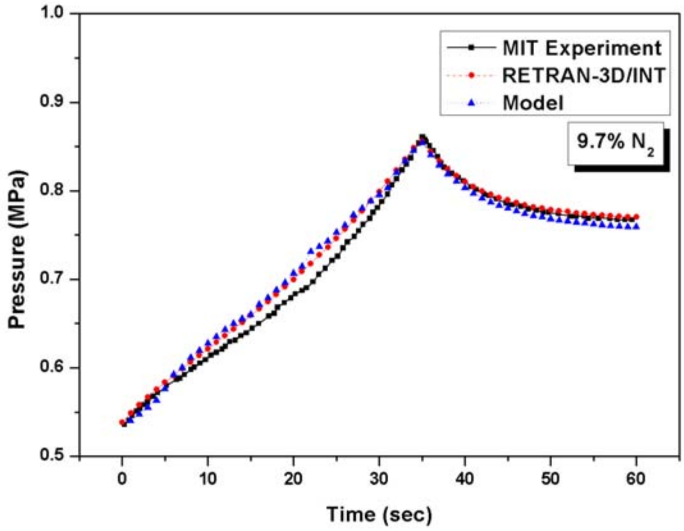

Figure 5: Pressure behavior with 9.7% mass fraction of nitrogen gas (Case N2-1).

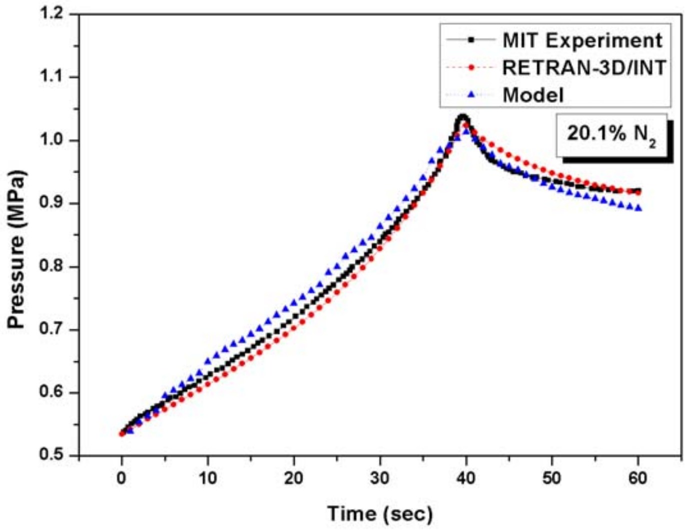

Figure 6: Pressure behavior with 20.1% mass fraction of nitrogen gas (Case N2-2).

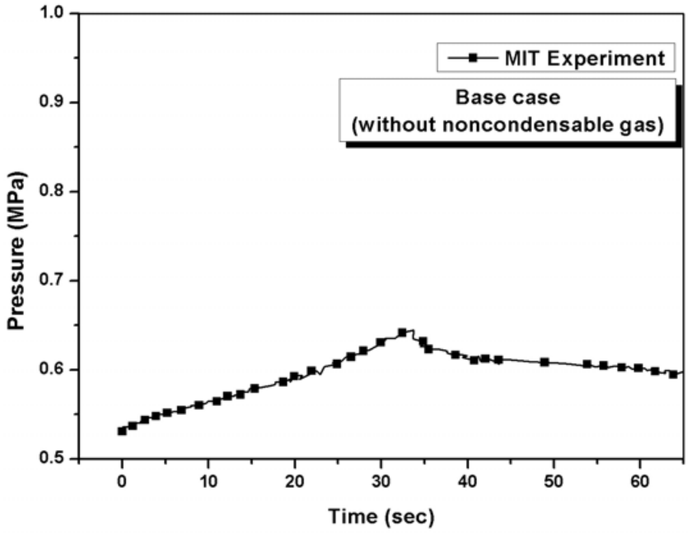

Figure 7: Pressure behavior without noncondensable gas (Base case).

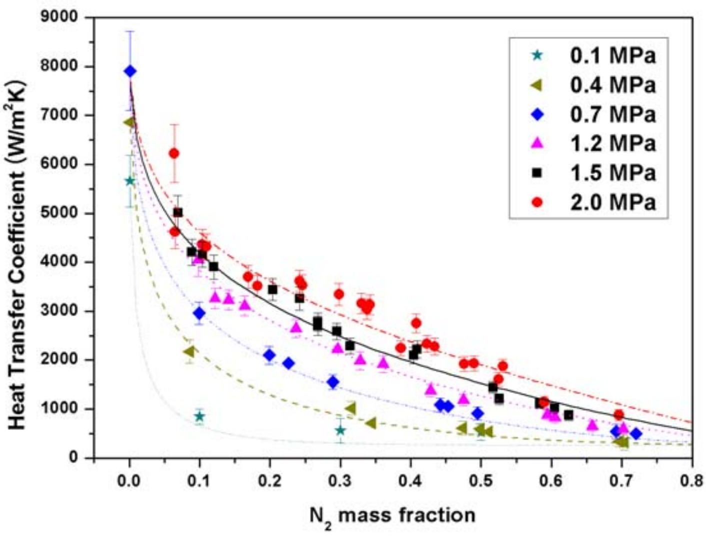

Figure 8: Condensation heat transfer coefficient (Seoul National Univ. experiment).

5 CONCLUSIONS

The built-in steam-gas pressurizer model applied to integral reactor was presented. This model was based on mass and energy balance equations for liquid and gas mixture regions in the steam-gas pressurizer volume. To describe the heat and mass transfer process in the steam-gas pressurizer volume, the rainout, flashing, inter-region heat and mass transfer model were introduced. Especially, the empirical correlation for condensation on the cold wall considering the effect of noncondensable gas at high pressure was applied to this model. This model was verified with experimental data on the pressurizer insurge transient performed in MIT. The results from the proposed model are in good agreement with the experimental data. In addition, this model can estimate the pressure behavior after the insurge. This means that the condensation heat transfer correlation predicts well at high pressure condition. However, the sensitivity test of the heat and mass transfer model is needed to predict more accurate. In near future, SET(Separate Effect Test) using autoclave chamber and IET(Integral Effect Test) using RTF(REX-10 Facility) pre-test experimental apparatus with natural circulation loop will be performed to evaluate the performance of the steam-gas pressurizer. In addition, this proposed steam-gas pressurizer analysis code will be verified with the results from SETs and IETs. The verified steam-gas pressurizer model is expected to estimate the performance such as thermo-dynamic characteristics and pressure behavior of steam-gas pressurizer.

ACKNOWLEDGEMENTS

This work has been supported by KESRI (Korea Electrical engineering & Science Research Institute), which is funded by MOKE (Ministry of Knowledge Economy) in Korea.

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