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Estimation of pressure-equalizing time for a hybrid safety injection tank used in a passive safety injection system

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ABSTRACT

In this paper, a method for estimating the time required to reach the equalizing pressure between two tanks for a hybrid safety injection tank (SIT) system is proposed. The hybrid SIT allows a coolant injection over a wide range of operating pressures without using active systems such as a high-pressure pump. The pressure of the SIT can be equated to that of the reactor vessel through a pipe connected between the SIT and the pressurizer (PZR). Thus, the coolant is injected into the reactor vessel via the gravitational head of water. In this study, a zero-dimensional calculation with a simple approach was employed to estimate the pressure-equalizing time of the hybrid SIT. The real gas equation of state was used to estimate the time with mixture properties. The mass of the injected steam was calculated using the relationship between the pressure difference and mass. The results showed that the difference in the pressure-equalizing times is less than 5% compared to the test results. Accordingly, a guideline is proposed for the design of hybrid SITs for new nuclear power plants. Appropriate pipe loss coefficients for a pressure balancing line (PBL) were suggested for an integral effect test facility.

1. Introduction

Recently, research and development activities for a passive safety system instead of an active safety system have been increasing to ensure safety in the event of a station blackout (SBO) in a nuclear power plant. As part of the research, a concept of hybrid safety injection tank (SIT) was suggested by the Korea Atomic Energy Research Institute (KAERI) (Kwon et al., 2014). The conventional SIT used in existing nuclear power plants is actuated during a low-pressure accident. However, the hybrid SIT can be operated in the events of both the low and high-pressure accidents without requiring an auxiliary power system. The major difference between the conventional SIT and the hybrid SIT is the existence of a pressure balancing line (PBL). The PBL connects the hybrid SIT and the pressurizer (PZR), and a motorized valve is installed in the PBL pipe. The hybrid SIT can be used for the same purposes as that of a conventional SIT during a low-pressure accident in the event of a small break loss of coolant accident (SBLOCA). In addition, in the event of high-pressure accident such as an SBO, the pressure of the hybrid SIT can be increased until that of the PZR by equalizing the pressure through the PBL. Thereafter, the coolant is gradually injected into the reactor vessel under the effect of gravitational force. Hence, the set point of the hybrid SIT actuation is determined by the time difference between the opening of the isolation valve and the injection of the coolant.

To validate the design of the hybrid SIT, many researchers investigated the overall thermal-hydraulic phenomena occurring in the hybrid SIT. Ryu et al. (2016a) theoretically derived the pressure-equalizing point of the SIT. A parametric study was conducted by changing the coolant level, length of the PBL, and opening rate of the flow control valve (FCV) using a separate effect test (SET) facility (Ryu et al., 2016b). The results confirmed that the condensation rate of the SIT is a major parameter in determining the pressure-equalizing time, and the results were analyzed quantitatively. Kim et al. (2016) studied that the major phenomena determining the pressure-equalizing time are wall condensation and direct contact condensation on the coolant. The results showed that the estimation of the condensate mass is important to accurately calculate the pressure-equalizing time, because the mass of the non-condensed steam, which contributes to pressurizing the tank, is decreased.

The pressure-equalizing and thermal-hydraulic phenomena can be understood using existing numerical simulation code. Reliable estimates are obtained for one-dimensional (1D) phenomena in terms of the two-phase flow using RELAP or MARS, which is a system safety analysis code developed by KAERI. However, the specific

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Nomenclature

Symbols

A	pipe cross sectional area (m^2)
c	mass fraction
c_p	constant pressure specific heat (kJ/kgK)
h_{fg}	latent heat (kJ/kgK)
h^*_{fg}	modified latent heat (kJ/kgK)
P	pressure (Pa)
K	loss coefficient
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
n	number of moles
Q	amount of heat transferred (kJ)
R	gas constant (kJ/kgK)
T	temperature (K)
V	volume (m^3)
y	mole fraction
Z	compressibility factor
α	thermal diffusivity (m^2/s)
ρ	density (kg/m^3)

Subscripts

con	condensate
mix	mixture
N_2	nitrogen
ncs	non-condensable gas
sat	saturation
SIT	safety injection tank
t	time
tot	total
wall	wall surface

heat transfer and pressure drop correlations considering a model characteristic are required to increase the accuracy and reliability of the analysis results. A transient three-dimensional computational fluid dynamics (CFD) yields more accurate solutions than a 1D analysis; however, the computation time and resources required are considerably large. Hence, in this study, a zero-dimensional analysis was conducted to quantitatively estimate the pressure-equalizing time using a real gas state of equation. In addition, the distorted factor affecting the similarity test was analyzed in terms of the pressure-equalizing time using the time estimation results.

2. Prediction of Pressure-equalizing time

2.1. Methodology

A flow passes because of the difference in the pressures in the case of a pipe connected between the two pressure vessels, and the mass flow rate through the pipe can be calculated as follows. The pressure drop in a pipe flow is expressed using Eq. (1).

$$\Delta P = \frac{1}{2}\rho u^2 K \tag{1}$$

The injected mass flow rate from the high to low-pressure tank via the pressure difference can be obtained using Eq. (2).

$$\dot{m} = A\sqrt{\frac{2\rho\Delta P}{K}} \tag{2}$$

Here, A is the cross-sectional area of the pipe, ρ is the fluid density, and K is the pressure loss coefficient of the pipe. Accordingly, the accumulated mass is calculated by integrating the mass flow rate. The internal pressure of the tank is estimated using the real gas equation of state as follows.

$$P = \frac{ZmRT}{V} \tag{3}$$

Here, Z, m, R, T, and V denote the compressibility factor, steam mass, specific gas constant, steam temperature, and tank volume, respectively.

In case of the hybrid SIT, two different fluids are filled initially in each tank. Two fluids are mixed and steam condensation occur. Hence, the pressure should be predicted considering these phenomena. Fig. 1 shows the pressure calculation flow chart, which is used to predict the time required for equalizing the pressure for the hybrid SIT. First, the fluid properties are calculated using the initial temperature and pressure. The steam mass flow rate through the PBL is then calculated using Eq. (2), after which the condensation rate can be calculated. The condensation is due to the temperature difference between the hot steam and the cold wall. The coolant level increases because of the condensed steam, and thus, the tank free volume is recalculated. The difference in masses between the injected and condensed steams is the remaining mass of the steam in the SIT. Thereafter, the nitrogen and steam mixture properties are calculated. The SIT pressure is calculated for each time step using the real gas equation of state until the pressure is equalized. Thus, the pressure-equalizing time could be estimated.

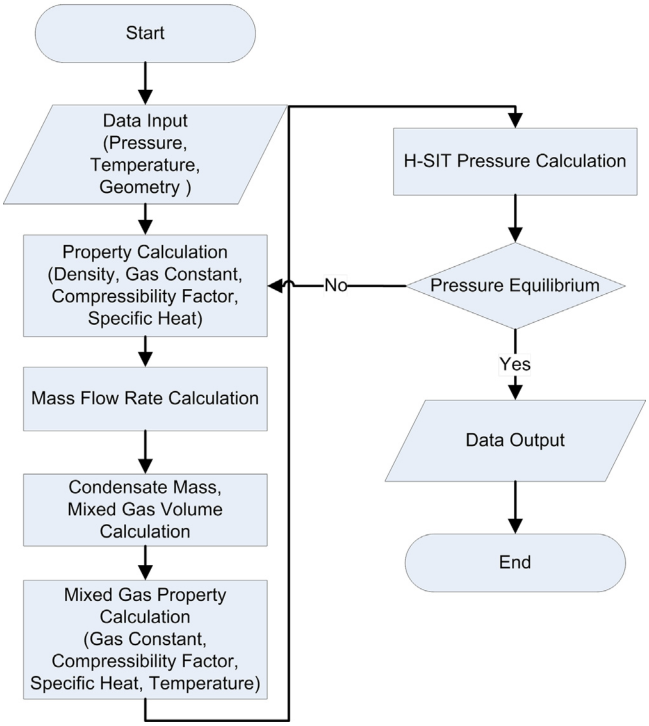

Fig. 1. Pressure calculation flow chart.