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An experimental study on the thermal-hydraulic phenomena in the Hybrid Safety Injection Tank using a separate effect test facility

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ABSTRACT

This paper reports an experimental research for investigating thermal hydraulic phenomena of Hybrid Safety Injection Tank (Hybrid SIT) using a separate effect test facility in Korea Atomic Energy Research Institute (KAERI). The Hybrid SIT is a passive safety injection system that enables the safety injection water to be injected into the reactor pressure vessel throughout all operating pressures by connecting the top of the SIT and the pressurizer (PZR). The separate effect test (SET) facility of Hybrid SIT, which is designed based on the APR+ power plant, comprises a PZR, Hybrid SIT, pressure balancing line (PBL), injection line (IL), nitrogen gas line, and refueling water tank (RWT). Furthermore, the pressure loss range of the SET facility was analyzed and compared with that of the reference nuclear power plant. In this research, a condition for balancing the pressure between the Hybrid SIT and PZR is examined and the effects of different variables affecting the pressure balancing, which are flow rate, injection velocity of steam and initial water level, are also investigated. The condition for balancing the pressure between the Hybrid SIT and PZR was derived theoretically from a pressure network for the Hybrid SIT, pressurizer, and reactor pressure vessel. Additionally, a sensitivity analysis as a theoretical approach was conducted on the pressure variations in relation to the rate of steam condensation inside the Hybrid SIT. The results showed that pressure of the Hybrid SIT was predominantly determined by the rate of steam condensation. The results showed that if the rate of condensation increased or decreased by 10%, the Hybrid SIT pressure at the pressure balancing point decreased or increased roughly by 10%, respectively.

1. Introduction

After the Fukushima nuclear power plant accident, demand for the enhancement of safety in nuclear power plants has increased. The accident showed that for the prevention of the core meltdown, the core makeup at high pressure of reactor coolant system (RCS) is crucial, and that even in a station blackout (SBO) situation, the core makeup water must be supplied smoothly by passive force. If the core makeup water is not sufficiently provided after the reactor trip, the steam will escape through the safety valve, causing a rapid loss of reactor coolant.

Among researches on the passive safety injection system (PSIS) for enhancement in nuclear power plant safety, the design of the core makeup tank (CMT) and its verification experiments have been studied by various organizations. VTT Energy in Finland has performed various verification tests on CMTs related to the design of the AP600, using a test facility of PACTEL (Chang et al., 1997; Tuunanen et al., 1998, 1999). They divided the CMT's operating modes into three phases (recirculation phase, oscillating phase, and injection phase), explained the various thermal-hydraulic phenomena that occur in each mode, and through 15 separate effect tests (SETs), examined the effects of the break size and location, and CMT location, on thermal hydraulic phenomena and coolant injection within the tank. The Korea Advanced Institute of Science and Technology (KAIST) performed a SET on CMT based on the design of the CARR passive reactor (CP1300) and tested the RELAP5/MOD3.1 code (Chang et al., 1997), while the Nuclear Power Institute of China (NPIC) and Japan Atomic Energy Agency (JAEA) used the NPIC CMT Test Rig (Zejun et al., 2003) and the Large-Scale Test Facility of the Rig-of-Safety Assessment Program (ROSA/LSTF) (Sibamoto, 2006), respectively, to study the CMT behavior during transients for the simulation of the small break loss-of-coolant accident (SBLOCA). The NPIC CMT Test Rig (Zejun et al., 2003) and ROSA/LSTF (Sibamoto, 2006) are downscaled test facilities of the AC600 and AP600, respectively.

The CP1300 and AP600 have the similar safety systems that are a combination of safety injection tanks (SITs) and CMTs (Lee and No, 1996; Zhang et al., 1998). The SITs, pressurized by nitrogen gas, are for the low-pressure LOCA condition and the CMTs,

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Nomenclature

Abbreviation

APR+	Advanced Power Reactor Plus
CARR	center for advanced reactor research
CMT	core makeup tank
CUPID	A Component-Scale Thermal Hydraulic Analysis Code developed by KAERI
DC	downcomer
DVI	direct vessel injection
FCV	flow control valve
HL	hot leg
IL	injection line
IRWST	in-containment refueling water storage tank
JAEA	Japan Atomic Energy Agency
KAERI	Korea Atomic Energy Research Institute
KETEP	Korea Institute of Energy Technology Evaluation and Planning
LCO	limiting condition of operation
LOCA	loss-of-coolant accident
LT	level transmitter
MV	manual valve
NPIC	Nuclear Power Institute of China
OV	operation valve
PAFS	passive auxiliary feedwater system
PBL	pressure balancing line
PECCS	passive emergency core cooling system
PSIS	passive safety injection system
PT	pressure transmitter
PZR	pressurizer
QM	mass flow meter
RCS	reactor coolant system
RPV	reactor pressure vessel
RWT	refueling water tank
SBLOCA	small break loss-of-coolant accident
SBO	station black out
SET	separate effect test
SIT	safety injection tank
TC	thermocouple
TF	thermocouple of fluid
TW	thermocouple of wall
VTT	VTT Technical Research Center of Finland

Symbols

C	core
c	specific heat (J/kg K)
D	diameter (m)
f	fanning friction factor
g	gravitational acceleration (m/s^2)
H'	substitution value
h_{LOSS}	head loss (m)
H_{SIT}	height of safety injection tank (m)
H_{PZR}	height of pressurizer (m)
H_{HL}	height of hot leg (m)
H_{DVI}	height of direct vessel injection (m)
K	coefficient of pressure loss
K_{total}	total coefficient of pressure loss
L	length (m)
M	mass (kg)
N	mole number (mol)
N_i	initial value of mole number (mol)
N_m	mole number of mixture gas (mol)
N_{N_2}	mole number of nitrogen (mol)
$N_{\mathrm{condensed\ water}}$	mole number of condensed water (mol)
$N_{\mathrm{non\text{-}condensed\ water}}$	mole number of non-condensed water (mol)
$N_{\mathrm{injected\ steam}}$	mole number of injected steam (mol)
N_2	nitrogen
P	pressure (MPa)
P_{SIT}	pressure of safety injection tank (MPa)
P_{PZR}	pressure of pressurizer (MPa)
P_{DC}	pressure of downcomer (MPa)
P_{m}	pressure of mixture gas (MPa)
P_{R}	reduced pressure
P_{cr,N_2}	critical pressure of nitrogen (MPa)
R	gas constant (J/K mol)
Q	heat (J)
Re	Reynolds number ($\rho vL/\mu$)
T	temperature (°C)
T_i	initial value of temperature (°C)
T_{cr,N_2}	critical temperature of nitrogen (°C)
T_m	temperature of mixture gas (°C)
T_r	reduced temperature
$T_{w,f}$	final temperature of the Hybrid SIT wall (°C)
$T_{w,i}$	initial temperature of the Hybrid SIT wall (°C)
V	volume (m^3)
V_i	initial value of volume (m^3)
V_m	volume of mixture gas (m^3)
$V_{\mathrm{condensed\ water}}$	volume of condensed water (m^3)
v_{steam}	velocity of steam (m/s)
$v_{\mathrm{Inj.DVI}}$	injection velocity at direct vessel injection (m/s)
Z	compressibility factor
Z_i	compressibility factor of initial value
Z_m	compressibility factor of mixture gas
Z_{N_2}	compressibility factor of nitrogen
μ	dynamic viscosity (kg/m s)
ρ	density (kg/m^3)
ρ_{steam}	density of steam (kg/m^3)
ρ_{SIT}	water density at safety injection tank (kg/m^3)
ρ_{PZR}	water density at pressurizer (kg/m^3)
ρ_C	water density at core (kg/m^3)
ρ_{DC}	water density at downcomer (kg/m^3)
R	gas constant (J/K·mol)
Δt	time interval (s)

pressurized by the RCS pressure, are for the high-pressure LOCA condition. However, the CMT cannot supply the coolant into the RCS during LOCA due to the low pressurizer (PZR) pressure after a large break LOCA (Kwon et al., 2011a,b).

The concept of Hybrid Safety Injection Tank system (Hybrid SIT) depicted in Fig. 1, proposed by the Korea Atomic Energy Research Institute (KAERI), has been introduced for the purpose of application to the Advanced Power Reactor Plus (APR+). The Hybrid SIT is a passive safety injection system that allows high-pressure core makeup over the all operating pressures (Kwon et al., 2012).

The current SIT filled with the coolant is pressurized with nitrogen gas to an intermediate pressure (generally about 4 MPa in conventional nuclear power plant), and thus the check valve opens and the SIT coolant is injected into the RCS when the RCS pressure drops below the SIT pressure. While, the Hybrid SIT can be pressurized equally to the RCS through a pipe connecting the SIT and PZR, along with nitrogen charging, in which case the coolant can be injected by the gravitational head between the RCS and SIT.

After introducing the concept of the Hybrid SIT, there have been some researches to confirm its performance or potential application. Kwon et al. (2011a,b) analyzed the SBO situation of the