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Depressurization study of supercritical fluid blowdown from simple vessel

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ABSTRACT

The loss of coolant accident (LOCA), particularly the depressurization process, is one of the difficulties in safety analysis of supercritical water-cooled reactor (SCWR). In this study, a comprehensive mathematic-physical model was established and a transient analysis code was developed to simulate the blowdown behaviors of SCWR in a large container. Three alternative phase separation models were adopted to calculate the stagnation enthalpy of the two-phase fluid in the container. Break flow rate models were established for different thermodynamic regions, including the supercritical region, the subcooled region, the overheating region and the two-phase region. The code was verified by comparison with blowdown experiment of supercritical CO_2 which shows a good agreement. Then the blowdown of supercritical water from simple vessel was investigated in detail with the code. The effect of initial conditions on pressure transitions was discussed for different regions divided by the relationship between the initial temperature and the corresponding pseudo-critical temperature. Furthermore, both the depressurization speed and the void fraction increase with the increase of initial temperature and the decrease of the initial pressure, yet the fluid inventory has an opposite trend. Discharge speed varies directly with break area, and the pressure transition which turns up earlier remains a constant value. These investigations may lay a theoretical foundation for the accident analysis of SCWR.

1. Introduction

Supercritical water-cooled reactor (SCWR) is one of the six innovative nuclear systems of Generation IV since it has many advantages, including small size, simplified system, good security and high economic efficiency. Previous studies and technologies of light water reactor (LWR) and supercritical fossil power plant have constituted a good foundation for the development of SCWR. However, some new technic challenges have been faced because of the high pressure and temperature of SCWR. LOCA simulations in particular present a unique challenge since the pressure and temperatures can change rapidly when coupled to significant property sensitivities in the supercritical region with temperature and pressure (Chatharaju, 2011). LOCA is a design based accident in the R&D of SCWR (Fig. 1), consisting of two stages: the blowdown process and the reflood process. It is also the most attractive accident in the SCWR safety analysis (Ishiwatari et al., 2006). Unlike in pressurized water reactor (PWR) and in boiling water reactor (BWR), the LOCA for SCWR has quicker depressurization and more dramatic transitions from initial supercritical pressure. Accidental depressurization will severely endanger reactor core safety due to a significant property variation near the pseudo-critical temperature (Fig. 2) (Licht et al., 2008). Supercritical blowdown meets challenges of trans-critical pressure drop and break discharge rate in different thermodynamic regions, therefore the blowdown from initially supercritical conditions is more complicated than that from initially subcritical conditions. The existing research conducted on supercritical blowdown is very insufficient while compared with the subcritical blowdown.

A limited number of experiments have been performed on supercritical water blowdown study because of the restrictions in experimental conditions. Lee and Swinnerton (1983) and Chen et al. (2009) explored the critical flow of supercritical water by experiment, and Chen applied several classical models for critical flow to supercritical fluids. Mignot et al. (2004, 2007, 2009) did some primary research on critical flow and the pressure release process of different fluids using both the theoretical and experimental methods. Three regions of behavior were proposed depending on initial conditions to investigate the specifics of depressurization in their study: The fluid remains a single phase from supercritical to subcritical blowdown in the first region; condensation occurs in the second region; evaporation appears in the third region. Most of the work above focuses on the critical flow of supercritical water, but little attention has been paid to the depressurization procedure. CO_2 (Gebbeken and Eggers, 1996) was

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Nomenclature

p	average pressure (MPa)	ρ	average density (kg/m^3)
h	average enthalpy (kJ/kg)	A_0	break area (m^2)
D	diameter of the container (m)	z_v	height of the container (m)
z_0	break location (m)	V	volume of the vessel (m^3)
W_0	break flow rate (kg/s)	Q	additional heat (kW)
h_0	stagnation enthalpy (kJ/kg)	h_v	enthalpy of saturated gas (kJ/kg)
h_l	enthalpy of saturated liquid (kJ/kg)	α	void fraction
ρ_v	density of saturated gas (kg/m^3)	ρ_l	density of saturated liquid (kg/m^3)
σ	surface tension (N/m)	g	acceleration of gravity (m/s^2)
v_b	bubble rising velocity (m/s)	j	apparent velocity (m/s)
T_{cri}	pseudo-critical temperature (°C)	p_c	critical pressure of critical flow (MPa)
p_o	stagnation pressure (MPa)	W_i	mass flux (kg/(m^2 s))
W_c	critical mass flux (kg/(m^2 s))	x	mass quality
p_{cr}	critical pressure of critical flow (MPa)	p_b	back pressure (MPa)
c_p	specific heat capacity (kJ/kg C)	T_o	stagnation temperature (°C)
p_{sat}	saturation pressure corresponding to the stagnation temperature (MPa)	p_{sats}	saturated pressure corresponding to the stagnation entropy at the break (MPa)
p_0	initial pressure (MPa)	T_0	initial temperature (°C)

adopted to observe the depressurization process from a simple vessel. The transients of pressure and temperature were discussed in their work, and the void fraction profiles influenced by phase separation effects were measured as well. R134a (Naji et al., 2012) was used to study the depressurization from one vessel to another.

Some LOCA analyses for SCWR were performed by modified system code in recent years. Considering a sudden void fraction change at critical point, system codes such as ATHLET, RELAP (Fu et al., 2012) and RETRAN (Wu et al., 2013) have been modified for the analysis of LOCA. In addition to the modification of system code, LEE et al. (1998) developed a LOCA analysis code for SCWR, consisting of the blowdown and reflood analysis modules. Nevertheless, it was validated by the REFLA-TRAC code which is just applicable to subcritical conditions, and there's no experimental verification in LEE's work. Therefore further theoretical research for the LOCA and blowdown process is necessary.

The knowledge of thermal–hydraulic behavior for the supercritical discharge from a simple vessel offers an insight on accident consequences and can help us define safety margins for inherently safer designs. The transients of pressure, temperature, void fraction and coolant inventory in the core are the concerned topics. Our research group has done much research on SCWR, covering subchannel analysis (Chaudri et al., 2012), flow instability analysis (Tian et al., 2012), fuel and core design (Chaudri et al., 2013), and studies on safety analysis (Zhu et al., 2012, 2013). Now we continue to carry out basic study on the LOCA of SCWR. The present study focuses on the depressurization stage during the whole discharge process. A transient code is developed by building

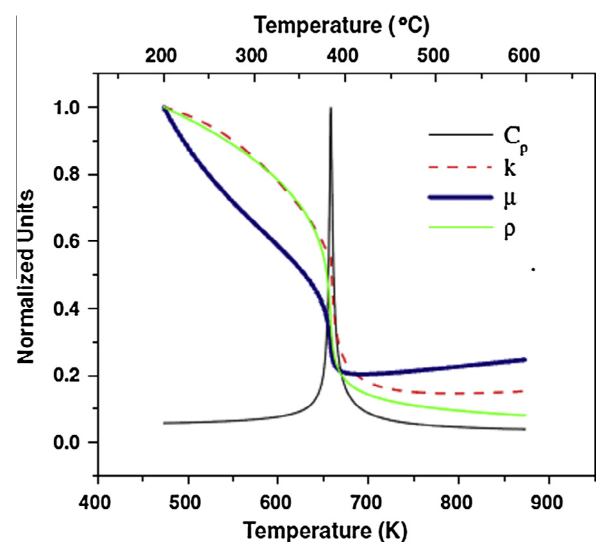

Fig. 2. Thermo-physical properties of water at 25 MPa (Licht et al., 2008).

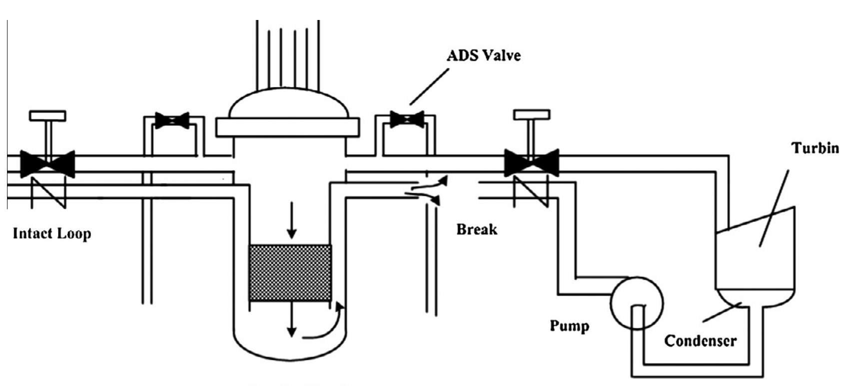

Fig. 1. Blowdown phenomenon of SCWR (Ishiwatari et al., 2006).