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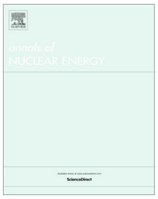

Study on structural response of reactor vessel under direct safety injection

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ABSTRACT

An emergency core cooling system for a pressurized water reactor adopts direct safety injection with reactor pressure vessel. In this design, a special flow guide device is introduced in order to minimize the heat effects on the reactor internals. But this design makes the pressure vessel bear stronger heat and current impact. To investigate the dynamic response of the pressure vessel during safety injection, the law of dynamic distribution of the heat and flow load are studied using three experiments: In the visualization experiment, the relationship between injection condition and distribution pattern in the downcomer is obtained. In the heat mixing experiment, measuring the temperature and pressure near the inner wall of the pressure vessel, enables us to find out the law that governs dynamic distribution of the heat and pressure load as well as the main distribution area of these loads, and analyze how the temperature oscillation generated. In the structural response experiment, the strain response of the pressure vessel to temperature and pressure is obtained. Moreover, the frequency range of its response to hot oscillation under safety injection is also obtained by analysis. This study provides support to recognize the action law of heat, pressure and structural response in the reactor during safety injection.

1. Introduction

As the third-generation reactor is designed and studied in recent years, the direct safety injection is adopted by many new pressurized water reactors for its unique properties. However, compared with the traditional reactors, instead of placing injection nozzle on the cold leg of main pipeline, the safety injection nozzle is directly connected to pressure vessel, thus the water can reach core more rapidly, and the safety injection won't be affected when the main pipe breaks.

However, when the direct safety injection is adopted, before mixing with high-temperature coolant, low-temperature water is in contact with pressure vessel as well as the reactor internals, which causes temperature fluctuation on the components of reactors. Therefore, a continuously changing thermal strain is generated. Its phenomenon will surely be greatly different from that of indirect safety injection.

In recent years, many researchers have studied the thermal mixing characteristics of fluid in the process of safety injection.

Wolf et al. (Wolf et al., 1986; Wolf et al., 1987; Häfner and Wolf, 1988) conducted a safety injection analysis on HDR-TEMB scaled test facility, using a cold leg injection type. In this test they found a localized, stripe-like asymmetric cool down of downcomer and vessel wall, fluid mixing behavior and the near wall temperatures in the downcomer were investigated. Also, transient strains at the RPV inner surface were measured in their test.

Many researchers (Cartland Glover et al., 2007; Kliem et al., 2010; Prasser and Kliem, 2014; Kliem et al., 2008; Höhne et al., 2006; Anis Bousbia Salah, 2017; Feng et al., 2017) have studied the thermal-mixing properties in reactor vessel using Rossendorf Coolant Mixing Model (ROCOM) test facility which is a four loop 1:5 scale facility with a cold leg injection nozzle for the investigation of coolant mixing and thermal shock. Two kinds of fluid with different density were used to simulate the mixing of cold water and hot water, and the test coincided about the momentum-driven and buoyancy-driven mixing. The distribution of two fluid was collected by visualization experiment and wire mesh electrode sensors.

The Korea APR1400 reactor has adopted a direct vessel inclined injection (DVII) structure for the emergency core cooling system, many thermal mixing tests (Kwon et al., 2003; Kwon et al., 2009; Yoon et al., 2006; Cho et al., 2005) were performed to study fluid mixing phenomena and air–water separate effect in the downcomer, potassium permanganate was added in the injection loop to show the flow distribution. In their study, the visualization tests

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Nomenclature

Symbols

D	diameter, m
m	dimensionless temperature
D_{DVI}	internal diameter of DVI nozzle, m
f	frequency, Hz
K	velocity ratio
T	temperature, K
St	Strouhal number
V	velocity, m/s

Greek symbol

θ	angle, degree

Subscripts

DVI	reactor vessel injection nozzle
RCS	reactor vessel inlet nozzle
D	reactor vessel downcomer

was performed to investigate the flow mixing and liquid-spread phenomenon in the downcomer.

The State Key Laboratory of Multiphase Flow in Power Engineering of Xi'an Jiaotong University conducted long-term study of the mixing phenomenon of hot and cold water in the pressurized water reactor consisting of experimental and analytical study on the flow and heat transfer performance of the injection and the pressurizer surge line of a variety of tube types in the high temperature different fluid mixing; study on transient experiment and numerical computation of a 1:10 scale direct injection device of an AP600 reactor. The transient distribution of temperature and the heat transfer coefficient on the pressure vessel under different transient conditions was obtained, and the applicability of the numerical method to solve the problem was verified (Dang et al., 2008; Donghua et al., 2013; Qiao et al., 2014; Cai et al., 2017; Cai et al., 2017).

The above-mentioned study gives a deep understanding of laws governing the flowing and heat transfer of various reactors during safety injection. But it focuses on the flow and thermal mixing phenomenon, mostly aiming at steady mixing. In addition, the structure response of the pressure vessel to thermal and pressure fluctuation, a deep-level objective of this type of study, is barely studied.

In order to further study the relationship between heat mixing and structural response, as well as the suitability of direct safety injection for a pressurized water reactor under development, this paper studies the dynamic flow and thermal mixing phenomenon of a 1000 MW reactor under the direct safety injection in the scaled experiment system. The study includes three experiments: visualization experiment for studying flow mixing pattern; heat mixing experiment for studying dynamic pressure and temperature distribution on wall surface; structural response experiment for studying dynamic structure strain of the reactor vessel. This study reveals the laws governing the distribution of thermal and pressure load of the fluid in the downcomer, and determines the influence rule of thermal and pressure load on the pressure vessel under direct safety injection.

2. Experimental procedures

2.1. Experimental facility

The experiment in this paper is completed in the low-pressure test facility of the State Key Laboratory of Multiphase Flow in Power Engineering of Xi'an Jiaotong University. The experimental medium is pure water, and Fig. 2 shows the schematic diagram of the test facility. The test facility includes feed water system for main loop and safety injection loop, experimental section and storage tank. The water extracted by main pump is injected into the main loop, and then enters experimental section through inlet nozzle of pressure vessel. The safety injection pump injects water from water tank into the injection loop, which then enters experimental section through inject nozzle. The fluid flow out of lower plenum after mixing together in the downcomer. The main pump can provide a flow rate of 400 m^3/h, while safety injection pump can provide that of 90 m^3/h. The flow rate of both loops are controlled by bypass valve. Since the two pumps have a 2900 rpm rotation speed and 5 blades, they produce a 245 Hz of first order oscillation frequency. The peak value under this frequency is removed during measurement data processing in order to analyze the physical quantity pulse caused by flowing and thermal mixing.

The pumps are installed in a separate room away from the experimental section to minimize the vibration transmitted from ground to test loop. To avoid the influence of pressure pulse induced by local resistance, like elbows, valves and other disturbing devices, based on the results of measurement, the experimental sections are installed on the section where fluid is fully developed. To free from the influence of mechanic vibration of pipeline, in front of and behind experimental items, fixed supports are placed to support pipeline, and flexible pipes are used to connect with loop pipes.

In the actual reactor design, a special guide device (as indicated in Figs. 2 and 3) is arranged where pressure vessel directly faces safety injection nozzle, in order to ensure that the injection fluid can enter the lower part of pressure vessel and minimize the impact of cold fluid on the wall of core barrel. The guide device can force injection fluid to flow downward after it flows out of pipe nozzle, and divert it to one side of pressure vessel with a deflector plate. This device will certainly make pressure vessel experience stronger heat and flow effect.

The reactor in this study includes two coolant loop, which has two hot legs and four cold legs, two safety injection nozzles are placed on both sides of pressure vessel symmetrically. As the pressure vessel and the reactor internals both meet the 1/2 axial symmetry conditions in the two aspects of geometry and flow field, and this study aims more at local response, this study adopts 1/2 symmetry model to avoid flow rate limitation of the main feed water pump.

For the test sections, the scale model and the actual reactor satisfy the geometric similarity first. Based on the feasibility and economy of the experimental research, test sections are designed as a 1:9 ratio, and the velocity range of the two loops in the experiment is in agreement with the actual reactor. For the structural response test section, carbon steel Q235B is used in the manufacture of the pressure vessel, so as to ensure the structural stiffness of the test model is similar to the actual reactor. The photos of the test sections are shown in Fig. 1(a) and (b). Moreover, to really reflect the flow phenomenon of lower plenum of the pressure vessel, the experimental section includes a simplified lower plenum, and its outlet is located at the lower part of lower plenum.

In order to conduct different measurements, 3 different experimental sections are made: visualization experimental section