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Experimental investigation on thermal stratification in a pressurizer surge line with different arrangements

Benan Cai, Yu Weng, Yanyan Wang, Xingchen Qin, Fangfang Cao, Hongfang Gu, Haijun Wang*

State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China

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ABSTRACT

Thermal stratification in a pipe, which can lead to temperature fluctuations, has attracted much attention from researchers who study nuclear power plants. In particular, temperature fluctuation in the pressurizer surge line has been assessed as being a significant technical and safety issue due to its high rate of occurrence. The present work investigated thermal stratification of the tilted arrangement. Both the outer and the inner temperature distribution were extracted and analyzed. As the surge line inlet velocity increased, the regions where thermal stratification occurred gradually approached the hot leg. In addition, thermal stratification for the tilted arrangement was compared with that for the horizontal arrangement. The temperature difference along the surge line and the temperature patterns for the different arrangements were compared and analyzed.

1. Introduction

The surge line connects the pressurizer filled with relatively hot water and the hot leg of the reactor coolant system containing relatively cold water. When the hot water and the cold water meet in the surge line, thermal stratification can occur. In this case, the hot water tends to occupy the upper part of the surge line and the cold water tends to occupy the lower part. The hot water at the top of the pipe causes greater thermal expansion compared with the cold water at the bottom of the pipe, tending to bend the pipe and accelerate pipe failure (Chattopadhyay, 2010).

Due to excessive thermal stratification, much serious damage, such as pressurizer surge line movements and pipe leakage incidents, has happened in nuclear power plants. For example, unexpected movements of a pressurizer surge line that led to gap closures and overall line displacement were observed by Trojan (USNRC, 1988) several years ago. The material fatigue of the nuclear power plant piping system caused by thermal stratified flows may limit the lifetime of the piping; therefore, the consideration of thermal stratification is crucial in the management of aging and for the lifetime-extension of nuclear power plants (USNRC, 1988).

Typical piping systems of nuclear power plants with thermal stratification include the pressurizer surge line, steam generator feed water piping, residual heat removal lines, and so on (Rezende et al., 2006). During the past decades, since the publication of Bulletins 88–08 and 88–11, numerous studies have been performed to investigate thermal stratification.

Kim et al. (2005) performed a series of experiments to measure thermal stratification in a 1/10 scale experimental rig. The test equipment mainly consisted of the safety injection system pipe, the shutdown cooling system pipe and the reactor cooling system pipe. The turbulent penetration depth and the temperature distributions in different abnormal cases were obtained.

Thermal stratification in the thermodynamic steam generator (SG) injection nozzle was simulated by Da Silva et al. (2011). They selected the injection nozzle Froude number as the similarity criterion number to design the experimental section. To study the effects of thermal stratification in the pipe material, forty-one thermal stratification experiments were performed. The researchers found that thermal stratified flows, stress, and strains caused the enlargement of the material's grain size and a reduction in fatigue life.

Kang et al. (2011) studied thermal stratification in a pressurizer surge line during two operating cases: the out-surge process with the out-surge flow, which was in the direction from the pressurizer to the hot leg, and the in-surge process with the in-surge flow, which was in the opposite direction.

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* Corresponding author.
E-mail address: whj@mail.xjtu.edu.cn (H. Wang).

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Qiao et al. (2014) investigated thermal stratification in a pressurizer surge line using a 1/3 scale model. Temperature distributions inside and on the outer surface of the surge line pipe were obtained and compared. The Richardson number was chosen as the similarity criterion number for the inlet velocities of both the hot leg and the surge line.

Nakamura et al. (2014) investigated flow structure and temperature fluctuation near the thermal stratified layers in a straight branch pipe and a bent branch pipe. The penetration length of the main flow and the mechanism of the temperature fluctuation near the thermal stratified layer were studied.

Zhang et al. (2016) used experiment and CFD simulation to study thermal stratification and turbulent penetration in a pressurizer surge line. They found that the most violent stratification tended to happen in the region near the elbow which connected to the horizontal part of the surge line. The depth of the turbulence was determined with the values of the mean velocities and the root-mean square velocities. The thermal stratification mainly occurred in the horizontal part of the surge line and the turbulent penetration was mainly located in the vertical part of the surge line.

Previous experimental research on thermal stratification in the pressurizer surge line has been limited. Moreover, no researchers focused on the effect of the arrangement of the surge line on thermal stratification. Therefore, this study focused on thermal stratification in the tilted surge line and compared thermal stratification in the horizontal surge line with that in the tilted surge line, extracting and analyzing the temperature distributions.

2. Experiment apparatus and methods

To investigate thermal stratification in the surge line effectively in the lab, a 1/3 scale experiment apparatus whose Richardson number (*Ri*) was equal to that of the actual nuclear power plant's apparatus was established. The Richardson number (*Ri*) for the inclined pipe was expressed as follows:

$$Ri = \frac{g\beta D_i (T_h - T_c)\cos\alpha}{u^2} \tag{1}$$

where g denotes the gravitational acceleration, β is the thermal expansivity, D_i represents the internal diameter of pipe, α is the inclination to the horizontal direction, u denotes the flow velocity, T_h and T_c denote the hot water temperature and the cold water temperature, respectively. A well-insulated stainless steel test section with an inner diameter of 94 mm for the surge line is plotted in Fig. 1. The surge line was connected to the hot leg with a upward angle of 30°, which means the surge line was oriented at an angle of 30° with the horizontal plane. The diameter of the hot leg was 170 mm.

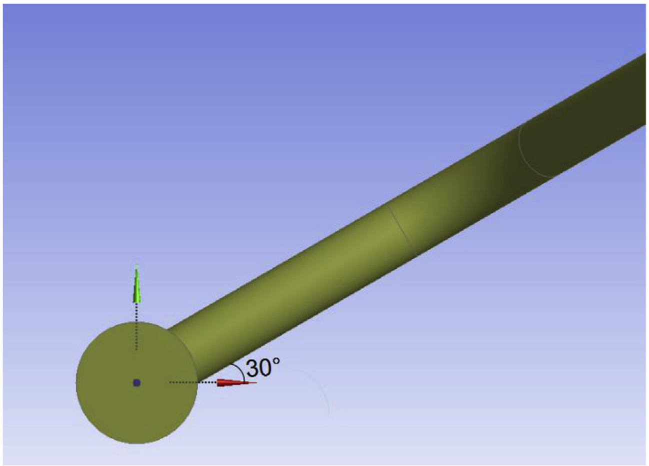

Fig. 1. Test section schematic diagram.

The schematic diagram of the 1/3 scale experiment facility is illustrated in Fig. 2. The experiment consisted of two test loops, the hot leg loop and the surge line loop, respectively. The hot leg loop mainly included the cold water tank, the cold water pump, the orifice plate flow meter and the hot leg. The surge line loop mainly contained the hot water tank, the hot water pump, the mass flow meter and the surge line. The cold water, which was room temperature, was driven by the cold water pump from the cold water tank to the hot leg inlet. The temperature of the hot water was controlled by the heater attached to the hot water tank. The heated water was driven by the hot water pump to the surge line inlet. Then the hot water and the cold water mixed in the test section and eventually flowed back into the cold water tank together.

To obtain the temperature distributions in the experiment, a total of fifty-eight T-type thermocouples, 0.1 mm diameter bare wires, were arranged along the surge line pipe. Since thermal stratification mainly occurs in the region near the elbow which connects to the horizontal part of the surge line (Zhang et al., 2016), five cross-sections along the surge line, as shown in Fig. 3, were picked to install thermocouples. The cross-sections were picked by *L*/*Ds* where L represents the length and *Ds* represents the internal diameter of the surge line. The coordinates are also shown in Fig. 3 and the origin of coordinates was set to the center of the connection between the hot leg and surge line. Five cross-sections were marked as 3.7*Ds*, 5.3*Ds*, 7.4*Ds*, 9.6*Ds* and 11.7*Ds* respectively. The cross-section 5.3*Ds* was near the elbow of the surge line. Fig. 4 shows the distributions and details of the monitoring points. Seven thermocouples were evenly inserted into the surge line pipe along the height direction of the pipe diameter to measure the inner fluid temperature for each cross-section at cross-section 5.3*Ds*, 7.4*Ds* and 9.6*Ds*. The inner measuring points were represented by *h*/*Ds*, where *h* is the height from the monitor point to the bottom point and *Ds* denotes the internal diameter of the surge line. The bottom of the cross-section was defined $h/Ds=0$. At the same time, eight thermocouples were evenly arranged every other 45° on the outer surface of the surge line pipe to obtain the outer wall temperature at cross-section 3.7*Ds* and 11.7*Ds*. The top of the cross-section was defined as 0° and thermocouples were counted in the clockwise direction. As can be seen from Fig. 4a, there were seven thermocouples along the outer surface of the surge line as a result of the existence of the inner monitoring points at cross-section 5.3*Ds* to 9.6*Ds*.

The hot leg velocity and the surge line velocity were changed using the test loop shown in Fig. 2. The flow rates of the hot leg and the surge line were measured by the orifice plate flow meter and the mass flow meter, respectively. For the actual operating conditions, the maximum temperature difference between the pressurizer and the hot leg can be up to 110 K. However, it was difficult for the experiment to reach that temperature difference with the actual working conditions. Therefore, the present experiment was carried out at a constant temperature and pressure condition. The temperature of the hot water was set at 343 K and the cold water was 283 K. The temperature difference between the hot leg inlet and the surge line inlet was 60 K, which was about 1/2 that of a nuclear power plant. The hot leg and surge line flow velocity was determined by the similarity criterion number *Ri*. The experiment parameters during the experimental process are listed and shown in Table 1. The experiment was carried out under 4 conditions. For different conditions, the hot leg inlet velocity was fixed and the surge line inlet velocity was varied.

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