Annals of Nuclear Energy 73 (2014) 211–217

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Experimental investigation of thermal stratification in a pressurizer surge line

Shouxu Qiao [a,b], Hongfang Gu [a], Haijun Wang [a,*], Yushan Luo [a], Dasheng Wang [c], Pan Liu [c], Qingli Wang [c], Qing Mao [c]

[a] State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China
[b] Department of Mechanical and Nuclear Engineering, The Pennsylvania State University, University Park, PA 16802, United States
[c] China Nuclear Power Engineering Co. Ltd., Shenzhen 518000, China

ARTICLE INFO

Article history:
Received 25 February 2014
Received in revised form 19 June 2014
Accepted 20 June 2014

Keywords:
Thermal stratification
Pressurizer surge line
Pressurized water reactor (PWR)

ABSTRACT

Thermal stratified flow in a pressurizer surge line was investigated on a 1/3 scaled model based on the Richardson number similarity. A database which could be used to verify the thermal stratification simulation was established. Temperature distributions inside and on the outer surface of a surge line pipe with different surge line inlet flow rates were monitored and compared. Thermal stratification occupied a large part of the surge line. Temperature differences at all the measured test sections reached half of the maximum inlet temperature difference. As the surge line inlet velocity increased, the pattern of temperature distribution showed a similar trend and the cross-section maximum temperature difference changed little. This was consistent with the existence of thermal stratification at operating conditions in the corresponding pressurized water reactor.

1. Introduction

Prediction of thermal stratification in piping systems, while challenging, is needed for the life management of a nuclear power reactor. Large numbers of pipe cracking and leakage incidents are directly or indirectly caused by thermal stratification (Bush, 1992). For example, Farley 2 detected a circumferential crack extending through the wall of a short section of emergency core cooling system (ECCS) piping (USNRC, 1988b). It was found that the crack was caused by valve leaking and temperature stratification. Trojan observed unexpected movements of a pressurizer surge line for several years (USNRC, 1988a). The movement led to gap closures and overall line displacement. The differential temperature was sometimes as high as 300°F. These events demonstrate that thermal stratification could cause unexpected piping movement, potential plastic deformation and pipe failure. In response, the United States Nuclear Regulatory Commission (USNRC) published Bulletin 88-08 (USNRC, 1988b) and Bulletin 88-11 (USNRC, 1988a), requesting all license holders to identify pipes subjected to big temperature differences, confirm their integrity and, finally, to take actions to resolve this issue.

In thermal stratification, hot water with low density flows over cold water with high density. It generally occurs in locations where low velocity water with high temperature differences exist, such as pressurizer surge lines, mixing T-junctions, leaking check valves and injection nozzles. Due to the high heat capacity and the small conductivity of water, as well as the low velocity in these locations, the difference in the buoyancy between hot and cold water could inhibit their mixing, resulting in a stratified flow (Yu et al., 1997). The hot water at the top of the pipe causes greater thermal expansion than the cold water in the bottom of the pipe, tending to bend the pipe and accelerate pipe failure (Chattopadhyay, 2010).

During the past decades, since the publication of Bulletin 88-08 and 88-11, numbers of experiments have been performed to investigate thermal stratification. Wolf et al. (1992) performed a group of seventeen tests on an HDR system at high pressures and high temperatures, simulating thermal stratification in a feed water pipe. They found that the flow velocity of the cold water determined the steepness of the temperature gradient between the cold and hot water. The results formed a database for validating the present and future computer codes, analytical methods, procedures and correlations related to thermal stratification in feed water pipes.

Kim et al. (2005) studied thermal stratification in the branch of an NPP and the inlet nozzle of a steam generator caused by valve leakage on a 1/10 scaled facility. The penetration depth and the

* Corresponding author. Tel.: +86 29 82667034; fax: +86 29 82669033.
E-mail address: whj@mail.xjtu.edu.cn (H. Wang).

http://dx.doi.org/10.1016/j.anucene.2014.06.045
0306-4549/

Nomenclature

D	pipe diameter (m)
g	gravity (m/s^2)
H	inner monitor height (m)
R_i	Richardson number, $g\beta D^3(T_{hot} - T_{ref})/u^2$
t	time (s)
T	temperature (°C)
u	fluid velocity (m/s)
β	volume expansion coefficient (1/K)
ρ	density (kg/m^3)
θ	inner monitor angle (°)
Subscripts	
hot	hot water
ref	reference temperature

amount of heat transfer through the valve were obtained. In addition, the authors defined a criterion to identify thermal stratification caused by leakage.

Kim et al. (1993) investigated the interaction between main coolant piping and stagnant attached lines by turbulence penetration. During the experiments, hot water penetrated into the stagnant region filled with cold water. The authors proposed a theory to relate the turbulent penetration distance to a modified Reynolds number as a parameter.

Navarro et al. (2008) studied low flow rate hot water injected into cold water in a horizontal pipe which was a scaled steam generator injection nozzle. During the experiment, the Froude number was kept close to that of nuclear reactors in operation. The authors proposed the measured vertical temperature gradient in the fluid and in the piping wall as a function of the Froude number.

However, experimental studies on thermal stratification in the pressurizer surge line are scant. Abourjeily and Barois (1994) conducted an experiment on surge line thermal stratification on the L'EXPRESS experimental facility operated by EDF. The test section was a 0.64 nearly horizontal scaled pressurizer surge line of a Framatome PWR. The experimental data were used to verify the simulation results using the TRIO-EF code. Unfortunately, the literature provided so little experimental data that they cannot be applied to verify other simulation results.

Yu et al. (1997) measured the temperature and displacement of the surge line during the heat up and cool down process on the Korean YGN Unit 3. They observed large wall top to bottom temperature differences with large vertical displacements. They proposed that the measured temperature differences and the pipe displacements could be correlated, but we did not find any further related work.

As can be seen, according to the previous experimental studies, much work has been done to investigate thermal stratification in the steam generator injection nozzle and the feed water pipeline caused by leakage, injection or penetration. However, research on the stratified flow in the pressurizer surge line caused by turbulent penetration is scant.

Due to the high temperature difference between the water in the pressurizer and the water in the hot leg, as well as the small velocity in the surge line, thermal stratification in the surge line is unavoidable. Measures such as monitoring the temperature distribution through the surge line have been taken by many nuclear power plants. However, it is not only time and energy consuming, but it is also difficult to get the maximum temperature difference along the cross section. Therefore, it is meaningful to continue studying the mechanism of thermal stratification and find ways to mitigate it. To investigate thermal stratification in the pressurizer surge line, a 1/3 scaled experimental apparatus based on an actual nuclear power plant unit was established. Experiments with R_i number equal to the operating conditions of the nuclear plant were conducted.

2. Experimental facility and methods

Fig. 1 shows the schematic diagram of the experimental system built for the study of thermal stratification in the pressurizer surge line. The experimental system consisted of two test loops, simulating the hot leg loop and the surge line loop, respectively. In the hot water loop, the insulated hot water tank (6) was used to simulate the pressurizer. Water was heated directly to 70 °C by AC power supplies with maximum heating capacities of 50 kW. Then the hot water was driven by the pump (5) through the mass flow meter (7) to reach the inlet of the surge line (8). In the cold water loop, cold water was drained out from the cold water tank (1) by a pump (2). After flowing through an orifice plate flow meter (3), the cold water reached the hot leg inlet (9). The hot water and the cold water mixed at the test section (10) and the mixed water flowed back into the cold water tank (1).

The prototype of the current study was a 900 MW pressurized water reactor. Fig. 2 shows the test section, which is a 1/3 scaled model with a hot leg and a horizontal surge line. The hot leg was simulated with a stainless steel pipe with an inner diameter of 170 mm. A well-insulated bent stainless steel pipe with an inner diameter of 94 mm was soldered to the hot leg to simulate the surge line.

As is shown in Fig. 2, thermocouples located at five positions which were denoted as cross-sections 1 to 5 along the surge line pipe. Two ways were used to measure the temperature distribution of the surge line. First, thirty-three standard type T thermocouples 0.1 mm in diameter were soldered to the outer wall of the surge line to measure the outer surface temperature. Second, twenty-one standard type T thermocouples were positioned inside the surge line to measure the inside fluid temperature field directly. Further details of the thermocouples arrangement are provided in Fig. 3. At cross-sections 2 to 4, seven thermocouples were evenly arranged along the height direction of the pipe diameter. Another seven thermocouples were equally welded to the outer surface of the surge line at 45°, 90°, 135°, 180°, 225°, 270° and 315° in a circumferential direction to measure the temperature of the outer surface. Due to the arrangement of the inner thermocouples, there were no thermocouples at the top of the surge line, which is 0°. At cross-sections 1 and 5, eight thermocouples were equally welded to the outer surface of the surge line at 0°, 45°, 90°, 135°, 180°, 225°, 270° and 315° in a circumferential direction to measure the temperature of the outer surface. There were no inner thermocouples at these two cross-sections.

The flow rates of the hot leg and the surge line were measured by an orifice plate flow meter and a mass flow meter, respectively. Two sheathed standard type T thermocouples were mounted at the upstream of the hot leg and the surge line to measure the respective inlet temperatures. All instruments used to measure the loop parameters were thoroughly checked and calibrated.

The uncertainties of measuring in the experiment were dependent on the experimental conditions and on the measuring instru-