Available online at www.sciencedirect.com

ScienceDirect

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

Characteristics of flow field and pressure fluctuation in complex turbulent flow in the third elbow of a triple elbow piping with small curvature radius in three-dimensional layout

Shinji Ebara [a,*], *Hiroyuki Takamura* [a], *Hidetoshi Hashizume* [a], *Hidemasa Yamano* [b]

[a] *Tohoku University, Department of Quantum Science and Energy Engineering, 6-6-01-2, Aramaki-aza-aoba, Aoba-ku, Sendai 980-8579, Japan*

[b] *Japan Atomic Energy Agency, Advanced Fast Reactor Cycle System Research and Development Center, 402 Narita-cho, Oarai, Ibaraki 311-1393, Japan*

A R T I C L E I N F O

Article history:
Received 13 November 2015
Received in revised form
10 February 2016
Accepted 11 February 2016
Available online 16 March 2016

Keywords:
Elbow piping
Flow separation
Pressure fluctuation
Separated vortices

A B S T R A C T

In this study, a flow visualization and pressure measurement were conducted by using an experimental setup including test sections of 1/7-scale models of the cold-leg piping of Japan sodium-cooled reactor with high Reynolds number region up to about one million. Regarding the flow field, flow separation appeared in the intrados of the third elbow. However, the separation region was smaller than that observed in the first elbow in the direction normal to the mean flow and was larger in the streamwise direction. This can be considered because of the swirling flow vgenerated downstream of the second elbow which flowed into the third elbow with a little reduction. From the pressure fluctuation test, it was found that prominent frequencies of the pressure fluctuation appeared at about 0.4 in Strouhal number, which corresponds to a nondimensional frequency, in the region from 0 *D* to 0.4 *D* downstream of the elbow outlet, where *D* is the diameter of the piping. And weak peaks of about 0.7 in Strouhal number were observed in the region far 0.75 *D* downstream of the outlet. The peak values were about 1/4 of those in the first elbow. This means that the excitation source in the third elbow becomes smaller than that in the first elbow for the fully developed inflow case.

Introduction

In an advanced loop-type Japan sodium-cooled fast reactor (SFR) of 1.5 GWe class, a two-loop cooling system is adopted with a close arrangement of the reactor core and the intermediate heat exchangers in order to realize a compact size of the reactor [1]. The close arrangement of the components could be realized by a shortened piping system, and the cold-leg piping comprises three 90° elbows and straight pipes connecting the

* Corresponding author.
E-mail address: shinji.ebara@qse.tohoku.ac.jp (S. Ebara).
http://dx.doi.org/10.1016/j.ijhydene.2016.02.068
0360-3199/

elbows. In specifications designed by 2010, the diameter of the piping is 930.0 mm and a curvature ratio of the elbows, which is the ratio of a curvature radius of the centerline of the elbow to the diameter, is 1.0 (called "short elbow"). In the cold-legs, the mean sodium flow velocity in the cold-leg piping reaches 8.4 m/s and the corresponding Reynolds number (*Re*) is 2.3×10^7. In addition to three-dimensionally connected piping of the cold-leg, a complex flow field with vortices shedding can be inferred to appear in it due to the presence of the short elbows which could induce flow separations [2]. Separation vortices could be given off from the intrados of the elbow and cause large pressure fluctuation downstream of the flow separation region [3]. Since the piping thickness of SFR is thin compared to that of light-water reactors so as to mitigate thermal stress on structure, this pressure fluctuation could be a trigger for flow-induced vibration (FIV) of the piping, which is one of the most undesirable events in the plant. Therefore, it is essential to clarify the complex flow field in the piping in order to evaluate the FIV.

Many experimental studies have been conducted to date to clarify the flow and pressure fields in the JSFR piping in terms of FIV evaluation. Regarding the JSFR hot-leg piping, which has only one short-elbow, frequency characteristics of pressure fluctuation and the total pressure loss coefficient were scrutinized by carrying out a 1/3-scale experiment at very high Re, over 10^6 [3,4]. In these studies, it was revealed that a power spectrum density (PSD) profile of pressure fluctuation obtained near the flow separation region had a peak at Strouhal number (*St*) based on the mean axial velocity and pipe diameter, which is considered as dimensionless frequency, of about 0.5. And this characteristic of pressure fluctuation was shown in the wide range of *Re* [5]. The flow structure in the single elbow piping can be inferred to have three periodic motions, i.e., periodic vortices shedding in the shear flow region between the flow separation region and high velocity region near the pipe center, periodic separated vortices shed from the separation region, and periodic circumferential flows toward the intrados side [6]. Regarding the pressure fluctuation characteristic, obtained normalized PSD profiles were independent of Reynolds number, and showed good agreement with each other [7]. As for the cold-leg piping, which has successive three short elbows, 1/13- and 1/7-scale experiments simulating the first and second elbow was conducted to clarify the flow field by using particle image velocimetry (PIV) system [8,9], and to clarify the pressure field and characteristic of pressure fluctuation by measuring pressure on the wall of the piping in detail [10]. In the dual elbow system, the flow separation region deformed and extended toward the intrados of the 2nd elbow according to the asymmetric configuration of the successive two elbows, and a swirling flow was formed downstream of the 2nd elbow. As for the pressure field in the dual elbow system, peaks at about $St = 0.5$ in the PSD profiles of pressure fluctuation were also observed but the positions where the peaks were observed were changed compared to the single elbow system. All of the above-mentioned findings were obtained in the condition of smaller Reynolds number than that assumed in the JSFR. However, all of the Reynolds numbers, including the JSFR condition, belongs to so-called the postcritical regime ($Re > 3 \times 10^5$) [11], and it is possible to apply the findings to the JSFR by assuming an analogy [12].

In this study, a triple elbow system, which is the authentic JSFR cold-leg model in terms of geometric configuration, was experimentally tested to clarify the flow field and characteristic of pressure fluctuation in the cold-leg by using a 1/7-scale model. Since the triple elbow model was made by adding the 3rd elbow to the dual elbow model previously tested in the reference [9,10], there is no change between the flow condition from the first to second elbow in the triple elbow system and the double elbow system. Therefore, the flow condition in and downstream of the 3rd elbow was scrutinized and evaluated in this study.

Experimental procedure

In the experiment, two-dimensional PIV measurement was conducted in order to visualize and evaluate the flow field by using transparent piping, and wall pressure measurement for the evaluation of pressure fluctuation characteristic. (Fig. 1) shows a diagram of the 1/7-scale experimental loop used in the experiment. The piping is made mainly of Stainless Steel (SS) with a diameter of $D = 126.6$ mm. Test section, the triple elbow system, is made of acrylic for PIV measurement and SS for pressure measurement. A straight entrance section of 28 *D* in length was installed upstream of the test section to obtain fully developed turbulent pipe flow as the inlet condition for the test section. The working fluid was tap water heated up 45 °C, and the mean velocity in the piping was measured by an ultrasonic flowmeter installed on the outside of the pipe wall of the entrance region. The geometric configuration of the test section is shown in (Fig. 2). It has three 90° elbows with the curvature ratio of 1.0. The first and second elbow is connected three-dimensionally via a short straight pipe with a length of 0.57 *D* while the third elbow is connected to the second elbow via a long straight pipe of 6.4 *D* in length so as to line in the same plane as that including the piping axis of the second elbow.

For the PIV measurement, nylon particles of 20 μm in diameter and of 1.02 g/cm^3 in density were seeded in the flowing water. Particle images were shot by a high-speed CCD camera (Photron FASTCAM) with spatial and gray-scale resolutions of 1024 × 1024 pixels and 10 bits, respectively, with the aid of pulsed laser sheets emitted by a diode laser (Oxford Lasers HSI5000) with a wavelength of 808 nm. Every one shooting, 1024 velocity vector data of the flowing water were calculated from the images by analysis software, VidPIV, at the rate of 30 data per second. Two kinds of visualization area were selected as shown in (Fig. 3), and they are hereafter referred to as "flow cross-section" and "pipe cross-section". The flow cross-section is parallel to the mean flow direction and contains the pipe center axis while the pipe cross-section is perpendicular to the axis. In the pressure measurement experiment, pressures on the inside of the pipe were measured by fiber-optic pressure sensors (FISO Technology FOP-M). The measurement locations and schematic illustration of the sensor installation are shown in (Figs. 4 and 5), respectively. In (Fig. 4), the symbol A to M represents the location of pipe cross-sections where the sensors were installed. On each pipe cross-section, 4 to 10 sensors were installed in the circumferential direction. Many sensors were