Unsteady elbow pipe flow to develop a flow-induced vibration evaluation methodology for JSFR

Hidemasa YAMANO*a
M. Tanaka a, A. Ono a, T. Murakami b, Y. Iwamoto c, K. Yuki d, H. Sago e, S. Hayakawa f

*a Japan Atomic Energy Agency (JAEA)
*b Central Research Institute of Electric Power Industry (CRIEPI)
*c Ehime University
*d Tohoku University
*e Mitsubishi Heavy Industries, Ltd. (MHI)
*f Mitsubishi FBR Systems, Inc. (MFBR)
Contents

1. Introduction
   ✓ JSFR design features & Objective

2. Approach to Flow-Induced Vibration (FIV) Evaluation
   ✓ Previous experiments
   ✓ FIV evaluation methodology for JSFR
   ✓ Approach to the methodology development for JSFR

3. Hot-leg pipe experiments
   ✓ Effect of pipe scale
   ✓ Effect of inlet swirl flow
   ✓ Effect of elbow curvature

4. Cold-leg pipe experiments
   ✓ Effect of multiple elbows

5. Computer simulation of unsteady pipe flow
   ✓ U-RANS approach
   ✓ LES approach
   ✓ DES approach

6. Conclusions
1. Introduction

## Major piping specifications

- **Two-loop system**: High flow rate per loop
- **Designed in 2007**: Japanese prototype
- **A large-diameter thin pipe**: Remarkably high coolant velocity
- **Flow-induced vibration (FIV) issue**

<table>
<thead>
<tr>
<th></th>
<th>JSFR</th>
<th>Monju</th>
<th>PWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric power</td>
<td>1500MWe</td>
<td>750MWe</td>
<td>500MWe</td>
</tr>
<tr>
<td>Number of loops</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Diameter (HL)</td>
<td>1.27 m</td>
<td>0.91 m</td>
<td>0.76 m</td>
</tr>
<tr>
<td>Thickness (HL)</td>
<td>15.9 mm</td>
<td>12.7 mm</td>
<td>12.7 mm</td>
</tr>
<tr>
<td>Velocity (HL)</td>
<td>9.1 m/s</td>
<td>8.8 m/s</td>
<td>8.6 m/s</td>
</tr>
<tr>
<td>Temperature (HL)</td>
<td>550°C</td>
<td>550°C</td>
<td>550°C</td>
</tr>
<tr>
<td>Re number (HL)</td>
<td>4.2 x 10^7</td>
<td>2.9 x 10^7</td>
<td>2.3 x 10^7</td>
</tr>
<tr>
<td>Diameter (CL)</td>
<td>0.86 m</td>
<td>0.71 m</td>
<td>0.56 m</td>
</tr>
<tr>
<td>Thickness (CL)</td>
<td>17.5 mm</td>
<td>17.5 mm</td>
<td>17.5 mm</td>
</tr>
<tr>
<td>Velocity (CL)</td>
<td>9.7 m/s</td>
<td>7.3 m/s</td>
<td>8.1 m/s</td>
</tr>
<tr>
<td>Temperature (CL)</td>
<td>395°C</td>
<td>395°C</td>
<td>395°C</td>
</tr>
<tr>
<td>Re number (CL)</td>
<td>2.5 x 10^7</td>
<td>1.5 x 10^7</td>
<td>1.3 x 10^7</td>
</tr>
</tbody>
</table>

1. Introduction

Piping configuration

<table>
<thead>
<tr>
<th>Hot-leg pipe of primary circuit</th>
<th>“MONJU”</th>
<th>JSFR (Designed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 304 stainless steel</td>
<td>High-Cr steel</td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>39m</td>
<td>12m</td>
</tr>
<tr>
<td>No. of elbows</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>Long elbow</td>
<td>Short elbow</td>
<td></td>
</tr>
</tbody>
</table>

Flow dynamics in the pipe should be investigated.

Flow separation behavior that would be major source of the pressure fluctuations

Objective and FIV project team

Objective

- Development of a flow-induced vibration methodology applied to JSFR
  - Serves us to confirm feasibility of the JSFR piping design
- In this paper, Investigation of unsteady flow characteristics
  - Mainly in the hot-leg piping at the first step through various exp. & cal. studies

FIV project team

Hot-leg experiments

- 1/10 scale: Ehime Univ. (2007~)
- 1/8 scale: JAEA (2008~)

Cold-leg experiments

- 1/4 scale: MHI (2009~)
- 1/7 scale: Tohoku Univ. (2007~)

Simulation

- LES approach: CRIEPI (2007~)
- DES approach: MFBR (2008~)

1. Introduction

3.1 Effect of pipe scale
3.2 Effect of swirl flow at the inlet
3.3 Effect of elbow curvature
4.1 Effect of multiple elbows
5.1 STAR-CD
5.2 SMART-fem
5.3 FLUENT

Will be explained later
2. Approach to FIV evaluation methodology development

1/3 scale water exp. for the hot-leg pipe

-Experimental facility-

1) Visualization exp. (acrylic resin)*
   - Flow Pattern
   - Velocity Profile
   - Pressure Loss of Elbow
   - Pressure Fluctuation
     (Exciting Force to Pipe) with 124 sensors

2) Vibration exp. (stainless steel)
   - Natural Frequency/Mode
   - Vibration Response
     (Stress, Amplitude)

Model Elbow (I.D.: 41cm)
(short elbow: R/D=1)

Intermediate tank
Inlet tank

- Mean Velocity: 0.8-9.2 m/s
- Water Temp.: ~15°C / 60°C
- Re Number: 2×10^5-8×10^6

Ref.) H. Yamano, et al., ICAPP08-8231, Anaheim, USA, June 8-12, 2008.

**Basic extrapolation logic to the JSFR Condition**

- Approach to the JSFR piping evaluation
  - To extrapolate the experimental evidence to the JSFR condition,
    - The present study takes an approach that investigates the dependency on the Reynolds number (i.e., velocity, viscosity and scale).

- Dependency on the Reynolds number
  - 1/3 scale exp. \((Re=3 \times 10^5 \text{ to } 8 \times 10^6)\)  \([\text{JSFR: } \sim 4 \times 10^7]\)
    - Velocity (0.8 to 9.2 m/s): No significant effect  \([\text{JSFR: } \sim 9.2 \text{m/s}]\)
    - Viscosity (0.47 to 1.1 mm\(^2\)/s): No significant effect  \([\text{JSFR: } \sim 0.27 \text{mm}^2/\text{s at } 550^\circ\text{C Na}]\)
  - 1/10 scale exp. \((Re=3.2 \times 10^5)\)
    - Pipe scale (0.13 to 0.42 m): ???

- Independent of velocity and viscosity
Experimental programs

### Major Elements for the JSFR Piping Evaluation

#### Hot-leg pipe
- Significant:
  - Flow separation from the elbow (single elbow),
  - Inlet condition (flow in the reactor upper plenum),
  - Outlet condition (flow at the inlet of IHX),
  - Reactor upper plenum flow outside the pipe.
- Less Significant:

#### Cold-leg pipe
- Significant:
  - Flow separation from the elbow (multiple elbows),
  - Inlet condition (flow at the outlet of IHX),
  - Outlet condition (ejection into RV lower plenum),
  - Reactor upper plenum flow outside the pipe.
- Less Significant:

---

### Hot-leg pipe experimental program

- **Objective:** Re number effect
- **Inlet effect:**
  - Velocity & Viscosity
  - RV+HL+IHX
- **Role:**
  - 1/10 scale
  - Rectified uniform
  - Separate-effect exp.
  - Integral exp.
- **Scale:**
  - 1/10 scale
  - 1/3 scale
  - 1/1 scale

### Cold-leg pipe experimental program

- **Scale effect:**
  - Multiple elbow effect
- **Inlet condition:**
  - Single elbow
  - Double elbow
  - Triple elbow
- **Role:**
  - 1/15 scale
  - 1/7 scale
  - Integral exp.
  - JSFR
- **Scale:**
  - 1/15 scale
  - 1/7 scale
  - 1/4 scale
  - 1/1 scale
3. Hot-leg pipe experiments

1/10 scale water exp. for the hot-leg pipe -Effect of pipe scale-

Re=3.2×10^5 (~2m/s)

St≈0.5 (9Hz)

Re=3.2×10^5 (~2m/s)

No effect of pipe scale

No dependency on Re number

These exp. evidences give the prospect that we can extrapolate to JSFR
1/3 scale water exp. for the hot-leg pipe
-Effect of inlet swirl flow on flow separation-

9.2 m/s -> Re: $3.6 \times 10^6$

15% of swirl flow velocity ratio

Slightly deformed by the swirl flow
3. Hot-leg pipe experiments

1/3 scale water exp. for the hot-leg pipe
-Effect of swirl flow on pressure fluctuation PSDs-

Averaged PSDs in each region

No clear difference!

- Less significant effect of swirl flow

9.2 m/s --> Re: 3.6x10^6
3. Hot-leg pipe experiments

1/8 scale water exp. for the hot-leg pipe

-Effect of elbow curvature-

- Short-elbow (3m/s)
- Long-elbow (3m/s)

Reattachment point (x/D=0.27, Short-Elbow)

The reverse flow is observed in the short-elbow. It indicates the occurrence of the flow separation.

The axial velocities near the inside wall were **locally accelerated** in both cases.

The difference of elbow curvature influenced on the formation of the separation region and the high turbulence intensity region.
4. Cold-leg pipe experiments

1/15 scale water exp. for the cold-leg pipe -Effect of multiple elbows-

(a) 0.18D downstream from 1st elbow exit

- High-velocity distorted flow
- Low-velocity unsteady flow

(b) 0.2D downstream from 2nd elbow exit

- Swirling Flow

The high-velocity flow flows into the separation region by turns.

Two kinds vortices coexist in the separation region, but the vortices are growing up toward the downstream in the low velocity region.

A swirling flow exists in the half region of the pipe and the maximum average velocity is 0.42m/s, which reaches approximately 54% of the mean flow velocity.

The swirling flow structure in the 2nd elbow is formed by the deflected flow and the geometry effect of the 2nd elbow.
5. Computer Simulation of Unsteady Pipe Flow

**U-RANS approach**

-Validation using 1/3 scale water exp.-

Radial profiles of time-averaged velocity component under the inlet uniform rectified flow condition

**Analytical conditions**

- Temporal scheme: 3-time-level implicit
- Momentum equations: MARS(1.0)
- Dissipation equation: Upwind
- Reynolds stress equations: Upwind
- Axial turbulence: 5% (based on exp.)

**STAR-CD code**

Ver.4.06

305,172 meshes

Re=3.6 × 10^6 (9.2m/s)

Good simulation of experimental velocity profile
Peak frequency is reasonably simulated. 
Applicable to unsteady elbow flow.

The plotted PSDs removed simultaneous pressure fluctuations with same phase, caused by the static pressure fluctuation specific to the experimental loop and the natural frequency of the facility.

Collision of alternatively supplied secondary flows

Pressure fluctuation PSDs in Re=$3.6 \times 10^6$ (9.2m/s) under the inlet uniform rectified flow condition.
5. Computer Simulation of Unsteady Pipe Flow

Les approach

-Validation using 1/3 scale water exp.-

Radial profiles of time-averaged velocity component under the inlet uniform rectified flow condition

Global trend of experimental velocity profile

Model improvement necessary

Flow resistance model

Analytical conditions

• Smagorinsky model

SMART-fem code

Re=1.2 × 10^6 (3 m/s)

Normalized velocity (local/mean)

Dimensionless length (z/D)

Separation

0.18D

0.62D

1.12D

Shorten by half

62 div.

95 div.

32 div.
5. Computer Simulation of Unsteady Pipe Flow

**DES approach**

- **Validation using 1/3 scale water exp.**-

Radial profiles of time-averaged velocity component under the inlet uniform rectified flow condition

**FLUENT Ver.6.3**

- Hybrid approach (Detached Eddy Sim.)
  - LES: Smagorinsky model
  - RANS: Spalart Allmaras model

**FLUENT**

- 40 meshes
- 90 meshes
- 150 meshes
- 120 meshes

**Re=3.6 \times 10^6 (9.2 m/s)**

**Good simulation of exp. velocity profile near wall**

**Applicability should be improved.**
Conclusions

1. The FIV evaluation methodology is being developed for the primary piping in JSFR.

2. Related experimental and simulation activities were performed:
   - The 1/10-scale experiment for the hot-leg piping showed
     - No significant effect of the pipe scale.
   - The 1/3-scale experiment for the hot-leg piping revealed
     - No significant effect of the inlet swirl flow.
   - The 1/8-scale experiment for the hot-leg piping observed
     - No clear separation in the long-elbow case.
   - 1/15-scale experiment with double elbows clarified
     - Flow in the first elbow influenced a flow separation behavior in the second elbow.
   - Numerical simulation including the U-RANS, LES and DES approaches
     - Their applicability were confirmed by comparison to the 1/3-scale hot-leg pipe exp.
   - The numerical simulation indicated
     - The U-RANS approach is applicable to different Reynolds number condition by comparing to the hot-leg piping experiments.

3. Future plan
   - The flow simulation results could be provided to input data for the fluid-structural vibration coupling evaluation of the piping.
   - The R&D results would be given to development of a technical standard of the flow-induced vibration methodology applied to the JSFR piping.
A Conceptual Design Study of An Advanced Sodium-cooled Fast Reactor, “JSFR” (JSFR: Japan Sodium-cooled Fast Reactor)

In the “Fast Reactor Cycle Technology Development (FaCT)” project

- Two-loop cooling system
to enhance scale merit, thereby reduction of construction cost of plant.

4-loop vs 2-loop

Amount of commodity of NSSS: 16% less

Experiment-based methodology

-Preliminary evaluation of the JSFR piping-

Reactor evaluation is possible by applying the assumption of analogy. Evaluated using simplified PSDs, which enveloped all the measured PSDs, for conservativeness.

The max. stress fulfilled the design criterion (49MPa at 550°C) of high-cycle structural fatigue of pipe material.

⇒ The feasibility of the JSFR hot-leg pipe structural integrity was confirmed.

Ref.) H. Yamano, et al., ICAPP08-8231, Anaheim, USA, June 8-12, 2008.