International Conference on Fast Reactors and Related Fuel Cycles (FR09), Kyoto, Japan, Dec. 7-11, 2009.

JAEA

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

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Contents

1. Introduction

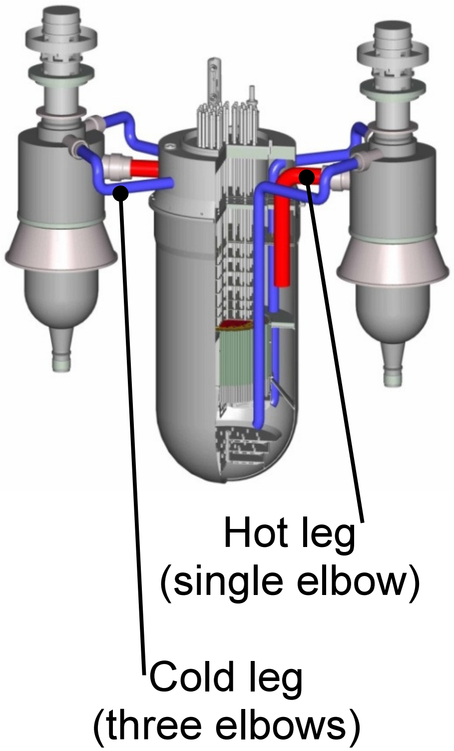
Major piping specifications

Two-loop system
→ High flow rate per loop

Designed in 2007

Japanese prototype

		JSFR			Monju	PWR
Electric power		1500MWe	750MWe	500MWe	280MWe	1160MWe
Number of loops		2	2	2	3	4
HL	Diameter	1.27 m	0.91 m	0.76 m	0.81 m	0.74 m
	Thickness	15.9 mm	12.7 mm	12.7 mm	11.1 mm	73.0 mm
	Velocity	9.1 m/s	8.8 m/s	8.6 m/s	3.5 m/s	14.5 m/s
	Temperature	550°C	550°C	550°C	529°C	325°C
	Re number	4.2×10^7	2.9×10^7	2.3×10^7	1.0×10^7	9.1×10^7
CL	Diameter	0.86 m	0.71 m	0.56 m	0.61 m	0.70 m
	Thickness	17.5 mm	17.5 mm	17.5 mm	9.5 mm	69.0 mm
	Velocity	9.7 m/s	7.3 m/s	8.1 m/s	6.1 m/s	14.3 m/s
	Temperature	395°C	395°C	395°C	397°C	289°C
	Re number	2.5×10^7	1.5×10^7	1.3×10^7	1.1×10^7	8.1×10^7



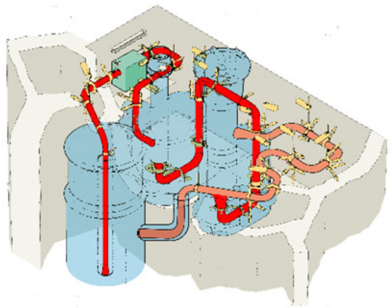
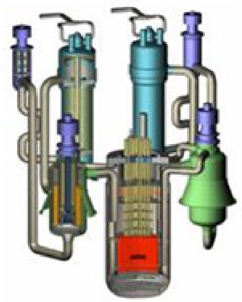
- ☐ A large-diameter thin pipe
- ☐ Remarkably high coolant velocity

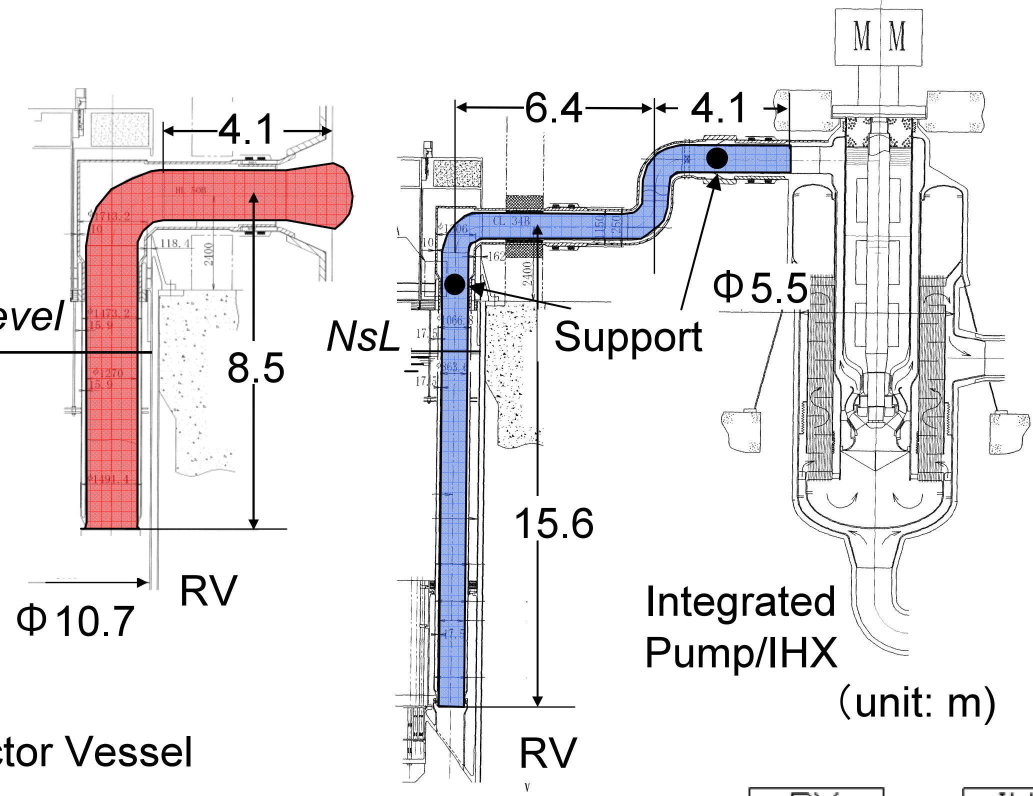
→ Flow-induced vibration (FIV) issue

Ref.) H. Yamano, et al., NURETH-13, N13P1186, Kanazawa, Japan, Sep. 27 - Oct. 2, 2009.

1. Introduction

Piping configuration

Hot-leg pipe of primary circuit		
	"MONJU"	JSFR (Designed)
	Type 304 stainless steel	High-Cr steel
		
Length	39m	12m
No. of elbows	9	1
	Long elbow	Short elbow

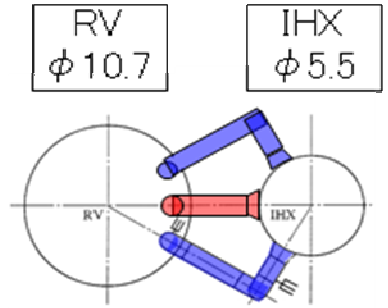


RV: Reactor Vessel
IHX: Intermediate Heat eXchanger

Flow dynamics in the pipe should be investigated.

⇩

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



Ref.) H. Yamano, et al., NURETH-13, N13P1186, Kanazawa, Japan, Sep. 27 - Oct. 2, 2009.

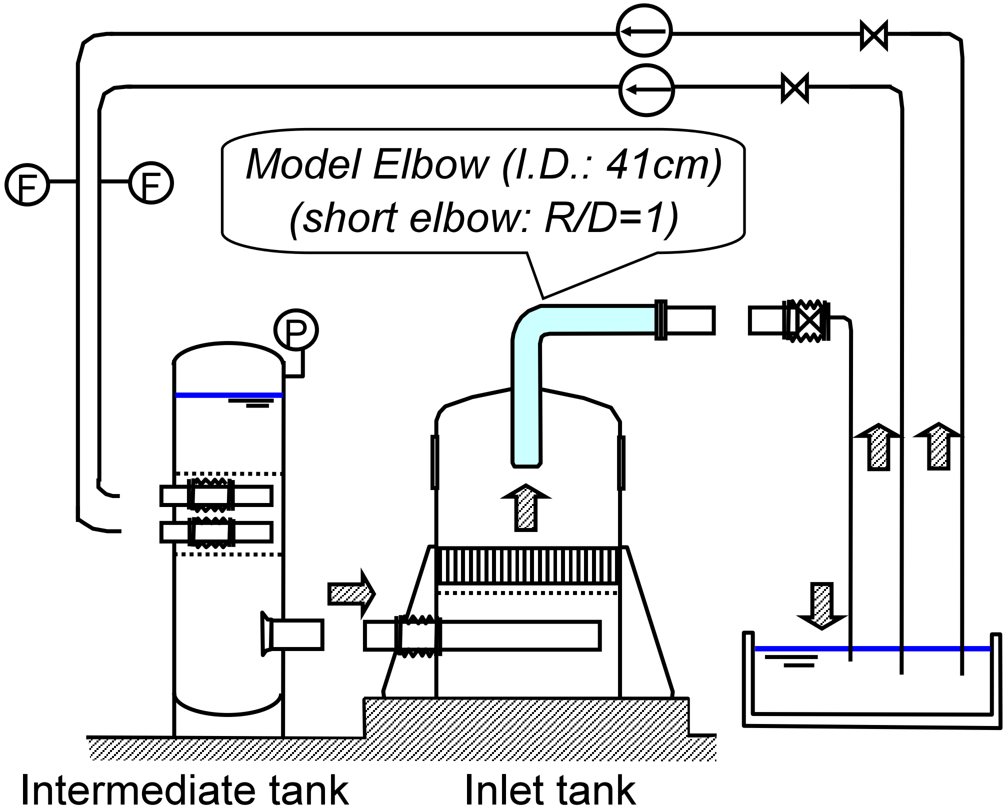
Objective and FIV project team

- 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~) → 3.1 Effect of pipe scale
    - 1/3 scale: MHI (2003~) → 3.2 Effect of swirl flow at the inlet
    - 1/8 scale: JAEA (2008~) → 3.3 Effect of elbow curvature
  - Cold-leg experiments
    - 1/4 scale: MHI (2009~)
    - 1/7 scale: Tohoku Univ. (2007~) → 4.1 Effect of multiple elbows
  - Simulation
    - U-RANS approach: JAEA (2007~) → 5.1 STAR-CD
    - LES approach: CRIEPI (2007~) → 5.2 SMART-fem
    - DES approach: : MFBR (2008~) → 5.3 FLUENT

Will be explained later

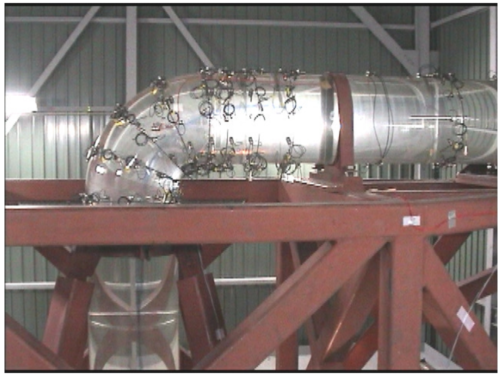
2. Approach to FIV evaluation methodology development

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



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

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)

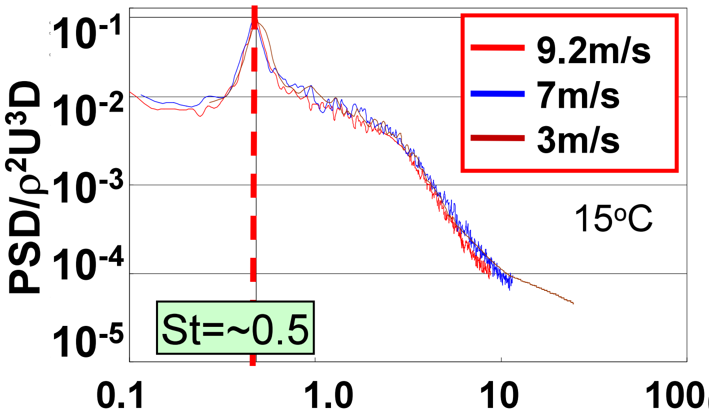
- Natural Frequency/Mode
- Vibration Response (Stress, Amplitude)

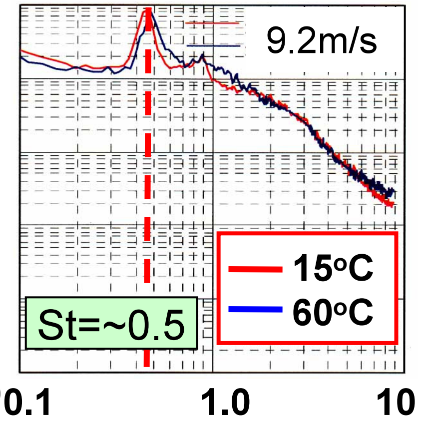
* T. Shiraishi, et al., *J. Fluids Engineering*, **128**, 1063-1073 (Sep. 2006).

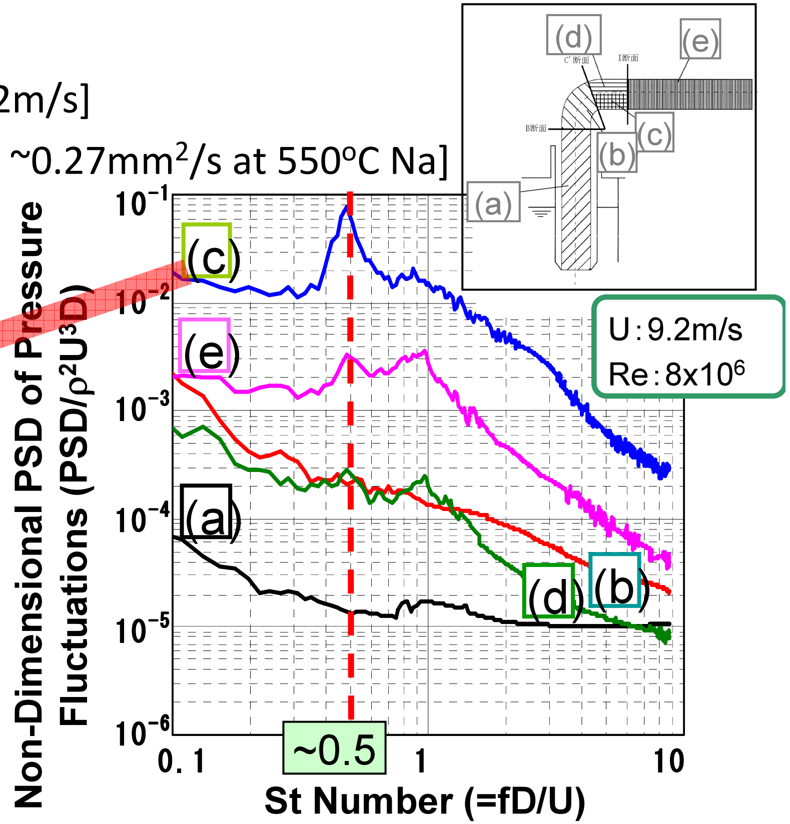
Ref.) H. Yamano, et al., ICAPP08-8231, Anaheim, USA, June 8-12, 2008.

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 (1/5)
  - 1/3 scale exp. (Re=3 × 10^5 to 8 × 10^6) [JSFR: ~4 × 10^7]
    - Velocity (0.8 to 9.2 m/s): No significant effect [JSFR: ~9.2m/s]
    - Viscosity (0.47 to 1.1mm^2/s): No significant effect [JSFR: ~0.27mm^2/s at 550°C Na]
  - 1/10 scale exp. (Re=3.2 × 10^5)
    - Pipe scale (0.13 to 0.42 m): ???







→Independent of velocity and viscosity

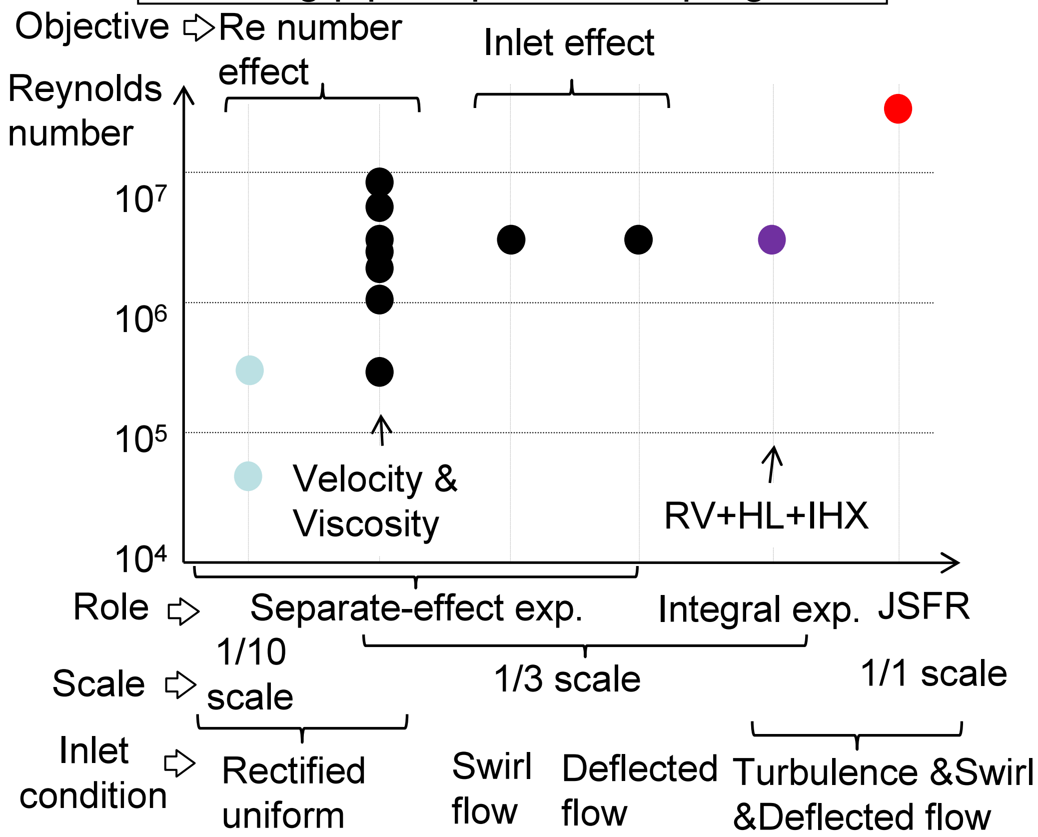
2. Approach to FIV evaluation methodology development

Experimental programs

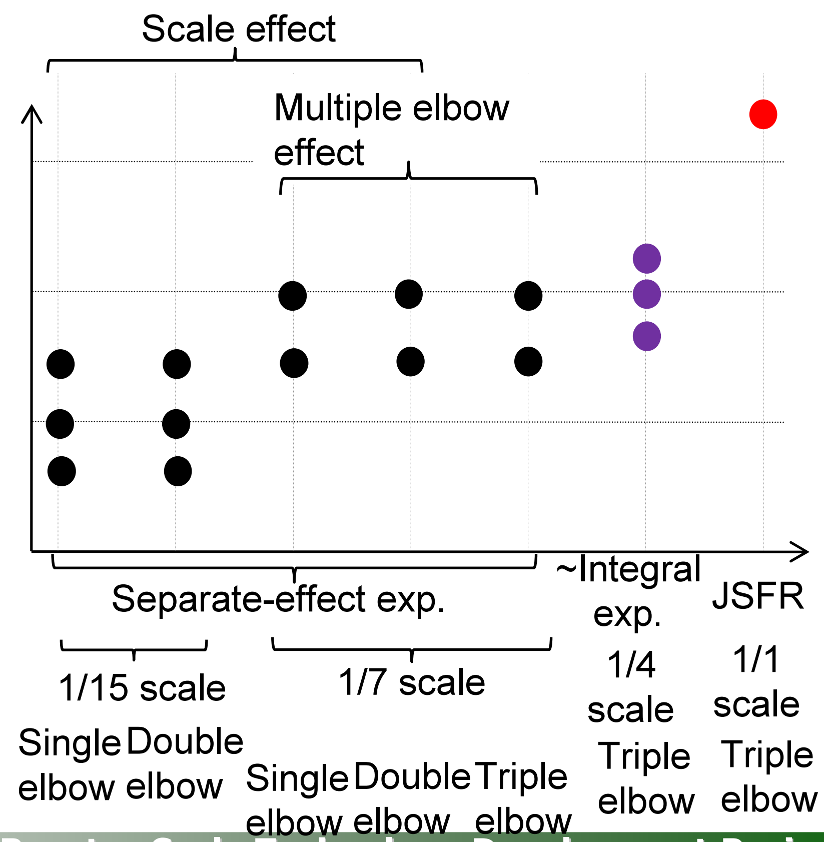
Major Elements for the JSFR Piping Evaluation

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

Hot-leg pipe experimental program

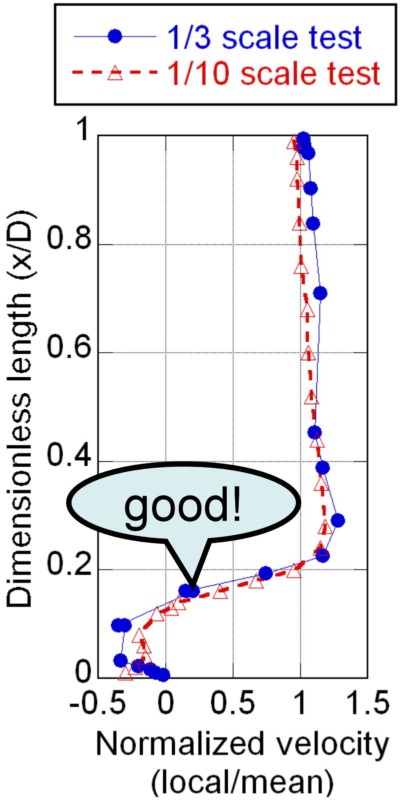


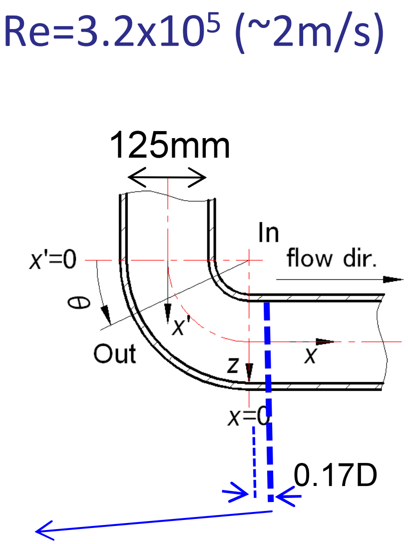
Cold-leg pipe experimental program

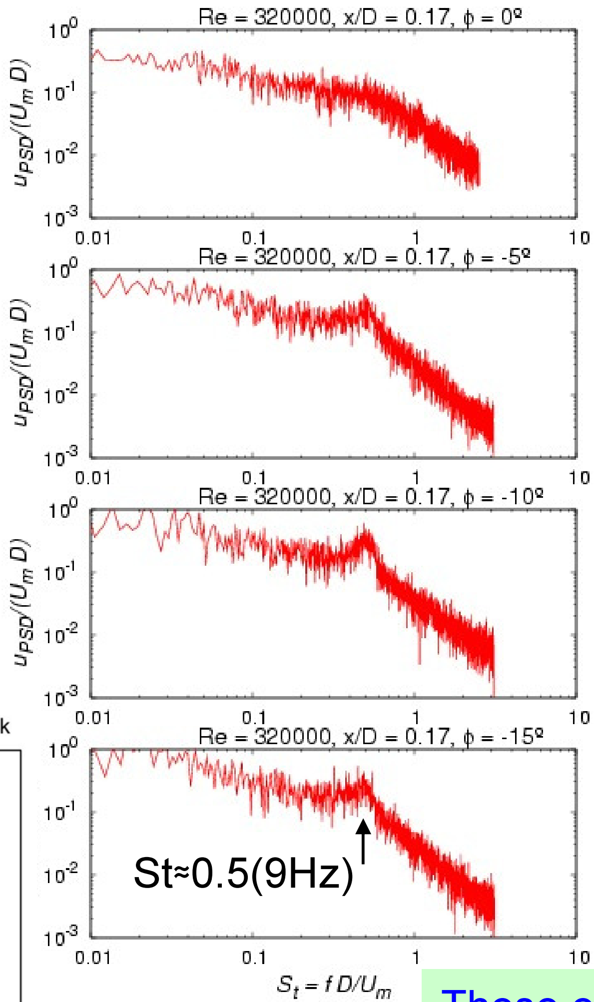


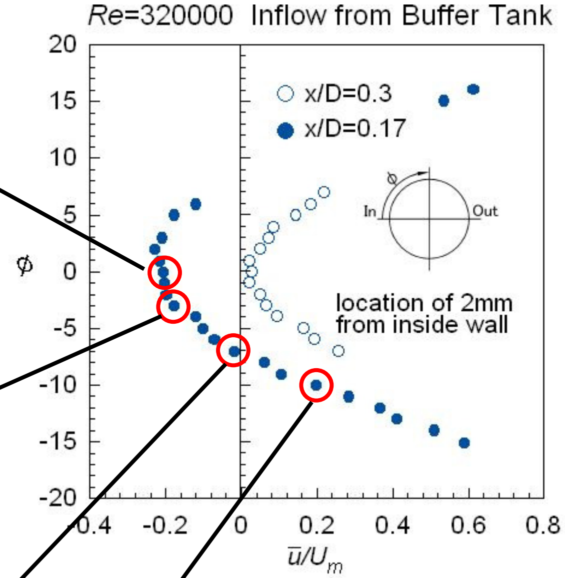
3. Hot-leg pipe experiments

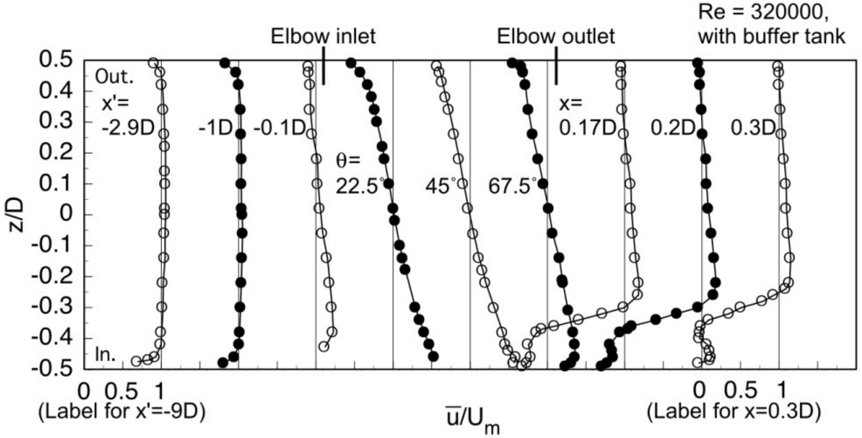
1/10 scale water exp. for the hot-leg pipe
-Effect of pipe scale-











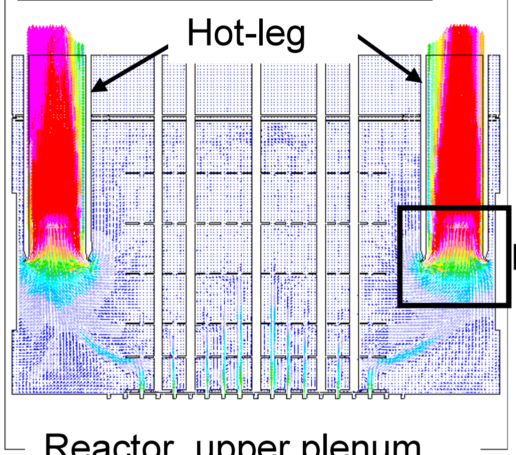
➔No effect of pipe scale

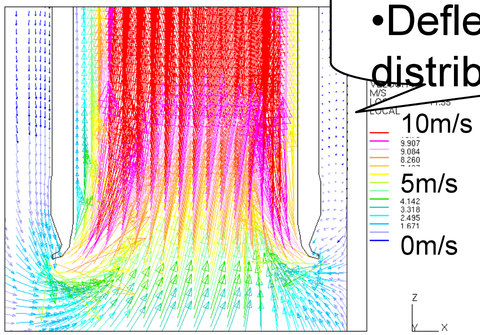
No dependency on Re number

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-

Steady-state cal.

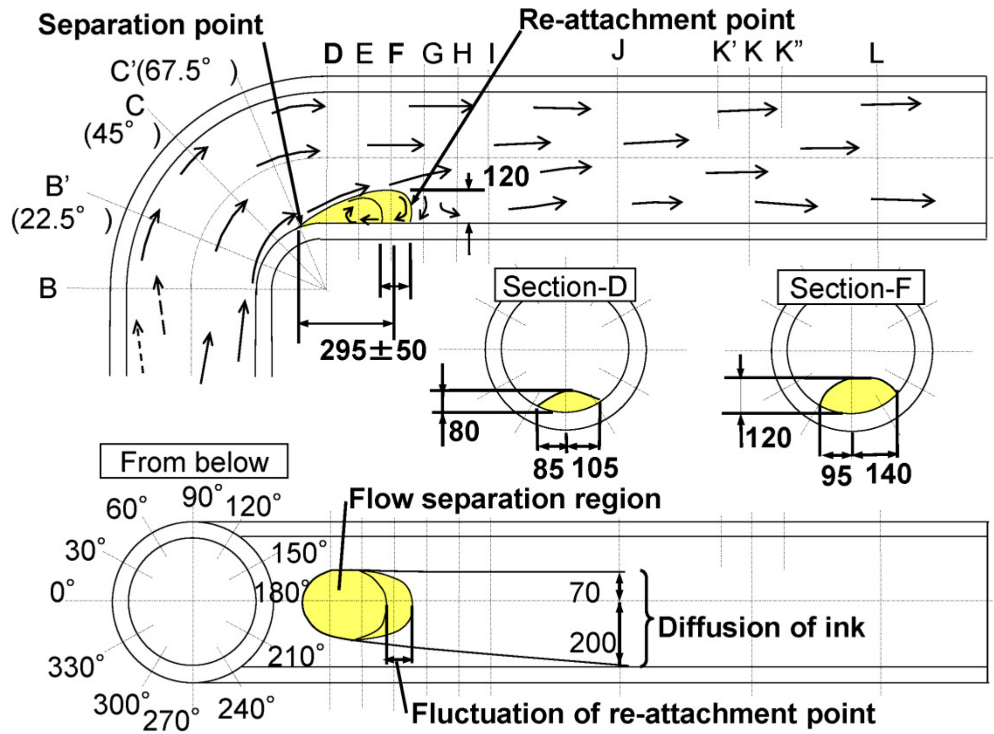


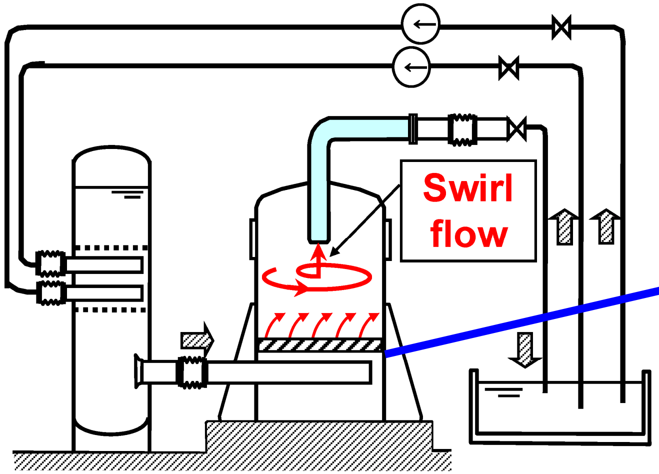


- Swirl flow
- Deflected flow distribution

9.2m/s --> Re: 3.6×10^6

15% of swirl flow velocity ratio





→Slightly deformed by the swirl flow

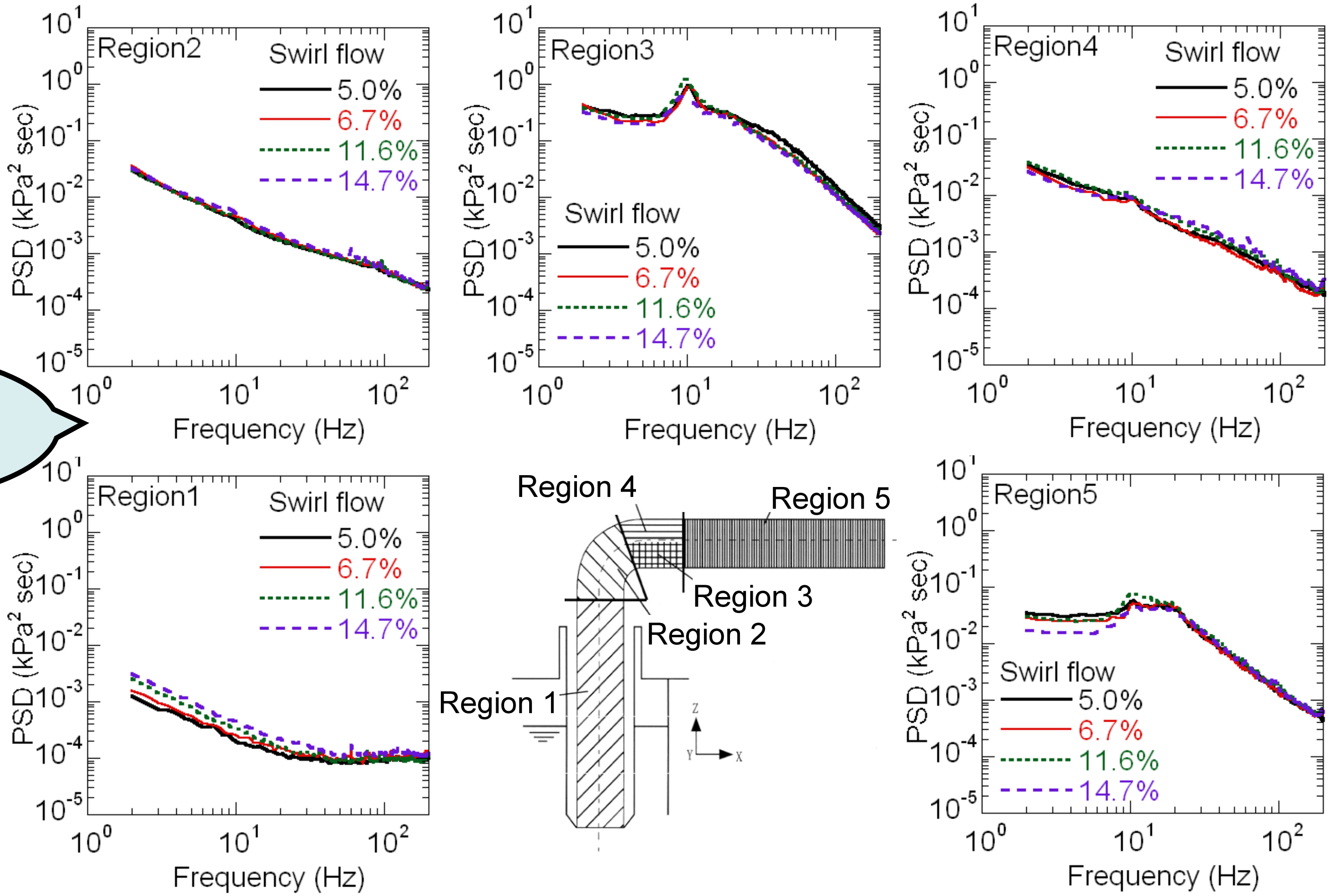
1/3 scale water exp. for the hot-leg pipe

-Effect of swirl flow on pressure fluctuation PSDs-

9.2m/s --> Re: 3.6×10^6

Averaged PSDs in each region

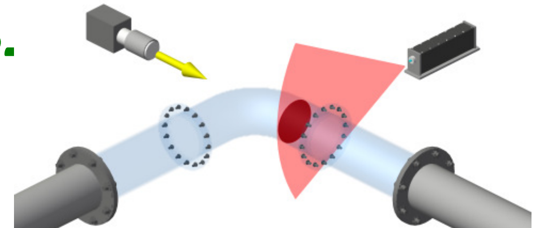
No clear difference!

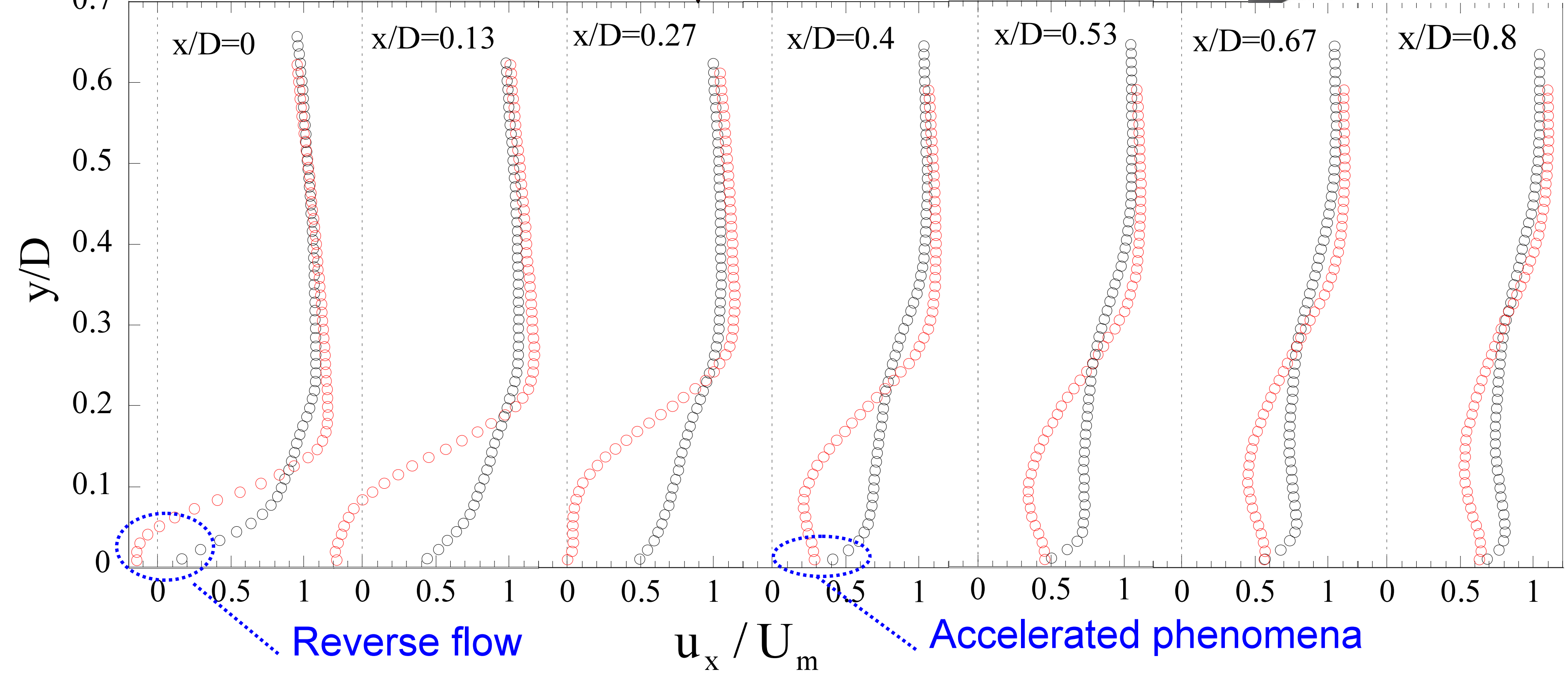


➔Less significant effect of swirl flow

3. Hot-leg pipe experiments

1/8 scale water exp. for the hot-leg pipe -Effect of elbow curvature-

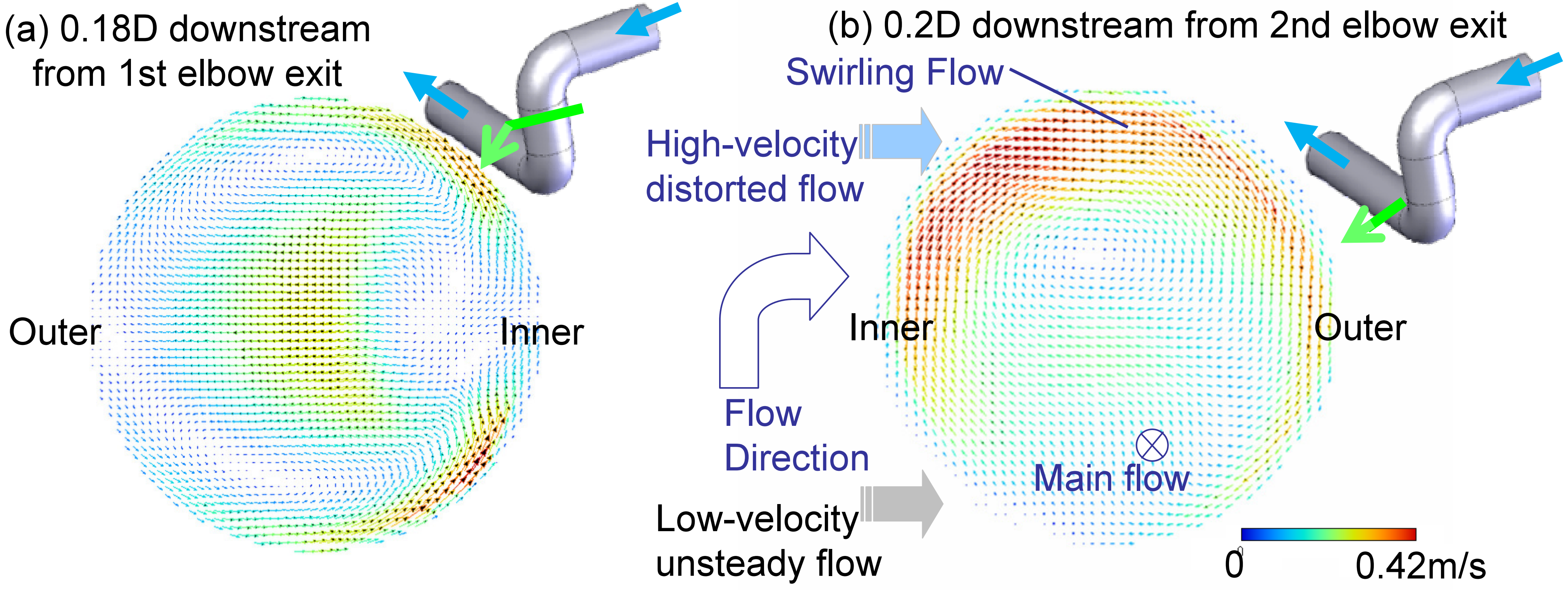




- The reverse flow is observed in the short-elbow. It indicates the occurrence of the flow separation.
- The axial velocities near the inside wall were locally accelerated in both cases.
- The difference of elbow curvature influenced on the formation of the separation region and the high turbulence intensity region

4. Cold-leg pipe experiments

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

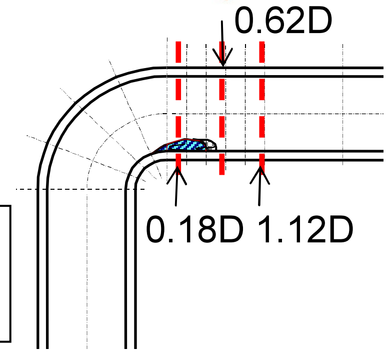


- The high-velocity flow flows into the separation region by turns.
- Two kinds vortices coexist in the separation region, but the vortices are growing up toward the downstream in the low velocity region.

- 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.

U-RANS approach

-Validation using 1/3 scale water exp.-

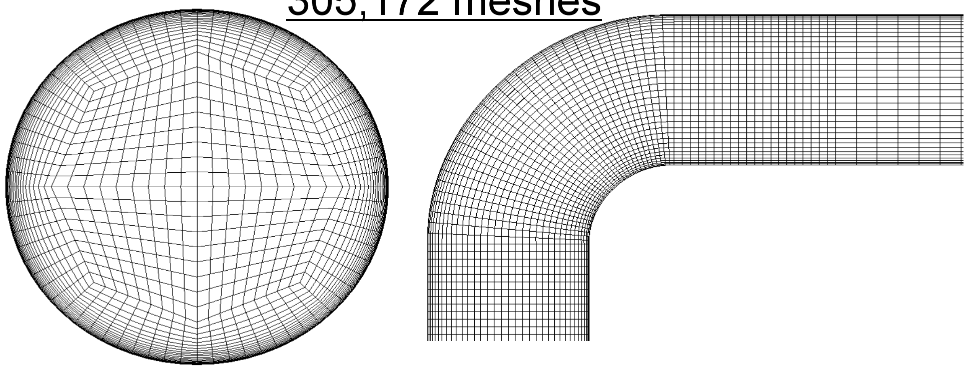


STAR-CD code
Ver.4.06

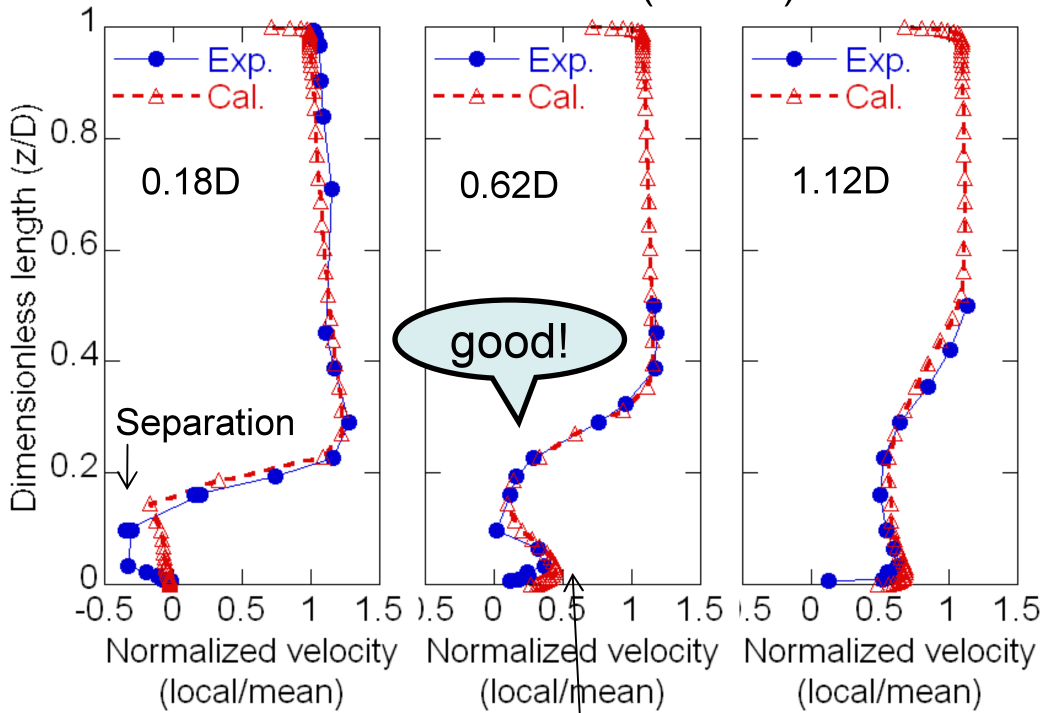
Radial profiles of time-averaged velocity component under the inlet uniform rectified flow condition

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.)

305,172 meshes



Re=3.6×10^6 (9.2m/s)



by the collision of the circumferential flows in the secondary flow pattern.

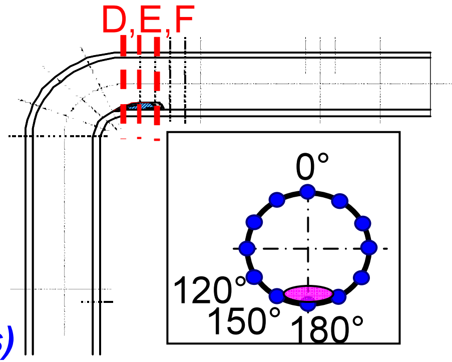
➔Good simulation of experimental velocity profile

5. Computer Simulation of Unsteady Pipe Flow

U-RANS approach

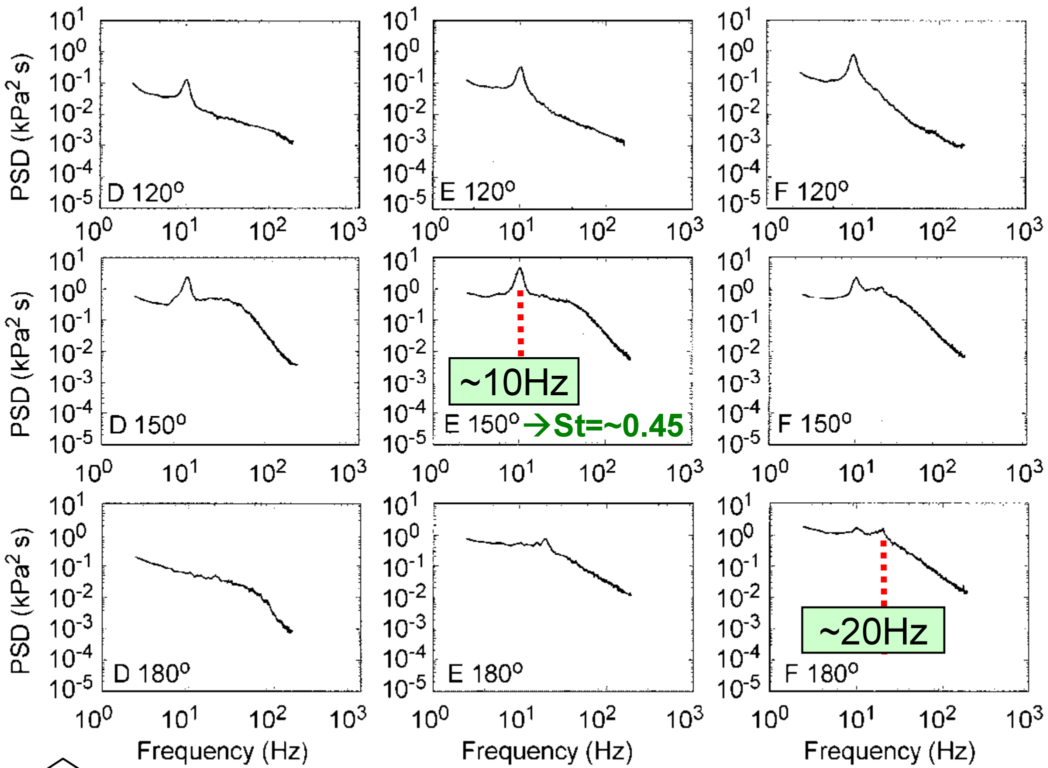
-Validation using 1/3 scale water exp.-

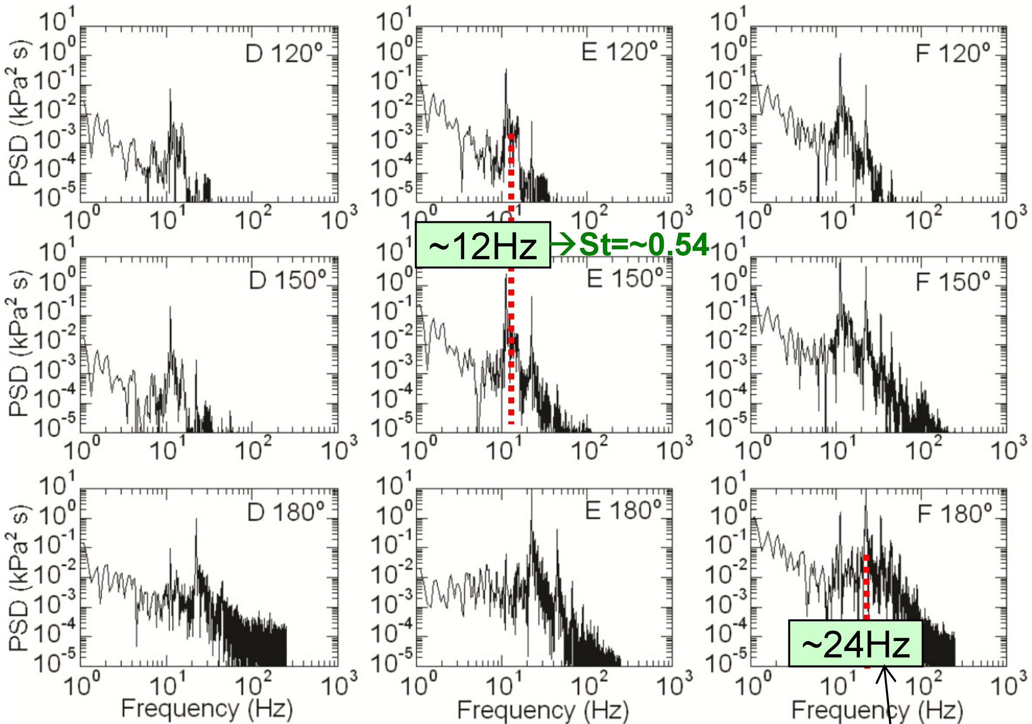
Pressure fluctuation PSDs in Re=3.6×10⁶ (9.2m/s) under the inlet uniform rectified flow condition.



Exp. (using 1kHz data for 180s)

Cal. (using 1024 data for 10s)





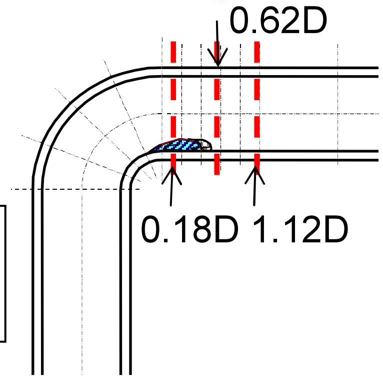
Collision of alternatively supplied secondary flows

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.

→Peak frequency is reasonably simulated.
→Applicable to unsteady elbow flow

5. Computer Simulation of Unsteady Pipe Flow

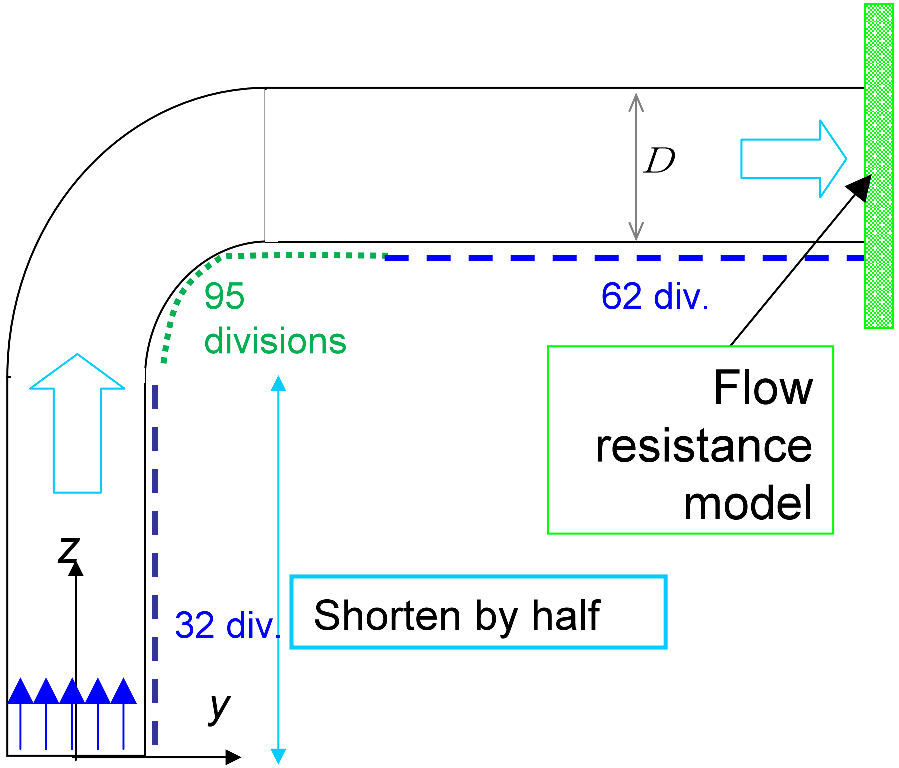
LES approach
-Validation using 1/3 scale water exp.-



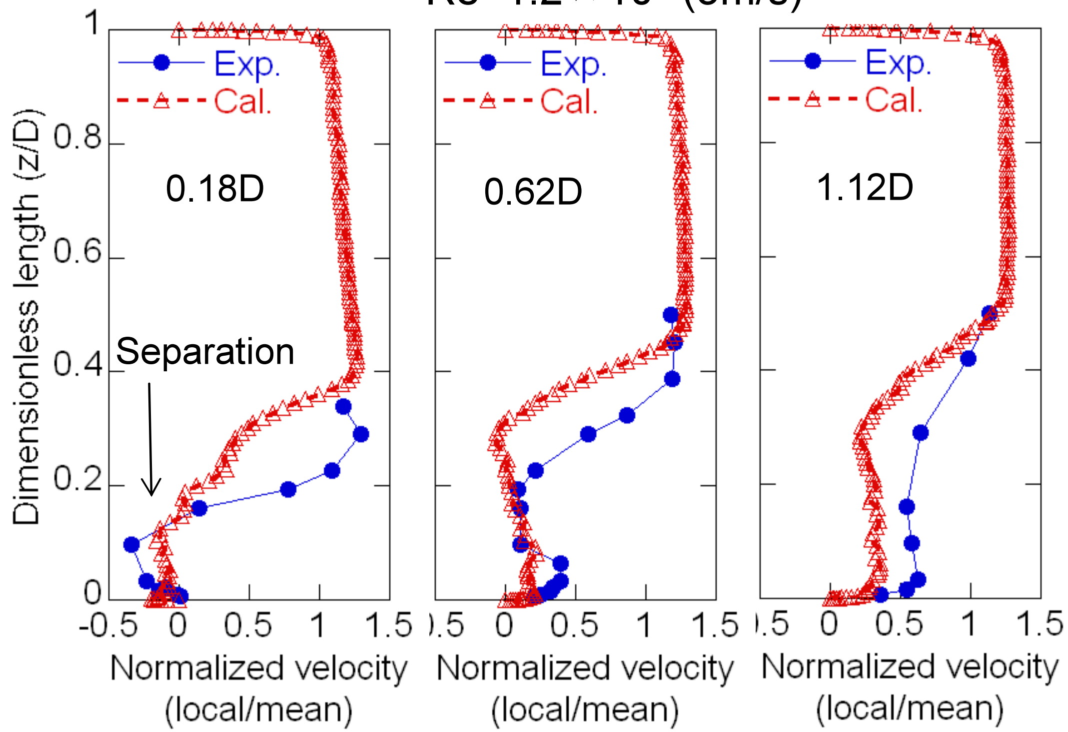
SMART-fem code

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

Analytical conditions
•Smagorinsky model

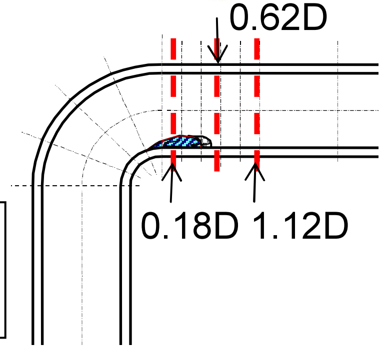


Re=1.2 × 10^6 (3m/s)



➔Global trend of experimental velocity profile
➔Model improvement necessary

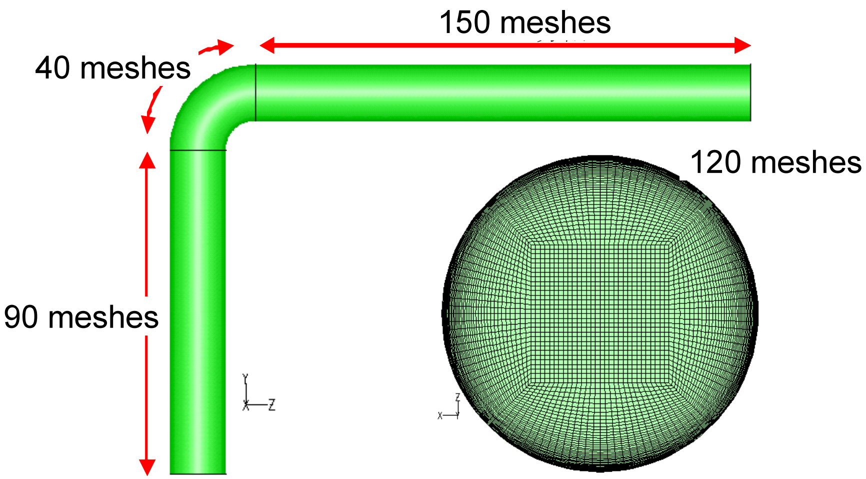
DES approach
-Validation using 1/3 scale water exp.-

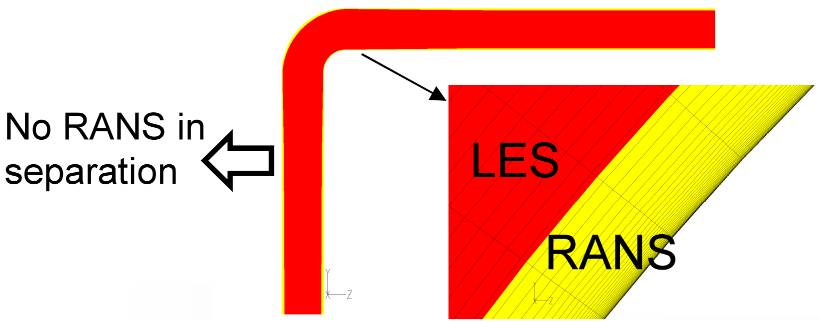


Radial profiles of time-averaged velocity component under the inlet uniform rectified flow condition

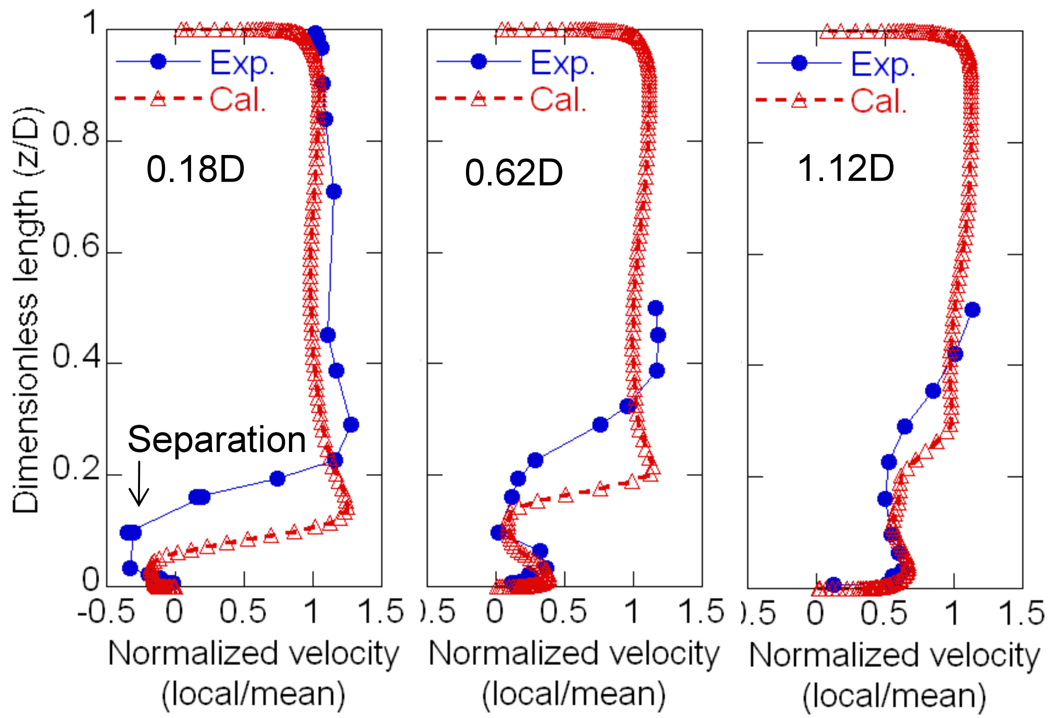
FLUENT Ver.6.3

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





Re=3.6×10^6 (9.2m/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.***

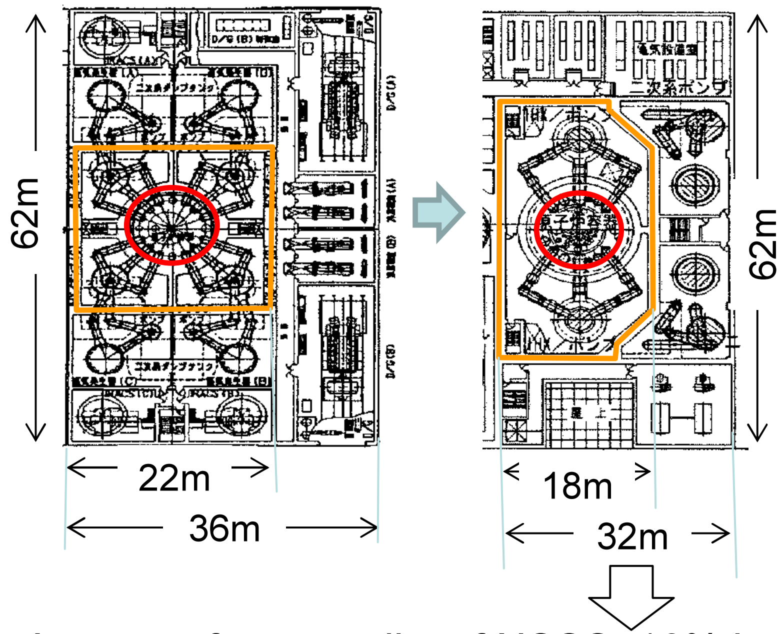
A Conceptual Design Study of An Advanced Sodium-cooled Fast Reactor, "JSFR" (JSFR: Japan Sodium-cooled Fast Reactor)

In the "Fast Reactor Cycle Technology Development (FaCT)" project

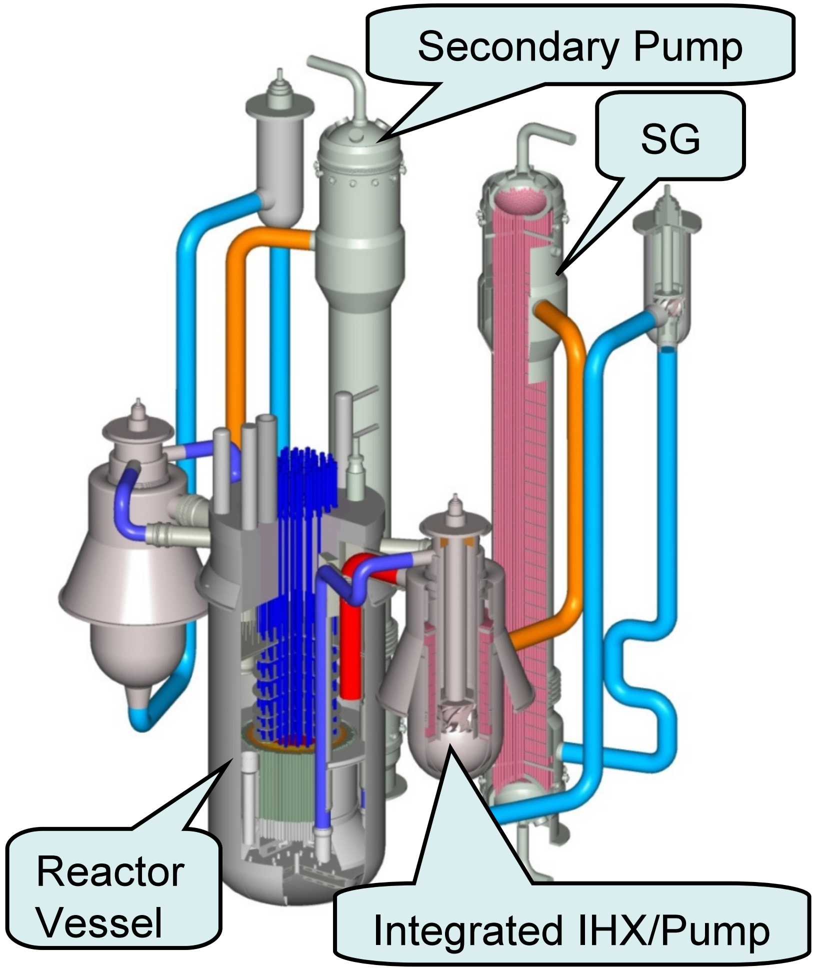
- Two-loop cooling system

  to enhance scale merit, thereby reduction of construction cost of plant.

4-loop 2-loop



Amount of commodity of NSSS: 16% less



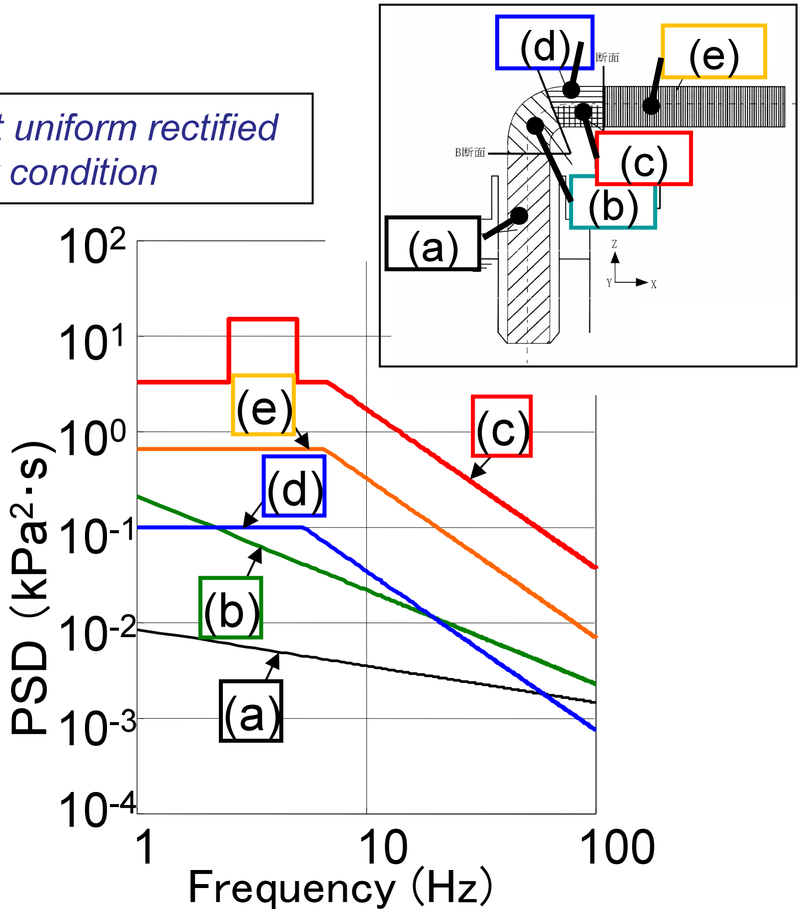
Ref.) H. Yamano, et al., NURETH-13, N13P1186, Kanazawa, Japan, Sep. 27 - Oct. 2, 2009.

Experiment-based methodology

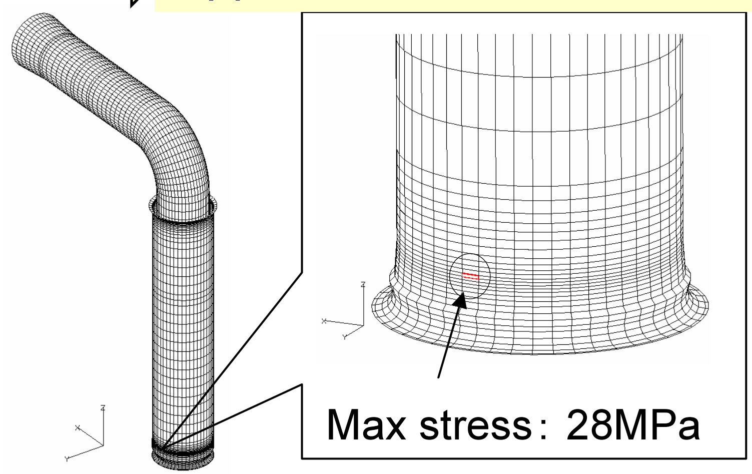
-Preliminary evaluation of the JSFR piping-

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

Inlet uniform rectified flow condition



Application to the JSFR hot-leg



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.