Preliminary Multi-dimensional Scaling Approach for IRWST Thermal Mixing Phenomena

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1. Introduction

One of the key role of IRWST (In-containment Refueling Water Storage Tank) in APR1400 is to increases the quenching efficiency of steam and to alleviate probable pressure surge induced by the sudden discharge of the high pressure steam during plant transient such as IOPOSRV (Inadvertent Opening of Pilot Operated Safety Relief Valve) accident or TLOFW (Total Loss of Feedwater) accident. When the POSRV opens in SDVS (Safety Depressurization and Vent System), the steam is discharged into the subcooled water in IRWST, following water clearing and air clearing. The discharged steam forms a 'jet' of vapor cone and ambient water near the sparger hole, and this jet propels a pool circulation. Continuous injection of high energy steam into the pool causes the pool temperature to rise, and eventually the steam condensing pattern may become very unstable by local temperature rise

For the sake of safe operation of such kind of pool like as IRWST, there have been several regulations on suppression pool in BWR (Boiling Water Reactor). The principal regulation is 'local pool temperature limits'. That is, the suppression pool local temperature shall not exceed certain limit [1]. And such a regulation is fully based on the pool mixing phenomena which largely depends on the geometry of pool, steam injection pattern, and so on. Thus, this guide cannot be directly applied to the design reference nor regulation guide of the IRWST.

The first job, therefore, for the design and regulation of IRWST can be said to understand the thermal mixing phenomena. Experiment with a scaled integral test facility is a very plausible approach. And, the test facility should be designed thoroughly based on the similarity analysis. This study is on the preliminary similarity analysis between IRWST phenomena and model test.

Thermal hydraulic behavior of IRWST thermal mixing by steam injection is fully 3-dimensional phenomena as shown in Fig. 1. Therefore, the scaling analysis should be based on 3-dimensional approach.

In general, following 3 similarity requirements should be achieved for the perfect conservation of 3-dimensional phenomena; geometric similarity, kinematic similarity, and dynamic similarity. In addition to these 3 similarity requirements, energetic similarity also has to be satisfied in the case that the energy behaviors including distribution are important.

I-type sparger is perforated system, and the layout of spargers is also complicated. Thus, it is almost impossible to keep the perfect geometric similarity under 3-dimensional linear scaling approach. Resultantly, our starting point is an approximate geometry similarity, by lumping a number of holes into single hole, based on rigorous similarity analysis. However, recalling that IRWST behaviors are motivated by discharging jets and each jet is considerably /relatively independent of each other, such an approximation in geometry does not fatally affect the local or overall phenomena

The experiments based on similarity analysis using above approximation are expected to provide us with sufficient information on the integral behaviors on IRWST. And even more, the measured data can be utilized in verification and validation of pool mixing analysis code such as CFD (Computational Fluid Dynamics) code.

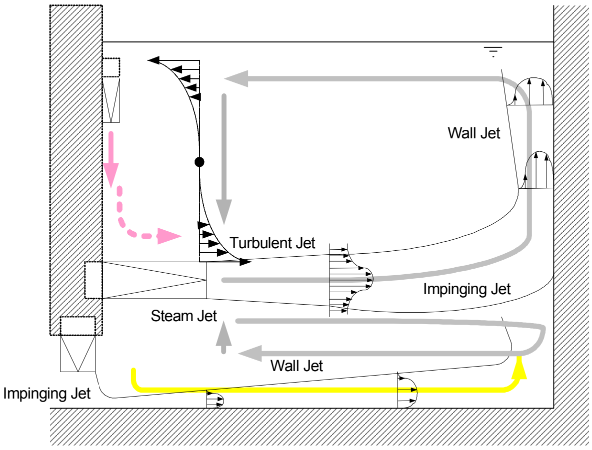
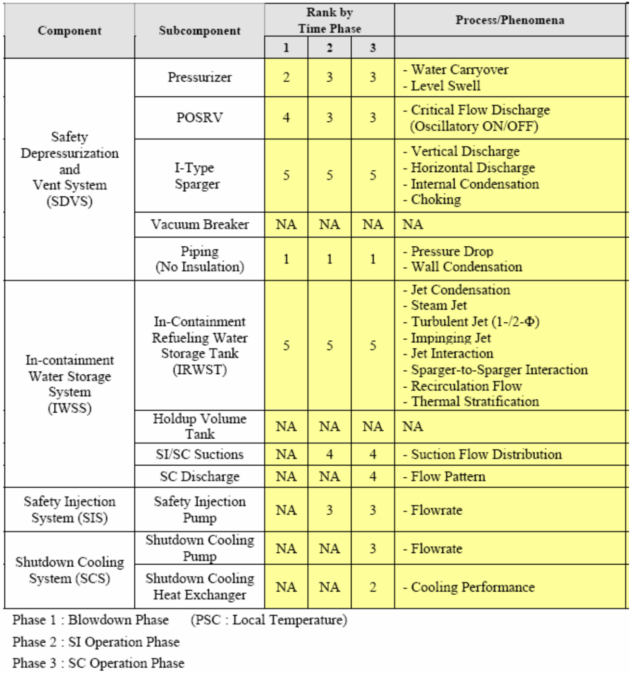


Fig. 1 IRWST Pool Water Behaviors in 3-dimensional Mode

Table 1 Results of the PIRT for thermal mixing phenomena in a IRWST pool for APR1400 TLOFW scenario



Component	Subcomponent	Rank by Time Phase			Process/Phenomena
		1	2	3	
Safety Depressurization and Vent System (SDVS)	Pressurizer	2	3	3	- Water Carryover - Level Swell
	POSRV	4	3	3	- Critical Flow Discharge (Oscillatory ON/OFF)
	I-Type Sparger	5	5	5	- Vertical Discharge - Horizontal Discharge - Internal Condensation - Choking
	Vacuum Breaker	NA	NA	NA	NA
	Piping (No Insulation)	1	1	1	- Pressure Drop - Wall Condensation
In-containment Water Storage System (IWSS)	In-Containment Refueling Water Storage Tank (IRWST)	5	5	5	- Jet Condensation - Steam Jet - Turbulent Jet (1-/2-Φ) - Impinging Jet - Jet Interaction - Sparger-to-Sparger Interaction - Recirculation Flow - Thermal Stratification
	Holdup Volume Tank	NA	NA	NA	NA
	SI/SC Suctions	NA	4	4	- Suction Flow Distribution
	SC Discharge	NA	NA	4	- Flow Pattern
Safety Injection System (SIS)	Safety Injection Pump	NA	3	3	- Flowrate
Shutdown Cooling System (SCS)	Shutdown Cooling Pump	NA	NA	3	- Flowrate
	Shutdown Cooling Heat Exchanger	NA	NA	2	- Cooling Performance

Phase 1 : Blowdown Phase (PSC : Local Temperature)
Phase 2 : SI Operation Phase
Phase 3 : SC Operation Phase

2. Major Phenomena and PIRT

The important thermal hydraulic phenomena in IRWST were identified by PIRT (Phenomena Identification and Ranking Table) [2]. In this development the considered initiating event was TLOFW, The principal safety criterion was determined as 'local temperature'.

3. Global Scaling

3.1 Scaling for 3-dimensional Flow

Global pool mixing phenomena can be described by three conservation equations. And we can get following dimensionless form of balance equations with suitable nondimensionalizing parameters.

$$\frac{\partial \rho^*}{\partial t^*} + \nabla^* \cdot \left(\rho^* \mathbf{u}^*\right) = 0 \tag{1}$$

$$\frac{\partial \mathbf{u}^*}{\partial t^*} + \left(\mathbf{u}^* \cdot \nabla^*\right)\mathbf{u}^* = -\nabla^* p^* - Ri\rho^*\mathbf{k} + \frac{1}{Re}\nabla^{*2}\mathbf{u}^* \tag{2}$$

$$\frac{\partial T^*}{\partial t^*} + \left(\mathbf{u}^* \cdot \nabla^*\right)T^* = \frac{1}{Pr \cdot Re}\nabla^{*2}T^* + \frac{E}{Re}\Phi^* \tag{3}$$

Order of magnitude of the coefficient in each term shows that Richardson number is most important.

$$Ri = \frac{\left(\rho_a - \rho_0\right)gL}{\rho_a u_0^2} \tag{4}$$

Conservation of Richardson number results in following velocity scale.

$$u_{0R} = \sqrt{L_R} \tag{5}$$

3.2 Mass and Heat Addition

Steam injection is choked flow. And the hole area of sparger should be determined with another scale different from reference length scale.

Energy in/outflow is more important than mass in/outflow. Thus, the ratio of each energy flow should be conserved prior to that of mass flow in case that the steam properties are not conserved by the limitation of steam generator in test.

3.3 Scale of Fundamental Variables

Velocity scale was already determined in Eq. (5), and following scale can be easily determined for time, mass flow, and heat addition, respectively.

$$t_R = \sqrt{L_R} \tag{6}$$

$$\dot{m}_R = L_R^{5/2} \tag{7}$$

$$\dot{Q}_{inj,R} = \left[\dot{m}_0 i_{fg}\right]_R = L_R^{5/2} \tag{8}$$

4. Scaling for Specific Phenomena

Scaling for integral thermodynamic state shows that the water property in pool should be same both in prototype and model. Considering condensation and mixing around the sparger we can derive the scale of injected steam mass flux. Relation of steam jet condensation length and transition distance at which the forced jet becomes buoyant jet identifies the scale of hole diameter [3]. Analysis on the hydraulic jump by impinging jet and its rise to surface restricts the direction of steam jet [4].

Condensation regime should be maintained same.

5. Conclusions

This study provides a preliminary scale relation for the conservation of IRWST thermal mixing phenomena. In further study this scaling should be checked by experimental or numerical analysis.

REFERENCES

[1] Su, T.M., Suppression Pool Temperature Limits for BWR Containments, NUREG-0783, USNRC, 1981

[2] Song, C.H., et al., Development of The PIRT for Thermal Mixing Phenomena in the IRWST of the APR1400, NTHAS5: Fifth Korea-Japan Symposium on Nuclear Thermal Hydraulics and Safety, Jeju, Korea, November 26- 29, 2006

[3] Jirka, G.H., Integral Model for Turbulent Buoyant Jets in Unbounded Stratified Flows. Part I: Single Round Jet, Environmental Fluid Mechanic Vol.4, pp.1-56, 2004

[4] Gamble, R. E., et al., Pressure Suppression Pool Mixing in Passive Advanced BWR Plants, Nuclear Engineering and Design, V.204, pp.321-336, 2001