Non–Proprietary

Performance Verification of APR1400 Safety Injection Tank -Fluidic Device

- Design Requirements for Fluidic Device
- VAPER Test Facility & Fluidic Device
- Test Conditions & Test Results
- Uncertainty Analysis
- Supplementary Works for the Issues Identified by the NRC Staff
- Summary

Design Requirements for Fluidic Device K Factor

- The following requirements are drawn from hypothetical LBLOCA analysis and conservative assumptions:

	Total K Factor	Piping K Factor	Fluidic Device K Factor
Large Flow Injection	**10 ~ 25**	**6 ~ 10**	**4 ~ 15**
Small Flow Injection	**80 ~ 120**	**6 ~ 10**	**74 ~ 110**

Reference area: APR1400 SI line pipe area

VAPER Test Facility (1/3)

- Full-Scale SIT & FD
  - I.D. : 2.74 m (8.0 ft)
  - Height : 11.9 m (39.0 ft)
  - Volume : 68.13 m^3 (68.13 ft^3)
- Air Compressor
  - Max P: 5.0 MPa (725 psi)
- **Final Goal**
  - **Verification of the pressure loss coefficient (K-Factor) of Fluidic Device**, which is used to evaluate SI water injection flow rate in safety analysis code

VAPER Test Facility (2/3)

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VAPER Test Facility (3/3)

- Geometrical differences between VAPER SIT-FD and APR1400 SIT-FD

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Dimensions of Fluidic Device

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	Standard FD	FD-S*
Dia. of Vortex Chamber		
H. of Vortex Chamber		
W. of Supply Nozzle		
W. of Control Nozzle		
Angle btw. Nozzles		
I.D. of Throat		
Height of Stand Pipe		
I.D. of Stand Pipe		

* FD-S : Fluidic Device for Sensitivity of H. of Stand Pipe & Manufacturing Tolerances

Test Matrix & Conditions (1/7)

Test ID	Objectives	Remark
Case-01	Repeatability of Standard Design FD	4 Tests (One Low Press. Test)
Case-02	Effect of Water Inventory (or Stand Pipe Height)	3 Tests
Case-03	Effect of Manufacturing Tolerance (Expected Max. Values)	Height of Vortex Chamber (3 Tests)
Case-04		Height of Vortex Chamber & Width of Control Nozzle (3 Tests)

Test Matrix & Conditions (2/7)

	Reference Condition [VAPER Tests]	APR1400 SIT Condition
Initial SIT gas pressure		
Outlet pressure		

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Test Matrix & Conditions (3/7)

	Reference Condition [VAPER Tests]	APR1400 SIT Condition
SI water volume for large flow		
SI water volume for small flow		
Initial SI water temperature		

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Test Matrix & Conditions (4/7)

- Case-01 Tests
  - Reference test for standard Fluidic Device
  - Three tests to check the repeatability
  - One low pressure test to check its sensitivity

Test ID	Initial SIT Pressure [kPa(g), (psig)]	Initial SIT Water Level [m (ft)]	Initial SIT Temperature [°C (°F)]
Case-01-01			
Case-01-02			
Case-01-03			
Case-01-04			

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Test Matrix & Conditions (5/7)

- Case-02 Tests
  - To check the sensitivity of the stand pipe height

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SI water volume for large flow was preserved.

Test Matrix & Conditions (6/7)

- Case-03 Tests
  - To check the sensitivity of the vortex chamber height

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Test Matrix & Conditions (7/7)

- Case-04 Tests
  - To check the sensitivity of the control nozzle width

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Test Results: SIT & Stand Pipe Levels

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$$h_{SIT} = \frac{(\rho_w - \rho_{air})gH - \Delta P}{(\rho_w - \rho_{air})g}$$

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Case-01 Tests

Case-01~04

Test Results: SI Water Injection Flow Rate

$$W_{SI}(t) = \rho_w A_{SIT} \frac{h_{SIT}(t) - h_{SIT}(t+\Delta t)}{\Delta t} \qquad \Delta t = 2\,\text{sec}$$

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Repeatability !!!

Reproducibility !!!
(Manufacturing Tolerance)

Test Results: Fluidic Device K Factor

TS

Repeatability !!!

Reproducibility !!!
(Manufacturing Tolerance)

Effect of Air Discharge on FD K Factor (1/3)

- The discharge flow rate of the air can be evaluated from the change rate of the total air mass.

$$W_{air}(t) = \frac{m_{air}(t) - m_{air}(t + \Delta t)}{\Delta t}$$

$$m_{air}(t) = \rho_{air}(t) V_{air}(t)$$

Effect of Air Discharge on FD K Factor (2/3)

- The air discharge begun at about 100 sec for Case-01, and reached its maximum at about 120 sec.

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End of SI Water Injection

Effect of Air Discharge on FD K Factor (3/3)

- Fluidic Device K Factor was not sensitive to the air discharge flow during 100~120 sec period.

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Uncertainty Analysis (1/5)

- **Uncertainty of FD K Factor** was analyzed at a **95% confidence level** in accordance with the guidelines of ISO1) & ASME 2)
- Total uncertainty is the root sum square of the systematic and random uncertainties

$$U_{95} = \left[B^2 + P^2\right]^{1/2} = \left[B^2 + \left(t_{95} S_{\overline{X}}\right)^2\right]$$

1) Guide to the Expression of Uncertainty in Measurement (1995)
2) Test Uncertainty, ASME-PTC 19.1-1998 (1998)

Uncertainty Analysis (2/5)

- **Systematic uncertainty** was evaluated by the propagation of the elemental uncertainty sources

$$B_K = \pm\left[\left(\frac{\partial K}{\partial \Delta P}B_{\Delta P}\right)^2 + \left(\frac{\partial K}{\partial \rho_w}B_{\rho_w}\right)^2 + \left(\frac{\partial K}{\partial A_{Pipe}}B_{A_{Pipe}}\right)^2 + \left(\frac{\partial K}{\partial W_{SI}}B_{W_{SI}}\right)^2\right]^{1/2}$$

$$= \pm\left[\left(\frac{K}{\Delta P}B_{\Delta P}\right)^2 + \left(\frac{K}{\rho_w}B_{\rho_w}\right)^2 + \left(2\frac{K}{A_{Pipe}}B_{A_{Pipe}}\right)^2 + \left(2\frac{K}{W_{SI}}\boxed{B_{W_{SI}}}\right)^2\right]^{1/2}$$

$$B_{W_{SI}} \approx \pm\left[\left(\frac{\partial W_{SIT}}{\partial \rho_w}B_{\rho_w}\right)^2 + \left(\frac{\partial W_{SIT}}{\partial A_{SIT}}B_{A_{SIT}}\right)^2 + \left(\frac{\partial W_{SIT}}{\partial \Delta h}B_{\Delta h_{SIT}}\right)^2\right]^{1/2}$$

$$= \pm\left[\left(\frac{W_{SIT}}{\rho_w}B_{\rho_w}\right)^2 + \left(\frac{W_{SIT}}{A_{SIT}}B_{A_{SIT}}\right)^2 + \left(\frac{W_{SIT}}{h_{SIT}(t) - h_{SIT}(t+\Delta t)}B_{\Delta h_{SIT}}\right)^2\right]^{1/2}$$

Uncertainty Analysis (3/5)

Systematic Uncertainty

- SI water flow rate
- Fluidic Device K Factor

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Uncertainty Analysis (4/5)

- **Random uncertainty** of Fluidic Device K Factor was evaluated by multiplying the **standard deviation** with a **coverage factor** of the student *t*-distribution
  - Standard deviation was determined from the K Factors obtained for all tests

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Uncertainty Analysis (5/5)

- Total Uncertainty of Fluidic Device K Factor

$$U_{95} = \left[B^2 + P^2\right]^{1/2} = \left[B^2 + \left(t_{95} S_{\overline{X}}\right)^2\right]$$

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Summary of Fluidic Device K Factor

- The measured Fluidic Device K Factor meets the design requirements for both the large and small flow injection periods.

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Issues Identified by the NRC Staff (1/7)

- Complete SIT-FD verification test result
  - Complete sets of graphs and/or tabulated test data can be provided on the request of the NRC staff.

Issues Identified by the NRC Staff (2/7)

- Effect of gaseous cavitation
  - Gaseous cavitation is expected to occur because some of the dissolved nitrogen gas comes out of the SI water when the water passes through the outlet nozzle throat.
    - ✓ Nitrogen gas release rate (kg/s) is estimated using the following eqn. by assuming that the nitrogen gas contents in the SI water reaches the equilibrium state of the solubility during the fast pressure transient process across the FD.

$$W_{N_2} = \left[m_{N_2}\left(P_{FD,in}\right) - m_{N_2}\left(P_{FD,throat}\right)\right] W_{SI}$$

$$P_{FD,throat} = P_{FD,in} - \Delta P_{FD} + \frac{\rho_{wtr}}{2}\left(U^2_{SI,FD,out} - U^2_{SI,throat}\right)$$

Issues Identified by the NRC Staff (3/7)

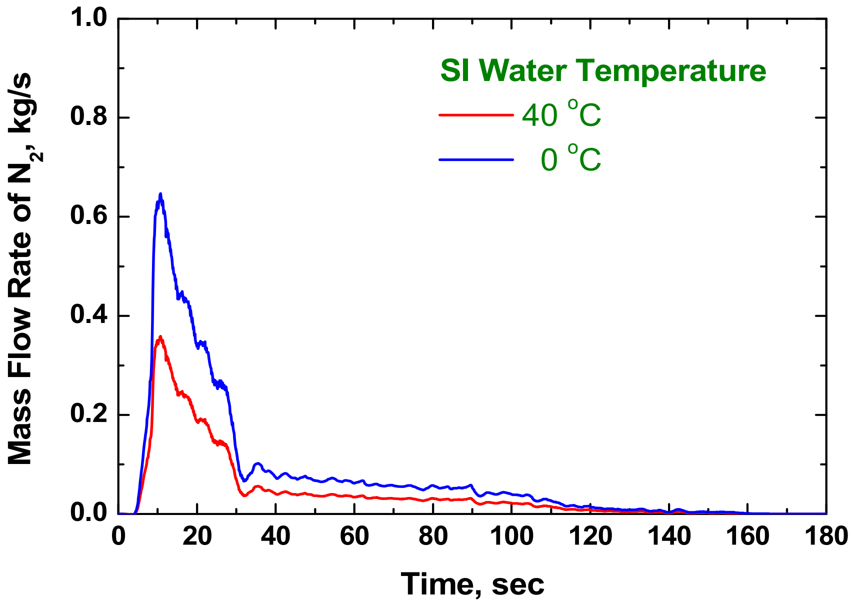
Effect of gaseous cavitation

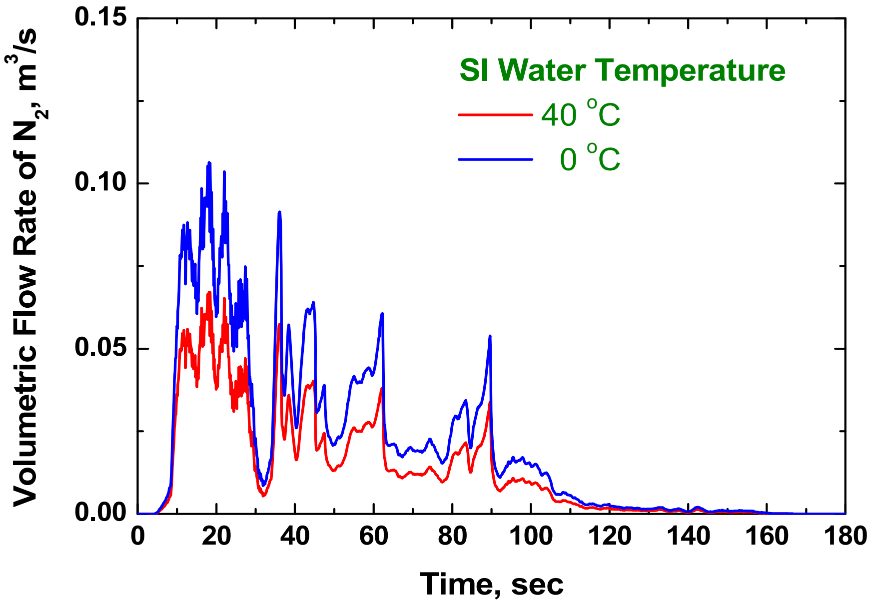
- The solubility of nitrogen gas is calculated by curve fitting the data provided by Sun et al. for the SI water at 0 °C (32 °F) & 40 °C (104 °F)

$$m_{N_2}(P) = -1.37578\times10^{-6} + 2.84063\times10^{-4}\cdot P - 5.04235\times10^{-6}\cdot P^2 \quad \textbf{; for 0 °C}$$

$$m_{N_2}(P) = -1.23253\times10^{-6} + 1.54337\times10^{-4}\cdot P - 1.90901\times10^{-6}\cdot P^2 \quad \textbf{; for 40 °C}$$

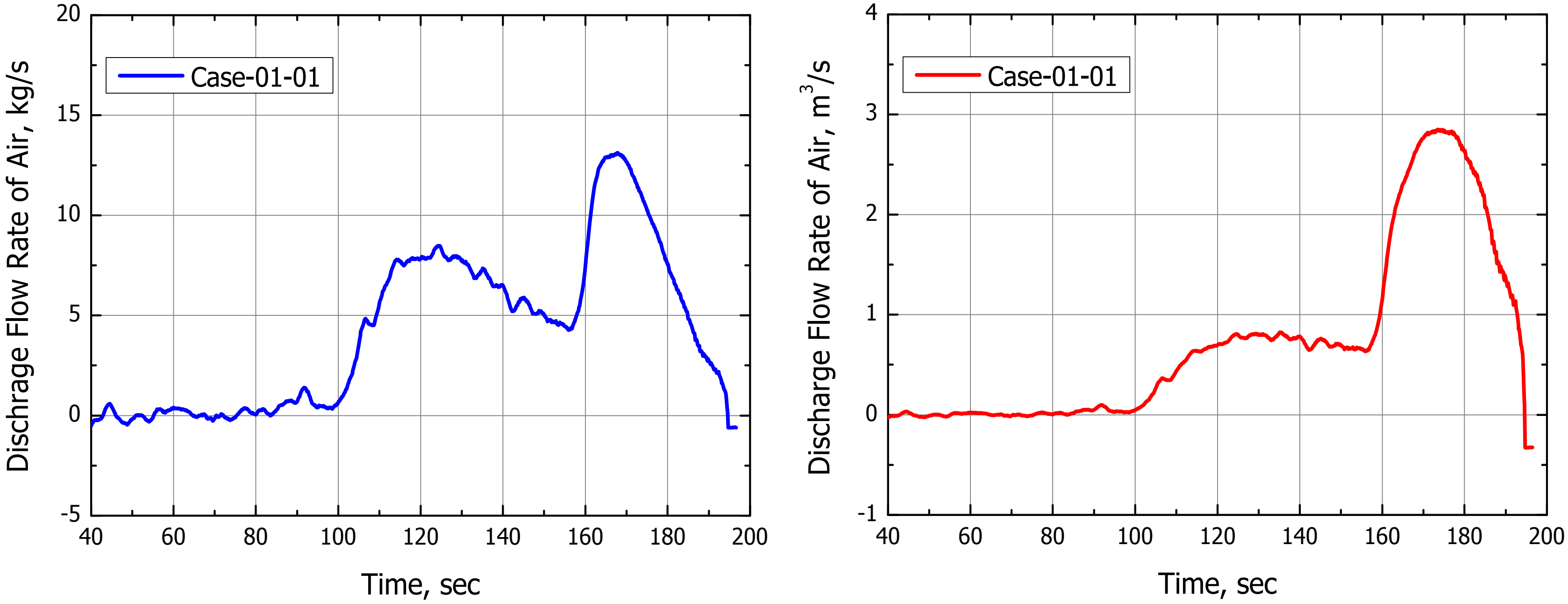
- Estimation of nitrogen gas release rate





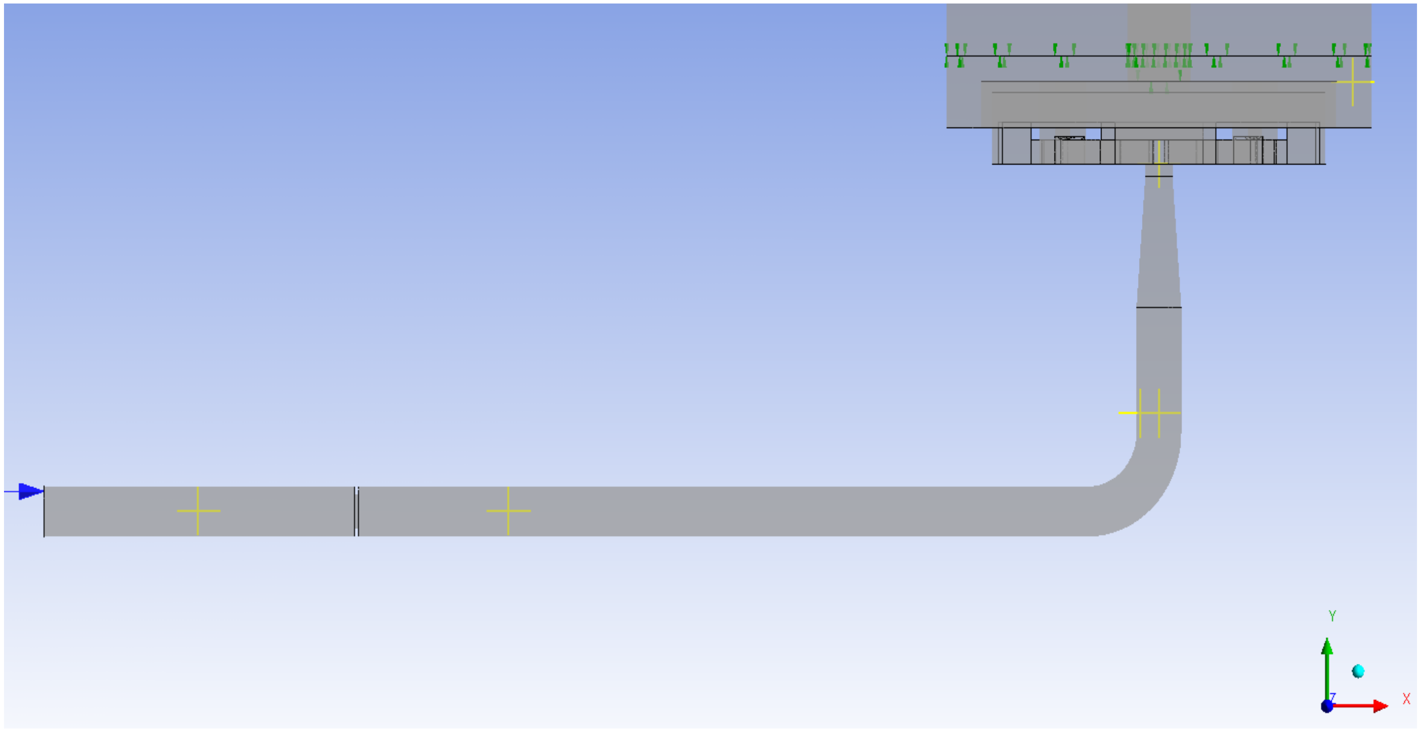
Issues Identified by the NRC Staff (4/7)

- Effect of gaseous cavitation
  - The maximum mass and volumetric flow rate of nitrogen gas are much smaller than the air discharge flow rate during the period of 100 ~ 110 seconds.
  - As a result, it is expected that the evolution of dissolved nitrogen gas does not materially affect the FD K-factor.



Issues Identified by the NRC Staff (5/7)

- Effect of vaporous cavitation
  - CFD analysis is being performed for a different SI water temperature.
    - ✓ Potential vaporous cavitation effect is expected on the pressure drop through the vortex chamber and outlet nozzle throat.



Issues Identified by the NRC Staff (6/7)

- Effect manufacturing uncertainty of facing angle between the supply nozzle and control nozzle
  - CFD analysis will be performed.
    - ✓ Manufacturing tolerance = ± 0.3°
    - ✓ Sensitivity analysis will be conducted for ± 0.5° ~ 1.0° .
  - Justification of the CFD methodology
    - ✓ Mesh sensitivity
    - ✓ Cavitation model sensitivity
    - ✓ Turbulence model sensitivity
  - CFD analysis will be performed based on "NEA/SCNI/R5(2007) Best Practice Guidelines for the Use of CFD in Nuclear Reactor Safety Applications".

Issues Identified by the NRC Staff (7/7)

- Application of FD K factor to safety analysis
  - The results of VAPER tests were used to confirm large break LOCA analysis code RELAP5/MOD3.3/K's predictive capability of observed flow injection behavior.
  - The test data were also used for nodalization development of SIT-FD.
  - The measured FD K-factor was confirmed to meet the design requirements of the SIT-FD.
  - The design requirement range of FD K-factors (for large and small flow) were used for safety analysis.
  - The details are described in topical report (APR1400-F-A-TR-12004-P Rev.0) for large break LOCA evaluation model CAREM.

Summary

- Full scale tests were performed to verify the performance of APR1400 Fluidic Device
- Reproducibility of the performance of Fluidic Device
  - Performance was not sensitive to the changes in the initial SIT pressure & stand pipe height.
  - Performance was also not sensitive to the manufacturing tolerances examined.
- APR1400 Fluidic Device meets the design requirements for both the large and small injection periods.

Thank you very much!!!

Summary of FD Performance (1/2)

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Test ID	Peak flow rate [kg/s (lb/sec)]	Duration of injection [sec]	Fluidic Device K factor a)
Case-01-01			
Case-01-02			
Case-01-03			
Case-01-04			
Case-02-01			
Case-02-02			
Case-02-03			

a) Large flow / small flow conditions. Reference area is APR1400 discharge pipe area

Summary of FD Performance (2/2)

Test ID	Peak flow rate [kg/s (lb/sec)]	Duration of injection [sec]	Fluidic Device K factor [a]
Case-03-01			
Case-03-02			
Case-03-03			
Case-04-01			
Case-04-02			
Case-04-03			

TS

a) Large flow / small flow conditions. Reference area is APR1400 discharge pipe area

Effect of Air Discharge on FD K Factor

Air discharges through the empty stand pipe before the depletion of SI water

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- The air volume expands due to the decrease of SI water volume.
  - Polytropic process is valid as long as the total air mass is conserved.
    - ✓ From the measurement results, the pressure & volume of air at any time can be evaluated.

$$\left(PV^n\right)_{air,o} = \left(PV^n\right)_{air,t} = \left(PV^n\right)_{air,t+\Delta t}$$

Effect of Air Discharge on FD K Factor

- The injection flow rate of SI water can also be evaluated from the volume expansion rate of the air.

$$Q_{SI}(t) = \left(\frac{dV}{dt}\right)_{air,t}$$

$$\cong \frac{V_{air,t+\Delta t} - V_{air,t}}{\Delta t}$$

$$= \left(P^{\frac{1}{n}} V\right)_{air,o} \frac{1}{\Delta t}\left[\left(\frac{1}{P}\right)^{\frac{1}{n}}_{air,t+\Delta t} - \left(\frac{1}{P}\right)^{\frac{1}{n}}_{air,t}\right]$$

$$W_{SI}(t) = \rho_w \cdot Q_{SI}(t)$$

Effect of Air Discharge on FD K Factor

- The injection flow rate matched well with each other until the time of { }TS & 120 sec for Case-01 & Case-02.
- Deviation occurred after the above times, implying that the air started to discharge through the empty stand pipe and the total air mass was no longer conserved.

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Polytropic Process of Air Expansion

- Background for the different indices of polytropic process for large & small flow injection period

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Uncertainty Analysis

- **Elemental uncertainties** were determined from inspection test reports or calibrations

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