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Numerical Analysis for the Steam Condensation by the Spray Water in the TOSQAN Test Using OpenFOAM

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3-D Analysis of Spray Droplet Flow in a Rx Containment

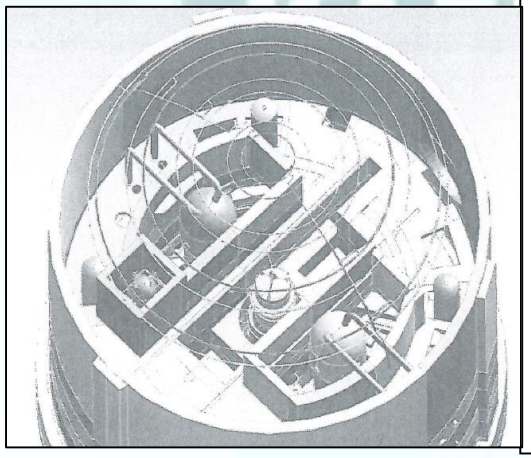
❑ Spray Operation during Severe Accidents

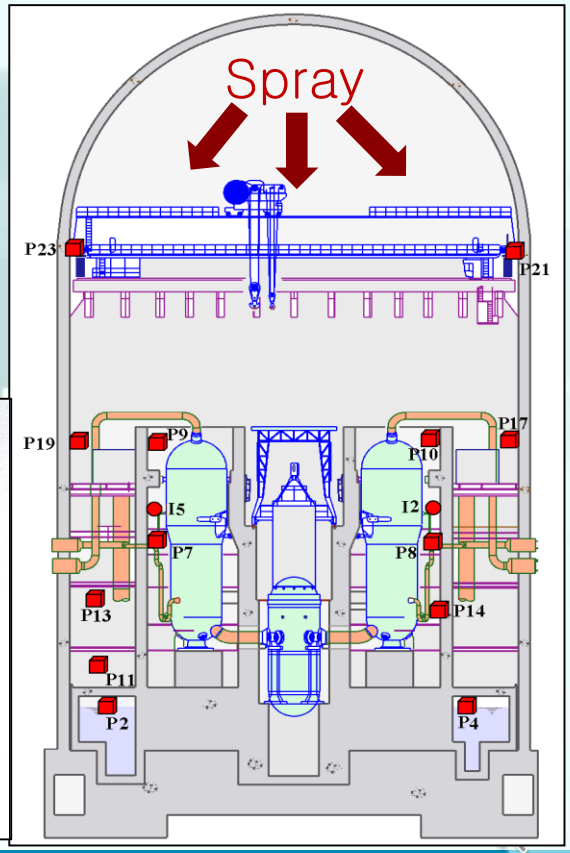
- ❍ Steam & H_2 are released to the containment during the severe accident
- ❍ Pressure decrease in the containment through the steam condensation
- ❍ Higher the hydrogen concentration through the steam condensation

❑ Spray Analysis Module using OpenFOAM

- ❍ Ref : KAERI/TR-7992/2019 (by J. T. Kim, et al.)
- ❍ Lagrangian & Eulerian method
- ❍ Particle Size Distribution
- ❍ Heat and Mass Transfer
- ❍ Spray Injection Nozzle
- ❍ Validation Calculation
  - ▸▸ CALIST(Hydraulic)
  - ▸▸ TOSQAN(Phase Change)

Spray Nozzle Ring





TOSQAN Experiment (IRSN in France)

❑ Validation using TOSQAN 101 test data

❍ Steam condensation by the spray water

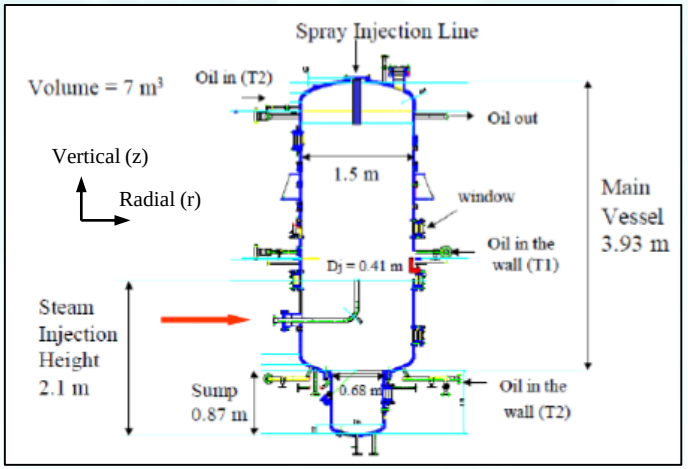
Test Condition

Gas Mixture	Temperature	Pressure	Steam volume fraction
Air-Steam	131 °C	2.5 bar	0.6

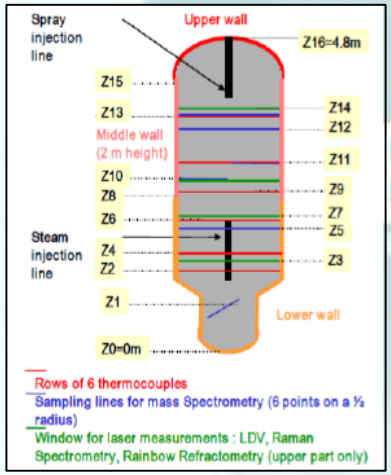
Flow rate	Angle	Initial size	Temperature (°C)
29.96 g/s	55°	130 μm	t = 0 s : 119.1 t = 311 s : 22.1 t = 1000s : 27.7

Time (s)	Upper	Middle	Lower
0 – 102	121.4	121.6	121.3
107 – 300	120.8	120.4	120.3
306 - 601	120.3	120.0	119.4
End of Test	119.3	120.1	115.4

Test Facility



Measurement Locations



Spray Nozzle (Full Cone)

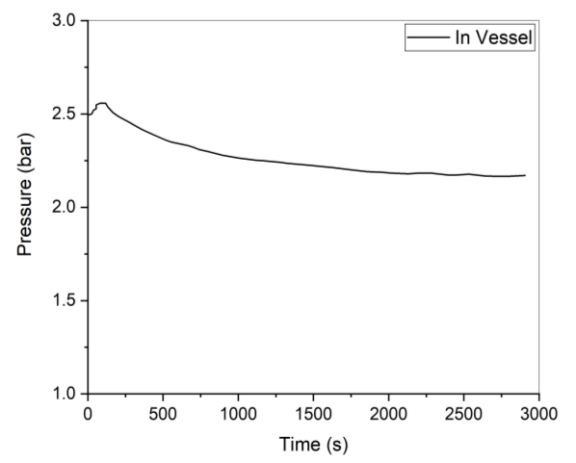
Ref : NED, Vol. 237, pp. 1862-71 (2007)

TOSQAN Test 101 Measured Data

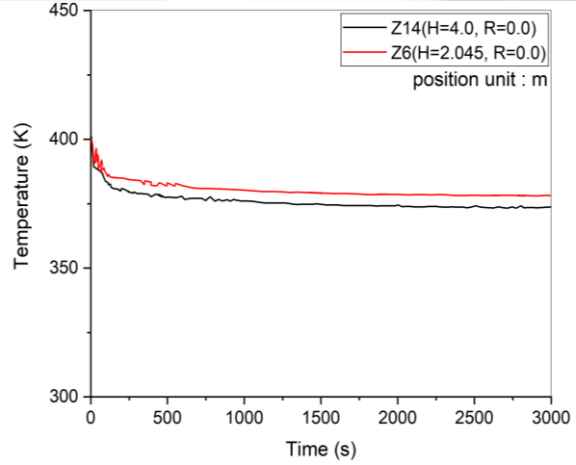
❑ Measured data

- ❍ Pressure : continuous decrease after slightly increase in 120 s
- ❍ Temperature : Z14 is approximately 5℃ lower than Z6
- ❍ SVF : Z14 is approximately 0.05 lower than Z6

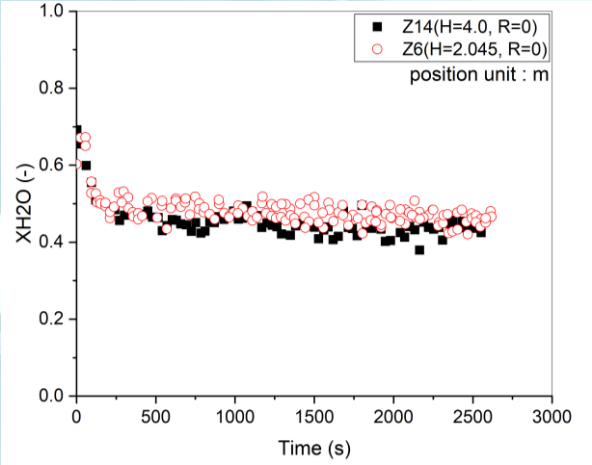
Pressure



Temperature



Steam Volume Fraction



Spray Analysis Module Using OpenFOAM

❑ OpenFOAM v-2012 (www.openfoam.com)

❍ Lagrangian-Eulerian method

- ⏩ Spray water : Lagrangian, Steam+Air : Eulerian

❍ Lagrangian Governing Equations

- ⏩ Mass/Momentum/Heat Transfer/Gas Species conservation eq.

$$m_p \frac{du_p}{dt} = F_D + F_G + F_P$$

Momentum eq. for spray water

Drag force

$$F_D = C_D \frac{\pi d_p^2}{8} \rho (U - u_p)\left|U - u_p\right|$$

Gravity force

$$F_G = m_p g \left(1 - \frac{\rho}{\rho_p}\right)$$

Pressure force

$$F_P = -\frac{\pi d_p^3}{6} \nabla p$$

$$m_p c_p \frac{dT_p}{dt} = \mathrm{h} A_p (T_\infty - T_p) - \frac{dm_p}{dt} h_{fg}$$

Heat Transfer eq. for spray water

$$\mathrm{Nu} = \frac{\mathrm{h} d_p}{k_\infty} = 2.0 + 0.6 Re_d^{0.5} Pr^{\frac{1}{3}}$$

Heat transfer coeff.

$$\mathrm{N_i} = k_c (C_{is} - C_{i\infty})$$

Mass Transfer eq. for water vapor

C_{is} : vapor concentration at the droplet surface
$C_{i\infty}$: vapor concentration in the bulk gas

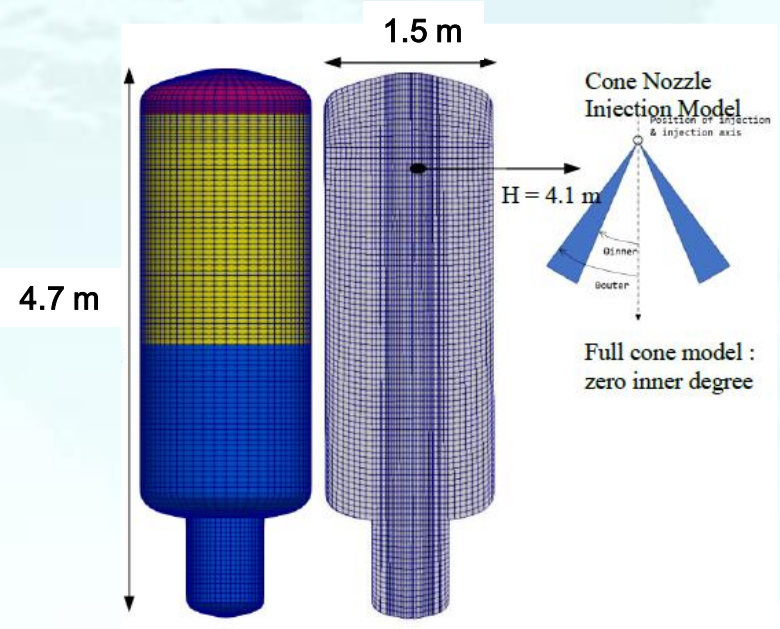
Grid Model and Boundary Condition

❑ Grid Model

- ❍ 74,088 Hexahedral Cells for the TOSQAN vessel

❑ Inlet Boundary Condition

- ❍ Measured data at Z=5 cm below from the spray nozzle
- ❍ Full Cone Nozzle Injection Model



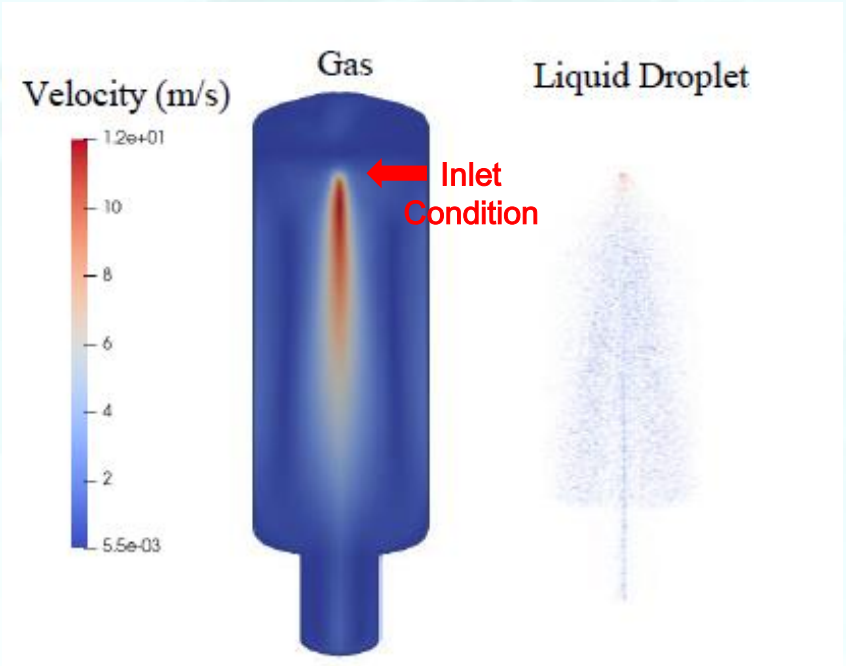
Full Cone Nozzle Injection Model

Spray Model (Lagrangian method)
- Diameter (d_{10}) distribution = mass Rosin Rammler model - Mass flow rate = 29.96 g/s - U_{mag} = 12.46 m/s - Nozzle outer diameter = 0.54 m - Nozzle outer angle = 57° - Parcel Per Second (PPS) = 5000 [#/s] *Inlet conditions were determined based on measured data at Z = -5 cm from the nozzle outlet.
mass Rosin Rammler model
$f(d, D, k) = \frac{k}{D}\left(\frac{d}{D}\right)^{k-1} \exp\left[-\left(\frac{d}{D}\right)^{k}\right]$ - Diameter : d - Min. / Max. diameter = 10 μm / 800 μm - Mean diameter (D)= 220 μm - Shape factor (k) = 1.5

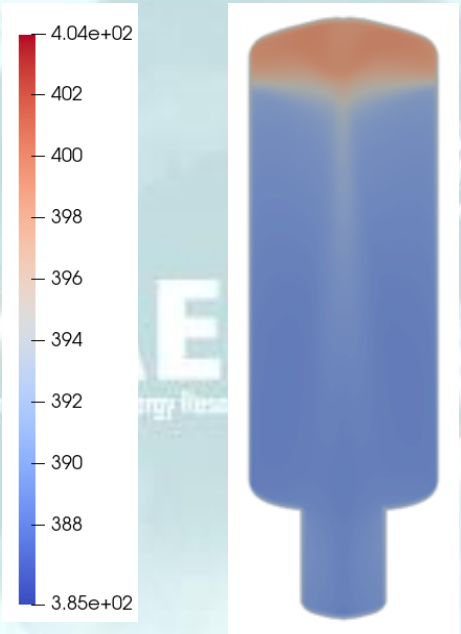
OpenFOAM Analysis Results (1)

- Injected spray water condensed the distribute steam in the vessel
  - This phenomenon was reasonably simulated by Lagrangian and Eulerian method

Injected Spray Water (100 s)
(Velocity Contour)



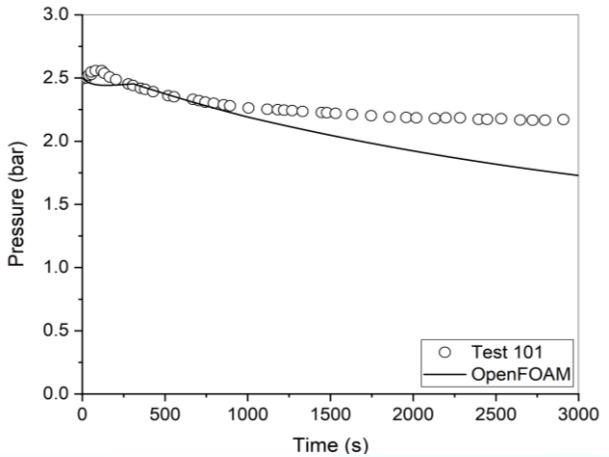
Gas Temp. (100 s)



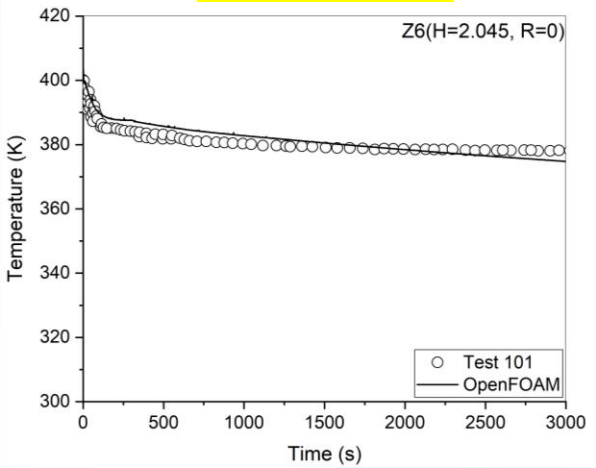
OpenFOAM Analysis Results (2)

- Comparison results of pressure, temperature, and steam volume fraction between test data and OpenFOAM results
  - OpenFOAM results predict the test data with an error range of about 10% except the pressure measured from 2000 s to 3000 s. This discrepancy may be resulted from that the CFD analysis did not simulate the water pool formation at the sump region in the TOSQAN vessel.
  - OpenFOAM results does not simulate the rapid decrease of the steam volume fraction from 100 s to 300 s. This discrepancy may be caused by the evaporation model in the OpenFOAM, thus further investigation is needed.

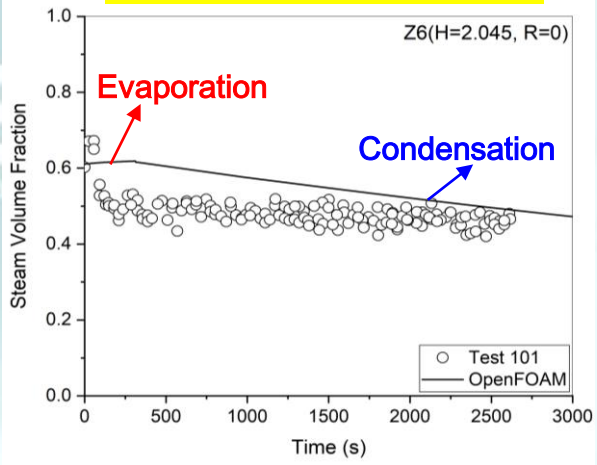
Pressure



Temperature



Steam Volume Fraction



Conclusion

❑ Conclusion

- ❍ We performed the CFD analysis against the measured data of the steam condensation by the spray water in the TOSQAN test 101 to validate the spray analysis module developed using OpenFOAM-2012.
- ❍ OpenFOAM results reasonably predicted the pressure, temperature, and steam volume fraction with an error range of approximately 10% when compared to the test data.

❑ Further Work

- ❍ The reason of the slow decrease steam volume fraction predicted by the OpenFOAM will be investigated.