Estimation of Reactor Building Humidity Distribution due to RCS Leakage

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1. Introduction

In order to enhance the safety of the operating nuclear power plants, the improvement of the reactor coolant system leakage detection system has been explored to detect the small amount of leakage within a limited time. Basically, the RCS leakage can be detected by online monitoring the measurements of reactor building air pressure and temperature, gaseous and particulate radioactivity and air humidity. Due to noises and diurnal/seasonal variations in the measurement data, both the hardware for measurement and the software for post-processing the data should be properly designed to achieve the timely detection with high accuracy.

Note that because there are a lot of possible leak locations, it would be impractical to use the local measurement methods and the global measurement methods would be cost-beneficially preferred. The leakages would be diffused and diluted to the entire reactor building atmosphere; thus, the global condition changes in reactor building would become minor and hard to be noticed before the significant time would be elapsed. Therefore, the measurement devices should be chosen to have the required sensitivity and installed at the proper locations. For that, the reactor building conditions would be critical.

In this study, the reactor building relative humidity distribution due to RCS leakage has been analyzed. The reactor building has been divided into six nodes and the flows between nodes by reactor building air handling units(AHUs) are modeled. Especially, the cooling and condensing inside of the AHUs are considered. The conservation equations are derived mathematically and solved by using OpenModelica. The relative humidity changes are analyzed by varying leak rate, locations and AHU flowrate.

2. Modeling of Reactor Building Conditions

2.1. APR1400 Reactor Building Configuration

The reactor building has the free volume 77,220 m^3 [1], which is divided into six nodes: Dome, Annular Compartment, Lower Compartment, Steam Generator Compartment #1, Steam Generator Compartment #2 and Cavity. Only AHUs which induce the inter-compartment flow are considered: Reactor Containment Fan Cooler (RCFC), Cavity AHU, Steam Generator Enclosure Recirculation Fans. The chillers are included in RCFC and Cavity AHU. The schematics of the Reactor Building nodalization and AHU connections is presented in Fig. 1.

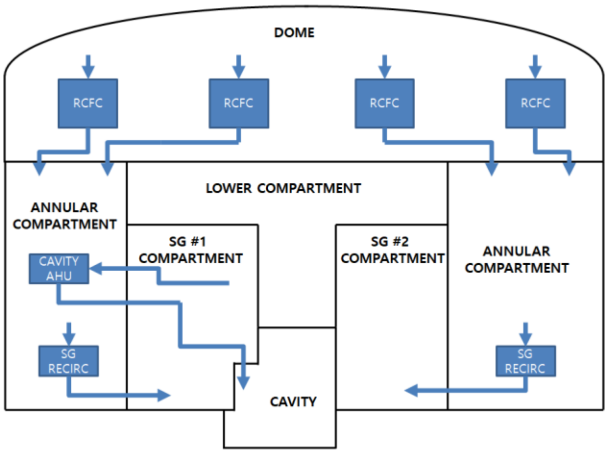


Fig. 1. Reactor Building Nodalization and AHU In/Out

2.2. Mathematical Derivation

Conservations of Volume, Mass and Energy are formulated as in Eq. (1) ~ Eq. (4). In volume conservation, it is assumed that the forced flow would be established by AHUs and other inter-compartment flows would be established to balance the compartment volume. In mass conservation, air and steam are considered separately. The leak is assumed to be 100% steam and the condensation of leak flow due to difference of saturated vapor enthalpy and leakage enthalpy is considered. In energy conservation, the mixture mass and the mixture enthalpy are employed and the cooling and the condensation are considered. It is assumed that the operator can control the target reactor building temperature and humidity by adjusting AHU chiller flow. The equation of state are summarized in Eq. (5) ~ Eq. (9).

○ Volume Conservation:

$$0=\sum_{j=1} Q_{j\to i}-\sum_{k=1} Q_{i\to k} \qquad (1)$$

○ Mass Conservation:

$$\frac{dm_{air,i}}{dt}=\sum_{j=1}\rho_{air,j}Q_{j\to i}-\sum_{k=1}\rho_{air,i}Q_{i\to k} \qquad (2)$$

$$\frac{dm_{steam,i}}{dt} = \sum_{j=1} \rho_{steam,j} Q_{j \to i} - \sum_{k=1} \rho_{steam,i} Q_{i \to k} + \dot{m}_{leak} - \dot{m}_{cond} \qquad (3)$$

○ Energy Conservation:

$$\frac{d\left(m_i h_i\right)}{dt} = \sum_{j=1} \rho_j \left(h_j - \delta h_j\right)\left(Q_{j \to i} - \delta Q_{j \to i}\right) - \sum_{k=1} \rho_i h_i Q_{i \to k} \qquad (4)$$

○ Equation of State:

$$P_i = \frac{\rho_i}{M_i} R T_i \qquad (5)$$

$$\rho_i = \rho_i\left(P_i, T_i, X_i\right) \qquad (6)$$

$$h_i = h_i\left(P_i, T_i, X_i\right) \qquad (7)$$

$$X_i[1] = \frac{\rho_{steam,i}}{\rho_{steam,i} + \rho_{air,i}} \qquad (8)$$

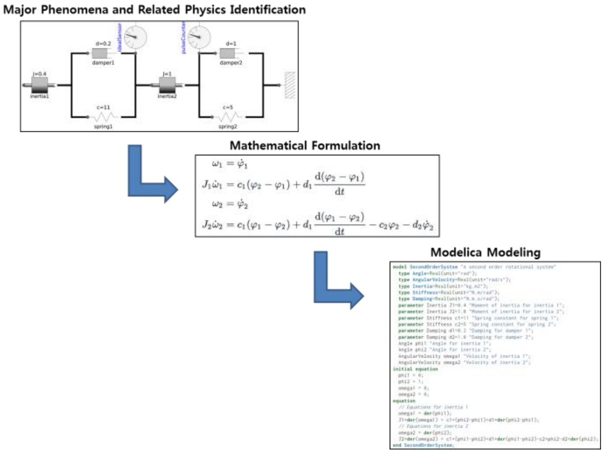
$$X_i[2] = \frac{\rho_{air,i}}{\rho_{steam,i} + \rho_{air,i}} \qquad (9)$$

where,

$Q_{j \to i}$	volumetric flowrate from j to i compartment
$m_{x,i}$	mass in i compartment of x (air or steam)
$\rho_{x,i}$	density in i compartment of x (air or steam)
m_i	mixture mass in i compartment
ρ_i	mixture density in i compartment
h_i	mixture enthalpy in i compartment
P_i	pressure in i compartment
T_i	temperature in i compartment
M_i	mixture molar mass in i compartment
$X_i[1]$	steam mass fraction in i compartment
$X_i[2]$	air mass fraction in i compartment

2.3. OpenModelica (OM)

Modelica is an equation-based, object oriented, non-proprietary language developed to model complex physical systems containing e.g., mechanical, electrical, hydraulic, thermal, control or process-oriented subcomponents. [2] OM is an open-source Modelica modeling and simulation(M&S) environment, which compiles the equation-based models into C code which is linked with a library of utility functions, a run-time library, and a numerical Differential and Algebraic Equation (DAE) solver. In this work, the OM has been used as a nonlinear differential equation solver and the thermodynamic properties of moist air have been calculated by using the Moist Air model in Modelica Standard Library (MSL).



$$\omega_1 = \dot{\varphi}_1$$
$$J_1\dot{\omega}_1 = c_1(\varphi_2 - \varphi_1) + d_1\frac{\mathrm{d}(\varphi_2 - \varphi_1)}{\mathrm{d}t}$$
$$\omega_2 = \dot{\varphi}_2$$
$$J_2\dot{\omega}_2 = c_1(\varphi_1 - \varphi_2) + d_1\frac{\mathrm{d}(\varphi_1 - \varphi_2)}{\mathrm{d}t} - c_2\varphi_2 - d_2\dot{\varphi}_2$$

```
model SecondOrderSystem "A second order rotational system"
  type Angle=Real(unit="rad");
  type AngularVelocity=Real(unit="rad/s");
  type Inertia=Real(unit="kg.m2");
  type Stiffness=Real(unit="N.m/rad");
  type Damping=Real(unit="N.m.s/rad");
  parameter Inertia J1=0.4 "Moment of inertia for inertia 1";
  parameter Inertia J2=1.0 "Moment of inertia for inertia 2";
  parameter Stiffness c1=11 "Spring constant for spring 1";
  parameter Stiffness c2=5 "Spring constant for spring 2";
  parameter Damping d1=0.2 "Damping for damper 1";
  parameter Damping d2=1.0 "Damping for damper 2";
  Angle phi1 "Angle for inertia 1";
  Angle phi2 "Angle for inertia 2";
  AngularVelocity omega1 "Velocity of inertia 1";
  AngularVelocity omega2 "Velocity of inertia 2";
initial equation
  phi1 = 0;
  phi2 = 1;
  omega1 = 0;
  omega2 = 0;
equation
  // Equations for inertia 1
  omega1 = der(phi1);
  J1*der(omega1) = c1*(phi2-phi1)+d1*der(phi2-phi1);
  // Equations for inertia 2
  omega2 = der(phi2);
  J2*der(omega2) = c1*(phi1-phi2)+d1*der(phi1-phi2)-c2*phi2-d2*der(phi2);
end SecondOrderSystem;
```

Fig. 2. Modelica Modeling Process Illustration

3. Simulation Results

3.1. Reference Case

As a reference case, it is assumed that the reactor building relative humidity would be initially 40% and 0.5gpm leak would occur at SG #1 Compartment after 1000 seconds. All AHUs are operated at full capacity. In Fig. 3, the relative humidity of each compartment is shown. Because of the leak at SG #1 compartment, its relative humidity would be increased about 2.8% and reach the saturate status within 500 seconds. The relative humidity at Lower compartment and Dome would be also increased due to inter-compartment flows. The relative humidity at Annular compartment and Cavity would not be changed because of condensation in AHUs.

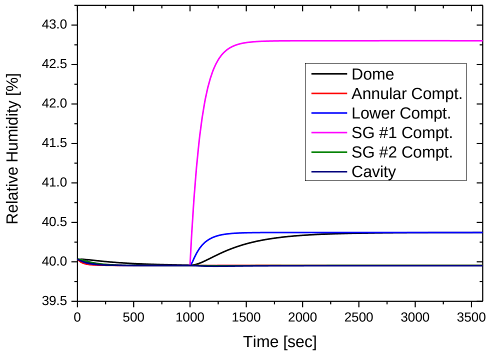


Fig. 3. Relative Humidity - Reference Case

3.2. Leak Rate Variation

The leak rate has been varied: 0.3gpm, 0.5gpm, 1.0gpm. As can be seen in Fig. 4, the relative humidity increment would be increased as the leak rate is increased. The relative humidity increments have been estimated as 1.6%, 2.8% and 5.7% for leak rates of 0.3gpm, 0.5gpm and 1.0gpm, respectively.

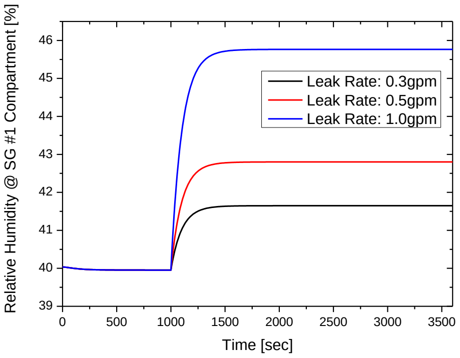


Fig. 4. Relative Humidity @ SG # 1Compt – Leak Rate Variation

3.3. Leak Location Variation

In Fig. 5, the relative humidity of each compartment with leakage at lower compartment is presented. Compared to SG #1 compartment, the volume of Lower compartment is about 3 times larger. Thus, the relative humidity increment would be much smaller than the one in the reference case (leak at SG #1 compartment). Due to inter-compartment flow from Lower compartment to Dome, the relative humidity in Dome would also be increased. Other compartments' relative humidity would not be changed much because of condensation in AHUs.

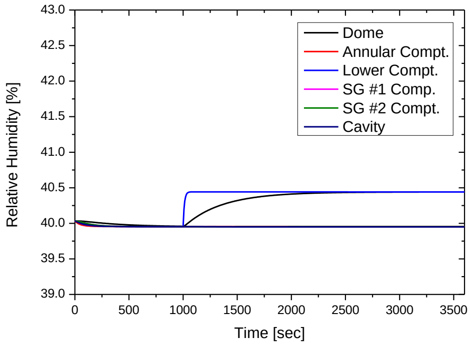


Fig. 5. Relative Humidity – Leak@Lower Compartment

In Fig. 6, the relative humidity of each compartment with leakage at Cavity is presented. Compared to SG #1 compartment, the volume of Cavity is about 3 times smaller. Thus, the relative humidity increment would be much larger than the one in the reference case (leak at SG #1 compartment). Due to inter-compartment flows, the relative humidity of other compartments except Annular compartment would also be increased.

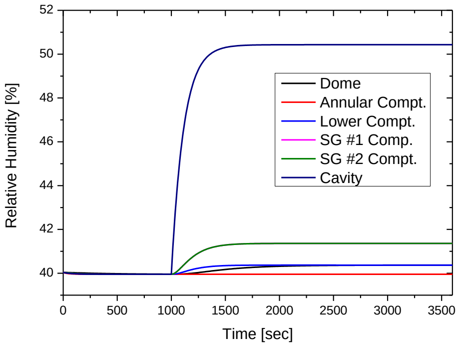


Fig. 6. Relative Humidity – Leak@Cavity

3.4. AHU Flowrate Variation

In Fig. 7, the relative humidity of each compartment with 50% RCFC flow is presented. Compared to Reference case, the behavior of relative humidity in SG #1 compartment would not be changed significantly. However, the relative humidity in other compartments would be changed significantly due to decreased condensation and inter-compartment flows.

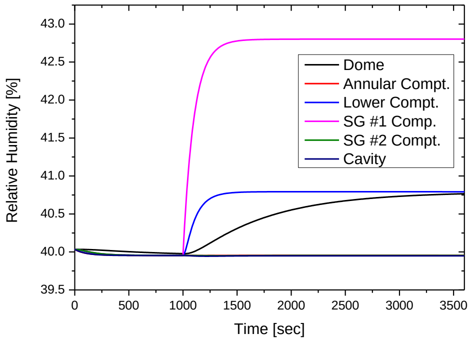


Fig. 7. Relative Humidity – 50% RCFC Flow

4. Conclusions

Modelica model has been developed for estimating the reactor building relative humidity change. The mathematical conservation equations and the equations of state are derived and solved by using OpenModelica M&S environment. The simulation results would be used to determine the measurement device specification and develop the advanced RCS leakage detection method. The model will be further developed by incorporating the gas diffusion and radioactivity estimation.

Acknowledgements

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[1] Chapter 9, APR1400 Final Safety Analysis Report, KHNP.
[2] P. Fritzson, OpenModelica User's Guide Release v1.19.0-dev-107-g6ae89ac5ea9, Open Source Modelica Consortium, 2021.