Numerical Simulation of Thermal Hydraulic Behavior in a Containment Filtered Venting System

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A containment filtered venting system (CFVS) protects the containment from overpressure when a severe accident occurs. It filters radioactive materials before the radioactive materials are released to the environment. After the Fukusima NPP accident, the issue of the necessity of CFVSs was raised and both foreign and domestic NPPs are preparing CFVSs. As the designs, manufacturing, performance tests for CFVS technology were mainly developed by foreign vendors, domestic vendors have become aware of their need to develop CFVS technology locally. It is essential to determine the thermal hydraulic behavior in the CFVS. Thermal hydraulic behavior depends on the CFVS's component configuration because a CFVS consists of various components. Thus, we need to verify a thermal hydraulic performance the CFVS's component configuration for the CFVS design. We conducted a 3-D CFD analysis for gas-flow on the CFVS components. We considered the 3-D geometry of the CFVS components, the moisture separators, metal fiber filters and other inner components, to perform the 3-D CFD analysis. We set some assumptions for this study. First, the gas in the vessel was a mixed gas and the metal fiber filter had porous media. Both were used to simulate the steam and non-condensate gas behavior. The ratio and flow rate of gas, which was filtered by the CFVS, were taken from MAAP results. The decay heat by the radioactive materials in metal filter was calculated as an energy source term. We chose a k-epsilon turbulent model to simulate the turbulent gas characteristics. We obtained the various results using the CFD analysis: the gas flow characteristics, pressure drop at the component inlet/outlet, hot spot by decay heat in the metal fiber filter and the hydrogen concentration by the inflow. The pressure drop by gas flow was under the design specification when the CFVS open operation reached a steady-state. We confirmed that the metal fiber filter integrity was adequate for use in the CFVS. We also verified that hydrogen concentrations in the vessel were dependent on the concentration at the inlet of the vessel because the hydrogen concentration at the vessel inlet did not exceed the design specification.

I. INTRODUCTION

The integrity of containment in a nuclear power plant is essential whether or not the nuclear power plant is operating. Generally, temperature or pressure rising above the design specifications is caused by a design-based accident. The effects of harsh conditions like high temperature and pressure spread beyond the design-based accident and can develop into a severe accident. If a severe accident occurs, it is highly likely that there is much radioactive material in the containment. When the containment develops a crack due to a severe accident, the radioactive material in the containment can be released to the environment. Therefore, there is no doubt that the containment is the last shield in the nuclear power plant. A Containment Filtered Venting System (CFVS) is installed in the containment to provide overpressure control inside the containment. When a containment develops overpressure, the CFVS operates to control the pressure inside the containment. The necessity of the CFVS was demonstrated by some severe accidents as in the case of the Fukusima accident. In Korea, much research has been conducted on the CFVS, a CFVS has even been installed in the Wolsung-1 nuclear power plant. CFVS venting strategies are considered in various accident scenarios and in the CFVS design parameters (N.R. LEE et al., 2016). If the CFVS is analyzed by a MELCOR computer code over a long operating time, thermal-hydraulic issues may occur (Y.S. NA et al., 2014). The overall features of the CFVS installation and determination of the optimal operating strategies have also been analyzed (Y.M. SONG et al., 2013).

The object of this research was to verify the thermal hydraulic behavior of the upper part of the vessel of the CFVS because it is critical to determine the thermal hydraulic behavior in the CFVS.

II. METHODS

II.A. Analysis Domain

We set the filtered venting vessel as the analysis domain. The analysis domain had the following components: the cyclone, the pre filter and the metal fiber filter [Fig. 1].

The CFVS used in this study consisted of two parts to the physical section: a filtered venting vessel and a molecular sieve. The mixed fluid that contains radioactive material with high temperature and high pressure shifts from the containment to the vessel bottom area when the CFVS operates. Then, the mixed fluid has low level radioactive material that go through the venturi nozzle and water pool, which are in the bottom area of the vessel. The mixed fluid moves ahead of the upper parts, such as the cyclone, pre filter and metal fiber filter. When the mixed fluid is discharged into the outside of the vessel, it almost never contains radioactive material.

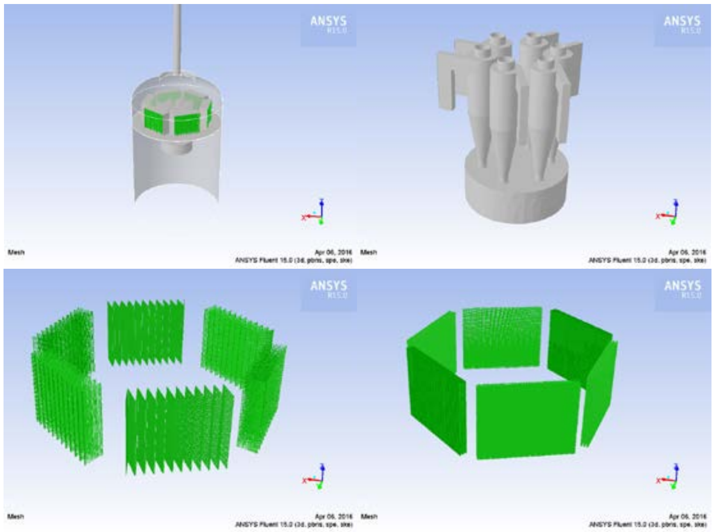

Fig. 1. CFVS geometry in this study
(Clockwise direction: Vessel, Cyclone, Pre filter, Metal fiber filter)

II.C. CFD Mesh Generation and Boundary Condition

The ANSYS tool was used to generate the geometry and mesh and to conduct the analysis. The generated mesh for this study was about 5,643,444 [Fig. 2].

Fig. 2. The generated mesh and geometry.

We assumed that the working fluid in this study was made up steam, air and hydrogen [TABLE 1], and the components of the CFVS were made of SUS-316L.

TABLE I. The working fluid properties.

	Steam	Air	H2
Molecular Weight [kg/kg-mol]	18.015	29.966	2.016
Density [kg/m3]	0.554	6.010	0.419
Specific Heat Capacity [J/kg-K]	Use Profile	1024.320	Use Profile
Viscosity [kg/m-s]	3.4E-4	2.49E-4	8.411E-5
Thermal Conductivity [W/m-K]	0.026	0.036	0.167

We assumed that the porous flow field is at the pre filter and metal fiber filter. We used the Darcy law to obtain a pressure drop between the filters [Eq. 1].

In the Darcy law, there is an assumption that a pressure drop is obtained according to the length. The assumption is that the inside of the filters are made of packed spheres instead of a porous filter material. Using the Darcy law equation, we experimentally obtained the properties such as pressure and filter length. C and D are from the Ergun equation. C and D are the set inertial resistance and viscous resistance, respectively.

$$S_{ij} = -\left(\sum_{j=1}^{3} D_{ij} m v_i + \sum_{j=1}^{3} C_{ij} \frac{1}{2} \rho |v| v_j\right) \qquad (1)$$

S_{ij}: Source term for the I th (x, y or z) momentum equation, v: velocity, ρ: density of gas,
C_{ij}: Inertial resistance, D_{ij}: Viscous resistance

The radioactive material accumulates around the metal fiber filter. We set the heat generation (1193690 W/m3) as the energy source in the metal fiber filter. The heat generation is based on the filter manufacturer. We chose the standard k-ε equations and the standard wall functions to solve the turbulent flow regime. The species transport was also chosen to consider the mixed fluid.

TABLE II shows initial conditions and input data in this study. We had two kinds of analysis in this study. First, the CFVS operation was in steady-state when the CFVS was operating. The other was after the CFVS operation stopped.

TABLE II. Initial conditions and Input data

Initial Conditions	Input Data
Fluid Domain initial conditions	• Velocity: 0 m/s
	•Relative pressure: 101325 Pa
The Pre Filter	• Porosity: 0.3
	•Heat Source: 397.9 W/m^3
The Metal Fiber Filter	• Porosity: 0.3
	•Heat Source: 1193690 W/m^3
Inlet/Outlet conditions	• Inlet: Mass flow inlet (15 kg/s)
	• Outlet: Pressure outlet (101325 Pa)
Total Run Time[sec]	•Step 1: by convergence
	•Step 2: 6,000sec after the convergence

III. RESULTS

III.A. Mixed Fluid Behavior

The mixed fluid goes into six cyclones via each cyclone inlet and it moves in rotation along with inside wall of the cyclone. The mixed fluid passes through the cyclone, the pre filter and the metal fiber filter in order. Finally, the mixed fluid is discharged outside of vessel [Fig. 3].

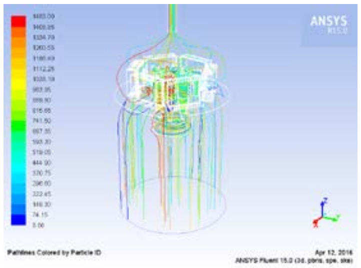

Fig. 3. The mixed fluid behavior in the analysis domain.

III.B. Thermal-Hydraulic Factor of the Mixed Fluid

TABLE III shows the results of case 1 in regard to the thermal-hydraulic factor of the mixed fluid in this study.

TABLE III. Velocity, Pressure, Temperature of each component

	Cyclone Inlet/Outlet	Pre Filter Inlet/Outlet	Metal Fiber Filter Inlet/Outlet	Vessel Outlet
Velocity [m/s]	49.80/36.22	4.53/4.53	4.53/4.53	49.8
Pressure [Pa]	151034/129,088 △P=21,946	129088/115,371 △P=13,717	115371/107,141 △P=8,230	101654
Temperature [K]	441.55/441.55	441.55/444.60	444.60/448.09	448.09

We found that the pressure inside the vessel increased to 151,034 Pa and the highest pressure drop occurred between the inlet and outlet of the cyclone [Fig. 4]. We also determined that the difference in velocity at the cyclone has the highest value because the pressure drop is proportional to the difference in velocity [Fig. 5]. Moreover, the temperature increased to 617.34K at the metal fiber filter [Fig. 6]. This is because, considering the radioactive material, we set the energy source at the metal fiber filter. We found that the temperature at the metal fiber filter rose as time passed. In 2, the change in pressure and velocity was slightly less than the temperature change. The temperature rose as time passed as in case 1 [Fig. 7].

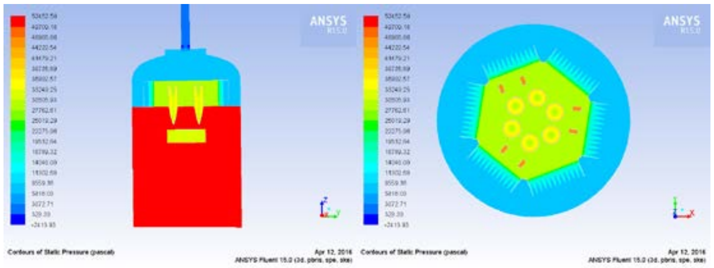

Fig. 4. The pressure distribution inside the filtered venting vessel.

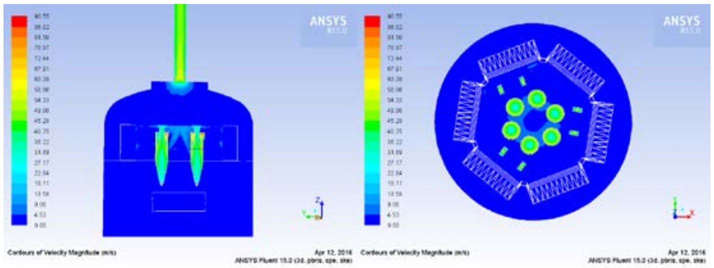

Fig. 5. The velocity distribution inside the filtered venting vessel.

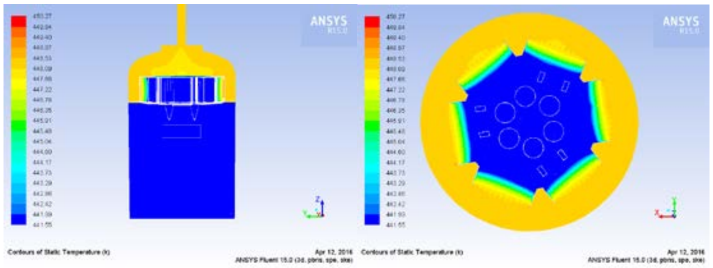

Fig. 6. The temperature distribution inside the filtered venting vessel.

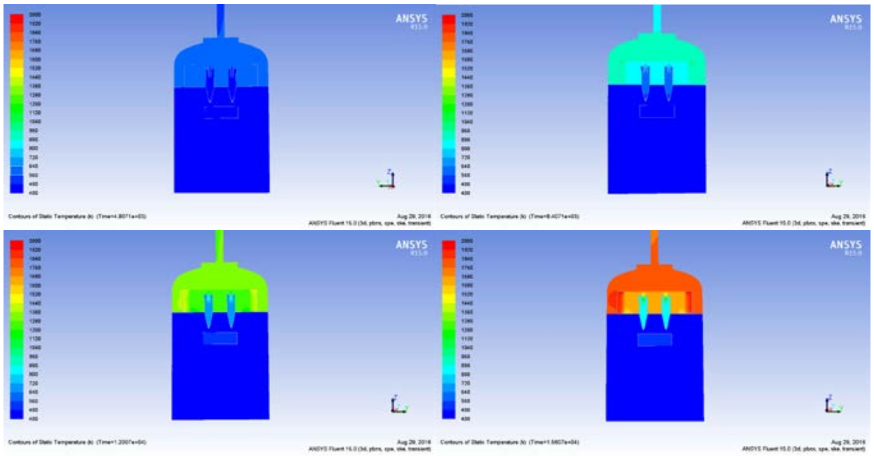

Fig. 7. The temperature distribution with time (1-4 hours, interval: 1 hour)

IV. CONCLUSIONS

We studied the mixed fluid behavior at the upper part of the filtered venting vessel and the thermal-hydraulic factors, such as velocity, pressure and temperature, for each component of the filtered venting vessel. The behavior of the mixed fluid was what we had expected. The results also confirmed that the pressure and velocity operated under the reasonable conditions. The main function of the cyclone is to separate the moisture. No one had attempted to install a cyclone in the CFVS system until now. We are trying to install a cyclone in the CFVS to separate the moisture for improved performance. Even though before starting this study we had been concerned that the cyclone would suffer from a high pressure drop, the calculated pressure drop (21,946 Pa) in the cyclone was reasonably under the designed total pressure (101,325 Pa).

ACKNOWLEDGMENTS

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