Thermal Hydraulic Analysis on Containment Filtered Venting System

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1. Introduction

Containment filtered venting system (CFVS) is a system to filter the fission products in the containment atmosphere prior to the release to environment in case of severe accident with containment over-pressurization. It mainly consists of discharge pipe from containment to CFVS system (inlet), the vessel containing the filtration components and exhaust pipe to atmosphere (outlet). Note that the efficiency of the filtration components (e.g. scrubber, droplet separator, metal fiber filter, molecular sieve) would depend on the flow conditions (e.g. pressure, velocity). In addition, the size of the filtration system is dependent on the characteristics of the discharged flows. Therefore, it is important to understand the thermal hydraulic properties of the flows and the behavior of filtration components.

In this study, the thermal hydraulic conditions (e.g. pressure and flow rate) at each component have been examined and the sensitivity analysis on CFVS design parameters (e.g. water inventory, volumetric flow rate). The purpose is to know the possible range of flow conditions at each component to determine the optimum size of filtration system. GOTHIC code has been used to simulate the thermal-hydraulic behavior inside of CFVS.

2. Overview of CFVS Behavior

The schematic of the typical CFVS is presented in **Figure 1**. CFVS can be composed of inlet pipe (i.e., discharge line from containment), filtration components (e.g., wet scrubber, droplet separator, metal fiber filter) and output pipe (i.e. stack). A valve can be placed in the inlet pipe so that the release from the containment to CFVS can be initiated by opening the valve manually if the preset pressure is reached. The released gases are filtered by flowing through filtration components. Several concepts have been proposed by vendors; however, the pool scrubbing method is dominant due to its high efficiency. To satisfy the specific decontamination criteria and regulatory requirements, more filtration components can be added so that released gases can pass through several filtration stages subsequently. The filtered gases can be vented to the environment through the outlet pipe. A rupture disk or an orifice can be placed in the outlet pipe to control the CFVS operating pressure. Note that in this study, the orifice is located in the outlet pipe to maintain the pressure in CFVS almost same with containment pressure (i.e. sliding pressure operation), that is beneficial because the CFVS vessel size can be reduced due to increased saturation temperature compared to operation in the atmospheric pressure (i.e. without orifice),

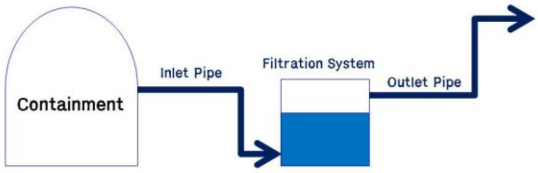

Figure 1. Schematics of CFVS

3. GOTHIC Modeling and Simulation

The CFVS is simplified with the components as mentioned above and modeled by GOTHIC code [1] as shown in **Figure 2**. The inlet pipe and the CFVS vessel are modeled by single control volumes. The valve component is put in the flow path between the inlet pipe and the vessel to model the CFVS operation initiation/termination according to the containment pressure (i.e. 500 kPa(a)[1] for initiation and 150kPa(a) for termination, respectively). The outlet pipe is separated by two control volumes to see the flow condition changes before and after the orifice component. Detailed modeling specifications of the reference case are summarized in **Table I**. Note that it is assumed that the pressure drop due to filtration components and pipes is 1 bar and modeled accordingly. The mass flow rate is assumed as 20 kg/s and the orifice size is specified accordingly.

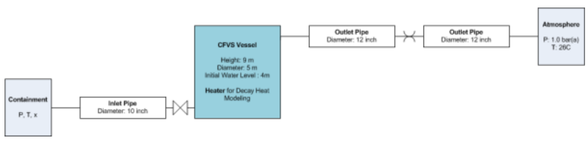

Figure 2. Nodalization of CFVS for GOTHIC simulation

Table I. Modeling Specification of reference CFVS

Parameter	Value
Inlet Pipe Diameter	10 inch

[1] the design pressure of the reference plant (OPR1000) is 4.93 kPa(a).

Outlet Pipe diameter	12 inch
Vessel Height	9 m
Vessel Diameter	5 m
Initial Water Level in Vessel	4 m
Mass flow rate of released gas	20 kg/s
Decay heat of Aerosols at CFVS vessel	400 kW

3.1 Case 1 - Constant Containment Condition

To investigate the pressures at CFVS components and the vessel water level changes, the condition of the containment is assumed as constant (i.e. containment pressure: 5 bar(a) / temperature: saturation temperature of partial steam pressure). Regarding the CFVS vessel water level as shown in **Figure 3**, the CFVS operation can be characterized into two phase: condensation phase and evaporation phase. Initially, the water in CFVS vessel is atmospheric condition (i.e. 20˚C and 1 bar(a)). As the release gases with high temperature flowed into the vessel, the water temperature inside of the vessel is increased due to delivered energy by flows and the water level is also increased due to steam condensation and thermal expansion. Once the pressure reaches the saturation temperature, the water in the vessel would be evaporated due to delivered excessive energy plus decay heat of fission product aerosol; thus, the water level starts to decrease.

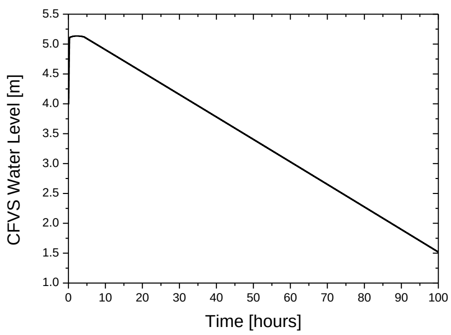

Figure 3. CFVS Vessel Water Level (Constant Containment Condition)

The calculated flow conditions in the CFVS components are summarized in **Table II**. It is important to note that the orifice plays an important role in flow conditions and filtration efficiency. Firstly, the choking at the orifice limits the mass flow rate in the entire system. Secondly, it keeps the system pressure high. Thus, the saturation pressure in the vessel increases and the excessive energy from containment decreases. As a result, the vessel size and water inventory can be reduced. Thirdly, the orifice induces the significant pressure drop, which results in the volumetric flow rate increase and adverse effects on the dry filters located at the downstream side (e.g. molecular sieve).

Table II. Flow Conditions in CFVS Components

Parameter	**Value**
Mass Flow Rate at Inlet and Outlet	20 kg/s
Volume Flow Rate of Inlet	6 m^3/s
Volume Flow Rate of Outlet (Orifice Upstream)	8 m^3/s
Volume Flow Rate of Outlet (Orifice Downstream)	20 m^3/s
Pressure at Orifice Upstream	4 bar(a)
Pressure at Orifice Downstream	1.8 bar(a)

3.2 Case 2 - Transient Containment Condition

Note that the containment pressure would be decreased as the venting is continued. Regarding the CFVS vessel sizing, the assumption of the constant containment pressure must be conservative because results in the large water level variation. However, in case of actual CFVS operation, the discharge flow rate would be decreased due to reduced containment pressure. Decreased flow rate might be problematic because the wet scrubber (e.g. Venturi scrubber) requires a certain level of flow velocity to maintain its filtering efficiency. To investigate the level of conservatism and the flow rate changes during the CFVS operation, the realistic simulation is conducted, i.e. containment conditions (e.g. pressure, gas composition, temperature) are modeled as boundary conditions so that the time-dependent behavior is explicitly examined. The containment conditions are extracted from the severe accident analysis [2]. As can be seen in **Figure 4**, the containment pressure is changed due to CFVS opening and closing. Other than pressure, the temperature, the gas composition and the decay heat are modeled as boundary conditions.

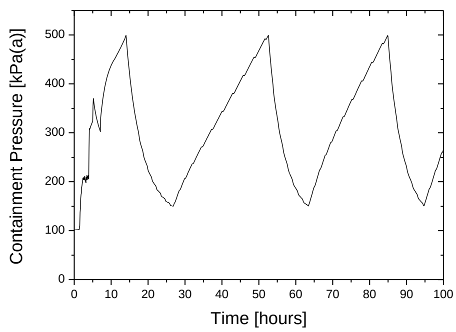

Figure 4. Containment Pressure

In **Figure 5**, the water level of the vessel is presented. Right after the CFVS operation, the water level is increased due to thermal expansion and condensation. After the saturation temperature reached, the evaporation occurs due to both of energy delivered by the superheated flows and decay heat. Due to the lowered containment pressure by venting, the CFVS operation is terminated and the valve is closed. Then, the decay heat from the fission products transported during the CFVS operation is the only energy source for evaporation. One can see the diminished slope in water level changes, i.e. reduced water evaporation rate.

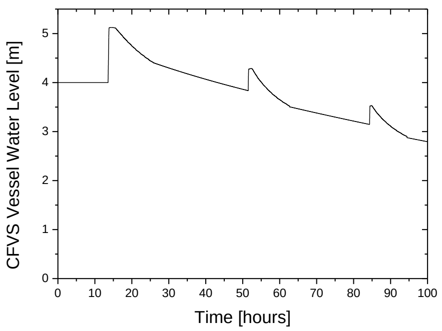

Figure 5. CFVS Vessel Water Level (Transient Containment Condition)

Figure 6 shows the flow rates at different locations in CFVS. Note that the volumetric flow rate is important parameter for filtration efficiency because it relates to the residence time in the filter components, i.e. the longer the particles stay in filters, the higher possibility those are filtered. One can notice that though the mass flow rate is varied significantly during the CFVS operation, the volumetric flow rates at the inlet and outlet (orifice upstream) are not changed much. This implies that the velocity at the filtration components would be maintained. However, the volumetric flow rate at the orifice downstream is very high and changed significantly. Therefore, it should be careful and properly designed to add the filtration component at the orifice downstream.

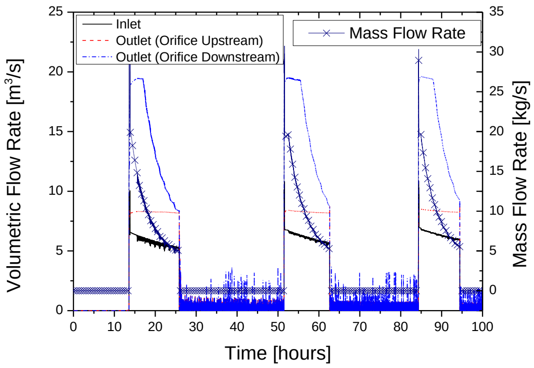

Figure 6. Volumetric and Mass Flow Rate

4. Conclusions

The behavior of flows in the CFVS has been investigated. The vessel water level and the flow rates during the CFVS operation are examined. It was observed that the vessel water level would be changed significantly due to steam condensation/thermal expansion and steam evaporation. Therefore, the vessel size and the initial water inventory should be carefully determined to keep the minimum water level required for filtration components and not to flood the components in the upper side of the vessel. In this study, swelling and droplet generation have not been considered but they must be important factors to determine the vessel size. Knowing that reliable physical model is not presented, they will be considered with the experimental data. It has been also observed that the volumetric flow rate is maintained during the CFVS operation, which is beneficial for pool scrubbing units. However, regarding the significant variations at the orifice downstream, careful design would be necessary.

Acknowledgements

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[1] Numerical Applications, Inc., GOTHIC Containment Analysis Package Version 7.2a, NAI 8907-02, Rev 17, 2006

[2] Youngsuk Bang, et al., “Severe Accident Analysis for Containment Filtered Venting System Design”, Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, May 29-30, 2014