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Design Aspects of Wet Scrubber System

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1. Introduction

A Containment Filtered Venting System (hereafter CFVS) is one of the major features to prevent the damage of the containment integrity from the severe accident such as a station blackout. The main functions of CFVS are the filtration of particulate and gaseous form of fission products as well as the discharge of steam with non-condensable gases from the containment. The pre-existing CFVS developed by global engineering companies can be classified into two types. One is the dry scrubber system with filtration components and connection pipes. The other is the wet scrubber system with water pool, filtration components and connection pipes. Since the decay heat from the filtered fission products is quite large, about several hundred kW, the design of scrubber system should consider the treatment of decay heat. The water pool in the wet scrubber system has advantage to cope with decay heat based on the thermal hydraulic balance such as condensation and evaporation inside it.

This study focuses on the design aspects of the wet scrubber system to estimate the required water pool mass during the mission time and size of the scrubbing tank including inner structures.

2. Design Aspects of Wet Scrubber System

The primary importance to design the wet scrubber system is the amount of water required to treat the decay heat as well as superheat between the discharged steam with non-condensable gases and water pool. The design variables of the required water mass are the decay heat and thermal conditions of discharge flow. The thermal conditions of discharge flow depend on the opening pressure from the containment. The opening pressure can be determined with the consideration of plant type and containment design pressure. Since the purpose of CFVS is to maintain the containment pressure below the design pressure during severe accident, the opening pressure is typically between the containment design pressure and ultimate pressure.

The amount of water pool required during the mission time should consider mass increase due to the condensation during the initial phase of the CFVS operation and mass decrease due to the evaporation after the water pool is saturated and boiling occurs.

2.1 Condensation period

The water pool and scrubber tank initial temperature is same as room temperature during the initial phase of the CFVS actuation. Thus, the steam from the containment under high pressure would be condensed inside water pool and at the wall of scrubber tank and surface of the inner structures. This increases the water mass until the temperature of the structure and water pool is saturated at operating pressure. During this period, the water level would be increased from the initial water level. The water mass increase can be estimated with following steps.

• Heat required for the structure temperature increase

$$Q_s = m_s c_s (T_{sf} - T_{si})$$

where, m_s, c_s, T_{sf} and T_{si} are structure mass, structure heat capacity, structure final temperature and structure initial temperature, respectively.

• Heat required for the water temperature increase

$$\boldsymbol{Q_{liq} = m_{liqi}(h_{liqs} - h_{liqi})}$$

where, $\boldsymbol{m_{liqi}}$, $\boldsymbol{h_{liqs}}$ and $\boldsymbol{h_{liqi}}$ are initial water mass, saturated water enthalpy and initial water enthalpy, respectively.

• Total heat required for the structure and water temperature increase

$$Q_{req} = Q_s + Q_{liq}$$

• Water mass increase due to condensation

$$M_{liqc} = Q_{req} / h_{fg}$$

where, h_{fg} is latent heat.

2.2 Evaporation period

After the water pool is saturated at the operating pressure, the water mass would be decreased due to the evaporation from the water pool surface. This causes the decrease of water level inside the scrubber tank. Once the water temperature reaches saturation temperature during the initial phase of the CFVS actuation, the water level would be continuously decreased during the remaining operation period of the CFVS. The evaporation can be estimated with following steps.

• Evaporation due to the superheat of steam
The heat transferred from inlet steam to water pool is estimated as

$$Q_{steam} = m_{steam}(h_{steamc} - h_{steamt})$$

where, m_{steam}, h_{steamc} and h_{steamt} are inlet steam mass flow, inlet steam enthalpy and scrubber tank steam enthalpy, respectively.

The water mass flow evaporated from the water pool is calculated as

$$M_{steame} = Q_{steam} / h_{fqt}$$

where, h_{fqt} is latent heat of the water pool.

The water mass evaporated due to inlet steam superheat can be estimated as

$$m_{steame} = m_{steame} \times t_m$$

where, t_m is CFVS mission time.

• Evaporation due to the superheat of non-condensable gas

The containment atmosphere would be the mixture of steam and non-condensable gases during the CFVS operation. Relatively large portion of non-condensable gas can be existed during the initial phase of the CFVS operation. On the other hand, the portion of it would be continuously decreased with CFVS operation time. The water mass evaporated due to inlet non-condensable gas superheat can be estimated by the same procedures as the evaporation due to inlet steam superheat.

$$m_{nce} = m_{nce} \times t_m$$

where, m_{nce} is evaporated water mass flow due to the non-condensable gas superheat.

• Evaporation due to the decay heat from filtered fission products

The water mass flow evaporated from the water pool due to the decay heat is estimated as

$$m_{decaye} = Q_{decay} / h_{fqt}$$

where, Q_{decay} is decay heat from filtered fission products.
The water mass evaporated from the water pool is then calculated as

$$m_{decaye} = m_{decaye} \times t_m$$

The water mass change due to the condensation and evaporation is directly related to the scrubber tank sizing. Firstly one assumes the diameter and height of the scrubber tank and initial water level inside the tank. Secondly the water level change due to the condensation and evaporation during the CFVS mission time can be estimated with the procedures described above. However, the lowest water level inside scrubber tank should be higher than the exit of the scrubbing nozzle to maintain the filtration capability of scrubbing nozzle. The highest water level should be lower than the elevation of filtration component or droplet separator installed at the gas space above the water pool.

2.3 Level Swelling

Another important aspect of the wet scrubber system is the water level swelling due to the non-condensable gas into the water pool. The water level increase due to the level swelling, so called two-phase mixture level should be considered to install the filtration component or droplet separator at the gas space inside the scrubber tank.

Fig.1 shows the effect of superficial gas velocity on gas hold-up in air-water system. As gas velocity is increased, the volume of water pool begins to expand homogeneously and the swelling water level is linearly increased with the superficial gas velocity in a fixed scrubber tank diameter. When the gas velocity reaches a certain velocity, so called a transition velocity, the bubble usually starts to coalesce to produce the large bubbles. The gas hold-up is generally correlated as

$$\varepsilon_g = a\, U_g^n$$

where, ε_g and U_g are gas hold-up and superficial gas velocity respectively.

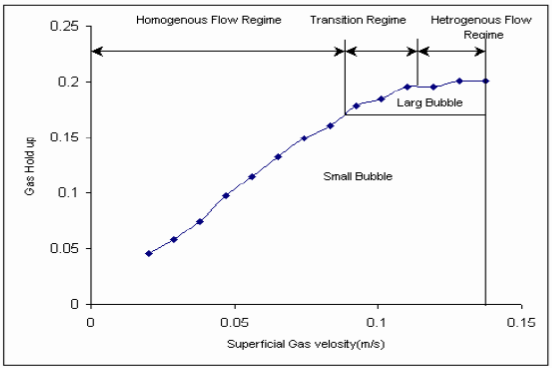


Fig.1 Effect of superficial gas velocity on gas hold-up in air-water system [1]

Paul Scherrer Institut (hereafter PSI) performed the experiments for the level swelling effect using the

VEFITA facility. PSI used the nitrogen gas at the inlet. Fig.2 indicates the level swelling results in the VEFITA facility. The gas hold-up is increased with the gas space pressure in the scrubber tank at the same gas superficial velocity. Since there are several mixing elements in the water pool, these might suppress the level swelling effect.

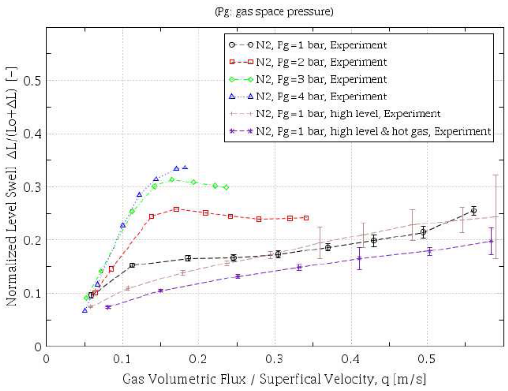
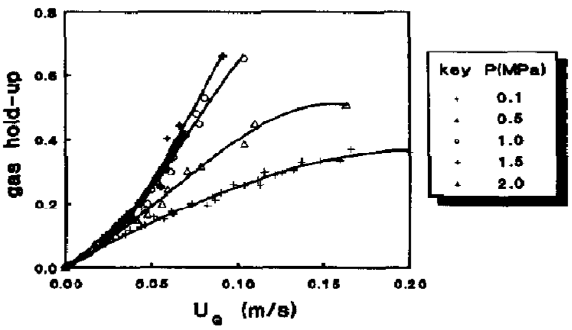
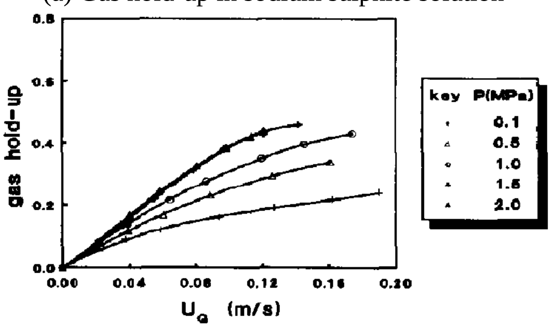


Fig.2 Level swelling results in VEFITA facility [2]

In the wet scrubber system, the chemical additives such as sodium thiosulfate, $Na_2S_2O_3$ to decompose the elemental iodine or organic iodide and sodium hydroxide, NaOH to control pH are mixed in the water pool. Fig.3 shows the gas hold-up in a sodium sulphite solution and that in deionized water. The results showed that the gas hold-up in sodium sulphite solution is increased, compared to that in deionized water at the same superficial velocity.



(a) Gas hold-up in sodium sulphite solution



(b) Gas hold-up in deionized water

Fig. 3 Gas hold-up in sodium sulphite solution and in deionized water [3]

4. Conclusion

The design of the wet scrubber system include the estimation of the required water mass during the mission time and sizing of the scrubber vessel to contain the water pool. The condensation due to the inlet steam and evaporation due to the steam and non-condensable gas superheat and decay heat from filtered fission products should be considered to estimate the water mass required to maintain its function during the mission time. On the other hand, the level swelling due to the non-condensable gas is another important design aspect on the sizing of the scrubber vessel and determination of the entry elevation of the filtration components such as the droplet separator or filter. The minimum water level based on the minimum collapsed water level should be higher than the exit of scrubber nozzle. The maximum water level based on the sum of the maximum collapsed water level and swelling water level should be lower than the entry of the component located at the gas space in the scrubber tank.

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