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Large scale experiments to capture aerosol particles released from NPP in a severe accident

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1. Introduction

In light-water reactors, the containment functions as a shield of the reactor core and related coolant system to prevent the release of radioactivity into the environment in the case of an event of core melt leading to severe accident. In case of containment leakage or rupture due to over-pressurization after severe accident or air plane strike from outside, the radioactivity can be spread out to the environment. This type of radioactivity release into the environment can have serious radiological consequences. The example of such calamity is Fukushima nuclear accident on March 11, 2011 in Japan which still has serious negative impacts today on nuclear industry, public health, national economy and public acceptance of nuclear power in neighboring countries and neighboring countries

To mitigate the radiological consequences of such releases from nuclear power plant, an emergency response spray system can be deployed outside the reactor containment [1]. The objective of this research is to examine the use of spray technology to capture the radioactive gases and aerosol particles released into the environment during the course of severe accident. For this purpose, a scaled down (1: 50) APR-1400 nuclear power plant model was designed and set up with the placement of leaked holes at different locations of containment structure to examine the spray performance to capture the aerosol particles released from leaked containment. The effect of several variables such as spray flow rate, spray material (water and foam), spray angle, gas release rate and windy conditions etc. on spray performance to capture the 0.02 µm TiO_2 aerosol particles were examined.

2. Experimental

A large-scale experimental facility was designed and constructed to evaluate the aerosol particle capture efficiencies of water and foam-based sprays.

The system comprised of eight parts based on their functions:

1. Large spray chamber (5m × 5m × 5m)
2. Scaled down (1: 50) APR-1400 nuclear power plant model
3. Spray solution tank along with spray pump
4. Compressed air system and aerosols generator and related piping
5. Spray nozzle mounted on the stand
6. HEPA filters at the outlet section of chamber
7. Sprayed solution collecting trays and tank
8. Electrical fans to generate windy conditions

The schematic diagram and photographs of experimental arrangement are shown in the Figures 1-2.

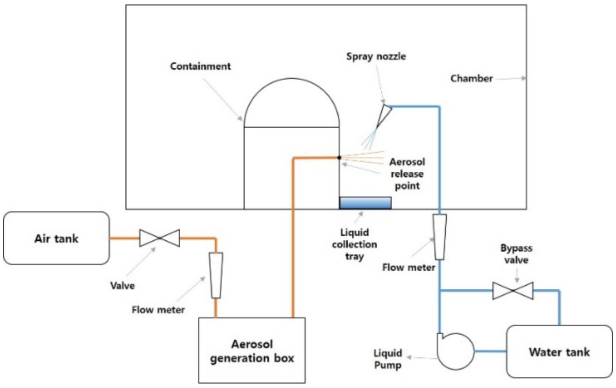

Fig. 1. Schematic diagram of experimental setup

Fig. 2 (a). Experimental arrangement

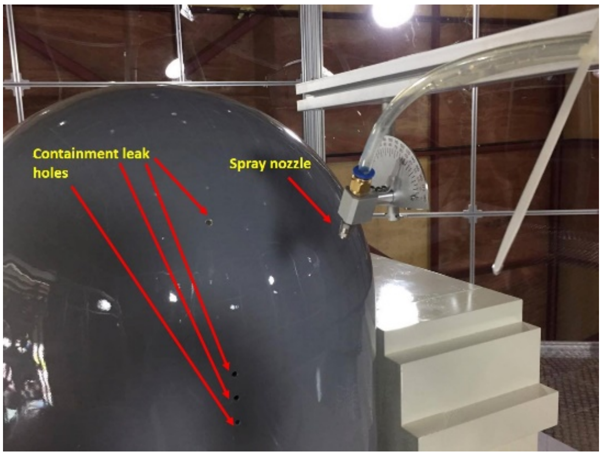

Fig. 2 (b). Experimental arrangement

Fig. 2(c). Experiment in process

The full cone 1/8G5 spray nozzle was used to generate water and foam sprays which was mounted on a movable stand at the distance of ~ 45 cm from leaked containment hole and was oriented at 55^0 toward the hole the floor of the chamber. The non-radioactive TiO_2 aerosol particles contained in the aerosol generating box were released from containment hole to the chamber environment through Teflon pipe by passing the compressed air as an aerosol carrier gas. A Total 5 grams of non-radioactive TiO_2 (79.866 g/mol) aerosols of 0.02 µm size was used in each experiment.

The water and foam solution was supplied to the nozzle through a pump installed in the experimental setup. Homogeneous foaming solution was prepared in a tank by mixing 3 % by weight of foaming agent-sodium lauryl sulphate ($NaC_{12}H_{25}SO_4$) in water.

In each experiment, the sprayed water and foam solution containing captured aerosol particles was collected in a tank and further analyzed to determine the amount of captured particles. UV-visible spectrometer was used to determine the amount of aerosols captured in the sprayed solutions. The UV-Visible spectrometer was first calibrated by obtaining the absorption spectra of standard solutions of different concentrations and drawing the calibration curve

Pre-experiments were conducted in order to develop the understanding of aerosol particle release and spray coverage on to the leaked location of reactor containment and to minimize the uncertainties in collection efficiencies. The procedures of aerosol particles release in the open atmosphere of spray chamber and spray operation of water and foam along with collection of sprayed material containing captured were carefully controlled to be identical in each of the experiments for quality control purposes. The mass balance of aerosols was determined by measuring the aerosol mass in the aerosols generator, supply pipes, and sprayed solutions.

3. Results and Discussions

3.1 Effect of water spray flow rate on aerosol removal efficiency

The results of aerosol removal efficiency as a function of water spray flow rates are shown in Figure 3.

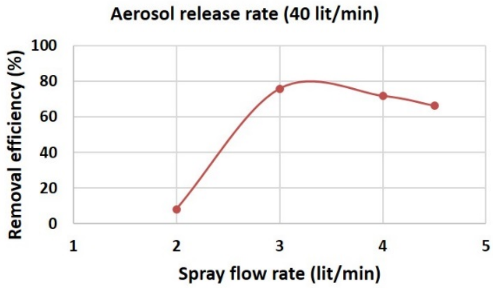

Fig.3 Effect of spray flow rate on aerosol removal efficiency

The flow rates used were 2, 3, 4 and 4.5 liter/min whereas the aerosolized air release rate was fixed at 40 lit/min. The results showed that removal efficiency increased from 8.05 % to 75.79 % by increasing the spray flow rate (2-3 lit/min) but decreased to 66.2 % by further increasing the spray flow rate (4- 4.5 lit/min).

At low spray flow rates, the particles were able to cross the spray region and less interactions of particles with spray droplets led to the decrease in spray removal efficiency. At high spray flow rates, relative velocity of sprays was much higher than aerosol release velocity and hydrodynamic effects were dominated on particles. The particles were dispersed around rather than going into spray region and resulted in less interaction with spray droplets. At medium spray flow rate (3 lit/m), the number of particles entering into spray region were greater and longer residence time of particles in spray region led to the high probability of diffusion into the spray droplets. Consequently, the removal efficiency at 3 lit/m spray flow rate was comparatively higher.

3.2 Effect of aerosolized air release rate on aerosol removal efficiency

Impact of *aerosolized air release rate* was also investigated to assess the removal efficiency of aerosols by water sprays (Figure 4).

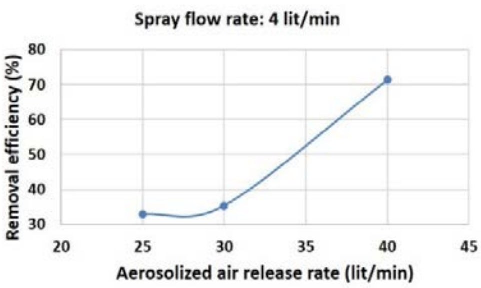

Fig.4. Effect of aerosolized air release rate on aerosol removal efficiency

In this case, the spray flow rate was fixed at fixed at 4 liter/min. Fig shows the results.

It was found that aerosols removal efficiency was increased from 32.9 to 71.3 % by increasing the aerosolized air release rate from 25-40 lit/min. At low aerosolized air release rates, aerosol particles were dispersed largely and lesser aerosols particles were able to enter into spray region. Furthermore, the contact time between the aerosols and the spray droplets was reduced and insufficient for the aerosol-liquid droplets interaction. On the other hand, at higher aerosolized released rates, large number of aerosols penetrated in spray region. The cross flow of aerosolized air through spray region enhanced the interaction probability of aerosols with spray droplets leading to higher removal efficiency. The removal efficiencies are being investigated by further increasing the aerosolized air release rate from 40 lit/min onward.

3.3 Comparison of Aerosol particles removal efficiency by water and foam-based sprays

The spray efficiencies were also investigated for the removal of aerosol particles (TiO_2) for two different types of spray liquids-city water (H2O) and aqueous sodium lauryl ether sulphate ($NaC_{12}H_{25}SO_4$). The results showed that foam-based sprays were more effective even at lower flow rates than water-based sprays in removing aerosol particles (Figure 5).

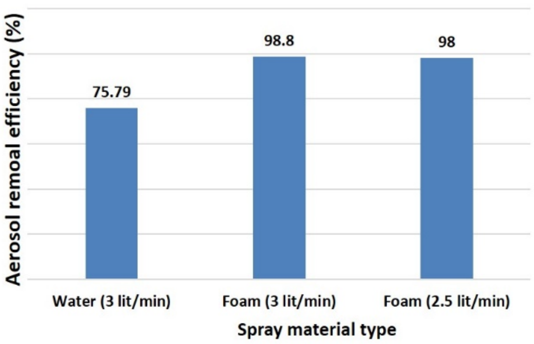

Fig.5. Aerosol removal efficiencies by water and foam sprays

The addition of foaming agent-sodium lauryl sulphate ($NaC_{12}H_{25}SO_4$) in water reduced the surface tension of water [2] which enhanced the captured efficiency of aerosols. Due to better removal efficiency at lower flow rates, foam-based sprays may have advantage over water-based spray in controlling and capturing the gaseous iodine which can minimize the volume of liquid waste.

3.4 Wind impact on aerosol removal efficiency

The water spray effectiveness to remove aerosols in the presence of wind was also studied. In this case, aerosolized air release rate was set to 25 lit/min and spray flow rate was fixed at 4 lit/min. The results showed that aerosol removal efficiency was reduced from 32.9 to 16.01 % in the presence of wind blowing with average velocity of 1.5 m/sec (Figure 6) As the radioactive aerosols particles released from a nuclear power plant during a severe reactor accident consist of various sizes, it was decided to study the impact of aerosol size on the spray removal efficiency. The aerosols of sizes 0.02, ≤0.15 and <5 μm were selected in the experiments based on their high mobility in the atmosphere. The spray removal efficiency for the large sized particles having high inertia was higher as compared with small sized particles (Figure 6).

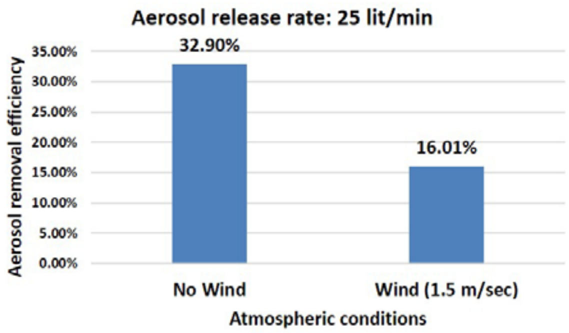

Fig.6. Spray removal efficiency of aerosols in windy environment

3.5 Impact of nozzle orientation in capturing the released aerosol particles

Aerosols removal efficiency was also studied at two different nozzle orientations- 55^0 to the containment leaked hole and vertically downward direction from the top.

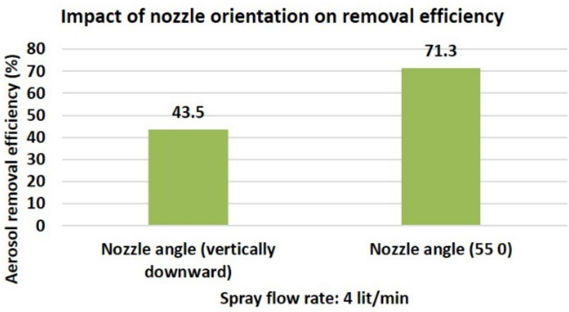

Fig.7. Impact of nozzle orientation on aerosol removal efficiency

The removal efficiency was higher (71.3 %) in case of spray cone directed toward the leaked hole (at 55^0) (enveloping more particles released from the leaked hole) than removal efficiency (43.5 %) with vertically downward direction causing dispersion of released aerosol particle (Fig. 7)

4. Conclusion

This research investigated the removal efficiencies of aerosols particles by water and foam-based sprays at large scale representing open atmosphere. The removal efficiencies were assessed as function of spray flow rates, spray orientation, particles release rates, and the assessment of removal efficiency in windy environment to get optimum operating parameters for spray technology to be used outside the leaked reactor containment building in severe accident.

The following observations were made:

1. The aerosol removal efficiency of foam-based spray is higher when compared with city water-based spray.
2. The aerosol particles removal efficiency largely depends on relative velocities of spray aerosolized air released from containment leaked hole at a particular spray and aerosol release rate
3. The nozzle orientation with large spray coverage area on leaked containment hole improves the aerosol removal efficiency
4. Foam-based spray consumed less water than water-based spray which can minimize the liquid waste volume.
5. Windy environment reduces the aerosol removal efficiency due to dispersion of both spray droplets and aerosol particles.

Based on this study, dimensionless numbers will be explored carefully, since sprayed liquid droplets could have same behavior if dimensionless numbers are equal. After the exploration of dimensionless number, scaling will be considered. Also, the studies regarding spray deployments using more than one of sprays will be conducted in order to cover a containment building under a variety of situations.

REFERENCES

[1] Irfan Younus, Man-Sung Yim, "Out-containment mitigation of gaseous iodine by alkaline spray in severe accident situation," *Progress in nuclear energy.* **83**, 167-176, 2015.

[2] L.Silverman, "Foam encapsulation of nuclear reactor safety," U.S. Patent: 3,338,665, (Aug. 29, 1967).