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Aerosol Deposition Characteristics inside Horizontal Piping

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1. Introduction

In nuclear power plants (NPPs), the interfacing systems loss of coolant accident(ISLOCA) is one type of containment bypass accident scenario resulting in the release of fission products(FPs) in the form of aerosols into the environment if appropriate actions are not taken to prevent core damage during the accidents. In case of ISLOCA scenario, piping networks and the auxiliary building can be the bypass flow path of the containment to release fission products towards the environment [1]. In addition, aerosol concentrations in a situation of a reactor accident can be more than $100g/m^3$ and the aerosol particle diameter can be estimated as 0.44μm (geometric mean diameter) with 1.81 of the standard deviation. The estimated range of released aerosol size distribution can be between 0.1μm and 10μm [2]. Therefore, it is important to estimate the amount of aerosols flowing on main carrier gas inside a piping system can be deposited in terms of the development of severe accident mitigation strategy for a NPP.

The aerosols flowing on the carrier gas inside a pipe can be deposited by several mechanisms such as Browian diffusion, sedimentation, thermophoretic deposition and turbulent deposition [3]–[6]. These deposition models were explained in [7]. Sedimentation (gravitational settling) in horizontal lines can be expressed by particle density and diameter, acceleration of gravity and viscosity of main carrier gas. Also, turbulent flow can lead deposition of aerosol particles in pipe by diffusive mechanism for small particle and inertial mechanism for large particle which can be expressed by dimensionless relaxation time. The relationship between the turbulent diffusion and the turbulent deposition can be defined by the deposition velocity with the deposition correlation of relaxation time [8, 9]. The deposition inside a bend pipe can be dominated by inertial impaction using the radius of the bend and the particle Stokes number [10].

However, it is very difficult to distinguish the single mechanism from the combined one in real life. In addition, the designed experimental facility cannot examine the effect caused by single mechanism. Therefore, quantitative analysis of the amount of removed aerosol during the carrier gas passing through a test section including effects of the combined mechanisms was conducted. The amount of aerosol removal can be evaluated by the decontamination factor (DF) shown as Equation (1) [11].

$$\mathrm{DF} = \frac{\dot{m}_{in}}{\dot{m}_{out}} = \frac{1}{1-\eta} \qquad (1)$$

where η is the particle collection efficiency $\left(\eta = \dot{m}_{ref}/\dot{m}_{in}\right)$, $\dot{m}_{ref} = \dot{m}_{in} - \dot{m}_{out}$.

2. Experimental set up and test conditions

The experimental facility consisted of three components as; a thermal-hydraulic supply system, aerosol related systems such as aerosol generator and aerosol sampling system, and a test section which was a piping system of a 2 inch straight pipe with 90° bend pipe in a horizontal plane shown as Fig. 1 and Fig. 2.

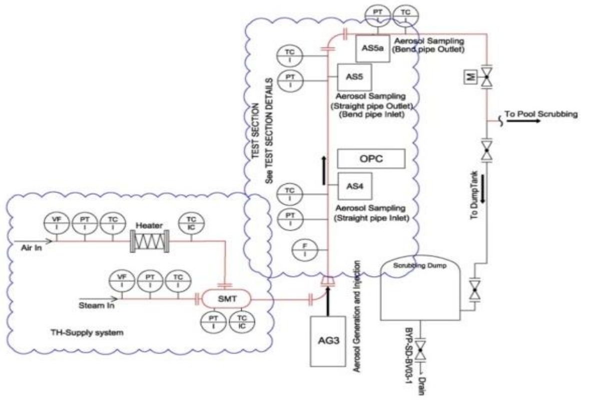


Fig. 1. Schematic of test loop

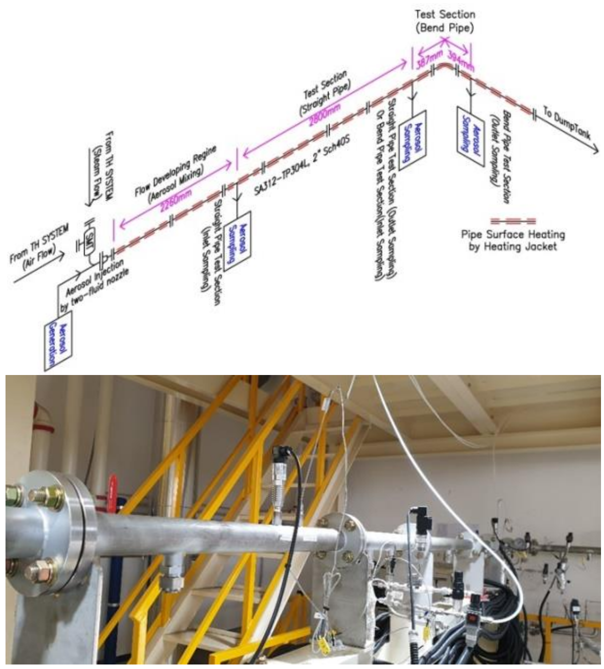
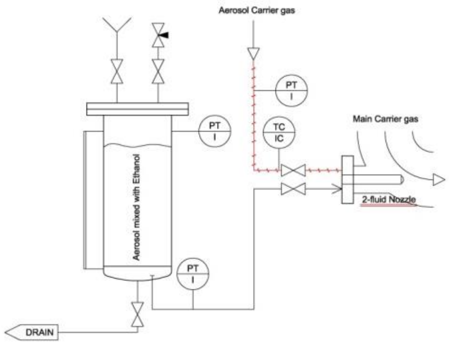


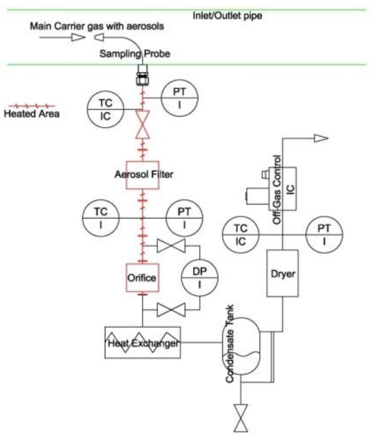
Fig. 2. Schematic and picture of test section

The size of the test section is 2 inch Sch.40S of SA312-TP304. The length of the straight pipe test section is 2800mm and the bend section is around 781mm long. The pressure and the temperature of the test section were measured by pressure transmitters and K-type thermocouple, respectively and the volumetric flow rate of each types of the carrier gas was obtained by vortex flow meter. Furthermore, this volumetric flow rate was converted to mass flow rate by using the pressure and the temperature measured at the each sampling points. The thermal-hydraulic conditions of the tests were controlled by valves in the TH-System.

The aerosol particles for the experiments were silicone-dioxide (SiO_2) which has a spherical shape with the diameter of 0.7μm and 1.5μm. These particles were mixed with ethanol for spraying aerosols into the main carrier gas through the two-fluid nozzle. In addition, the ethanol was vaporized by the heated aerosol carrier gas during the spraying. The schematic of aerosol related system was shown in Fig. 3. In terms of preventing aerosol losses during the aerosol sampling, the aerosol particles were collected at a filter where it is located at just right next to the sampling probe. In addition, the surface of the aerosol sampling path was heated for preventing steam condensation.



(a) Aerosol generator



(b) Aerosol sampling device

Fig. 3. Schematic of aerosol related system

The locations of the aerosol sampling were described in Fig.2. The inlet and the outlet of the straight pipe section were designed to have fully developed flow including aerosols.

The aerosol sampling location at the outlet of the bend test section was selected to evaluate the effect of the bend fitting on the aerosol deposition characteristics. According to JongTae Kim et., al.[12], the velocity profile after an elbow was analyzed by the numerical method. The study presented that the almost fully developed flow was expected after the location at 5 times of pipe diameter (5D) from the bend outlet for an elbow with 2D (2 times of pipe diameter) of R_c (Radius of Curvature) and at the 10D from the outlet, the fully developed flow can be shown under the condition of the Reynolds number between 50,000 and 200,000. The outlet sampling location after the bend of the facility was located at about 6.65D(with R_c:1.5D) from the outlet of the bend. In addition, the range of the Reynolds number of this study was from around 60,000 to 270,000. Therefore, the sampling location at the outlet of the bend was expected to have fully developed flow condition. Also, according to Ke Sun and Lin Lu [13], although the experimental results showed that the aerosol concentration at the bend outlet varied with the distance from the inside curvature of the bend and particle Stokes number, the concentration at the centerline of the bend was similar to the average aerosol concentration. Thus, this means that the aerosol concentration obtained at the bend outlet for this study can be expected as a representative value.

The test conditions of this study were established with respect to the vital parameters such as pressure, temperature, flow Reynolds number and aerosol particle size in terms of the test section of horizontal straight pipe and bend pipe section. The established test conditions are presented in Table I.

Table I: Test Conditions

Target Effect	Case No.(Condition)		Remark
	Straight	Bend	
System Pressure	HA-01(2bar), HA-02(3.5bar), HA-03(5bar)	BA-01(2bar), BA-02(3.5bar), BA-03R(5bar)	Air, 25℃, 0.21kg/s Re#: 273,815, 0.7μm
System Tempera ture	HA-03(30℃), HA-04(90℃), HA-05(150℃)	BA-03R(30℃), BA-04(90℃), BA-05(150℃)	Air, 5bar, 0.21kg/s, Re#: 273,815, 0.7μm
Reynold number	HA-03 (254,647), HA-06 (124,114), HA-07 (59,691)	BA-03 (254,647), BA-06 (124,114), BA-07 (59,691)	Air, 5bar, 30℃, 0.7μm
Aerosol Size	HA-03(0.7μm) HA-03-AS2 (1.5μm)	BA-03(0.7μm) BA-03-AS2 (1.5μm)	Air, 5bar, 30℃, 0.21kg/s, Re#: 273,815,

3. Test Results and Discussion

There were twenty four test conditions which were conducted for this study. The effects of the target variables on the aerosol removal efficiency during pool scrubbing were compared under the similar thermal-hydraulic conditions in order to verify the correlation between the variables and the scrubbing efficiency.

The decontamination factors of each test conditions were calculated by using the aerosol concentrations at the inlet and the outlet of the test section. These aerosol concentrations were converted using the aerosol sampled masses and the sampled flow rate obtained from the aerosol sampling systems. When the every test was conducted, the aerosol sampling was performed for 6 times at each sampling point with the period of 5 min. These sampled aerosol concentrations at the each point were averaged in order to get the representative decontamination factor.

The relationship between the system pressure and the DF in the straight and the bend pipe section was shown in Fig. 4 and Fig. 5, respectively. Three test conditions were conducted under the similar thermal-hydraulic condition. The results explain that the DF increased with the increase of pressure in both test section of straight pipe and the bend pipe. The deposition efficiency between the test conditions of 2 bar(a) and 5 bar(a) was about 20%(from the DF of 1.6 to 2.1) in the straight pipe and 35%(from the DF of 2.1 to 5.3) in the bend pipe. In straight pipe section under the turbulent flow condition, turbulent deposition and Brownian diffusion could be dominant mechanisms, in contrast, inertial impaction mechanism could occur higher deposition rate in the bend pipe [14]. According to [14], the CFD aerosol deposition analysis inside bend pipe with very small and large bulk Stokes number was conducted and the results showed that about 10 to 20% of the particles with Stokes number of 0.05 were deposited due to inertial impaction in turbulent flow condition. Most of the aerosol deposition mechanisms mentioned earlier are related to fluid properties such as density, viscosity of a fluid and etc. rather than directly related to the system pressure. Although these fluid properties can be affected by system pressure, the effect of the system pressure on the deposition efficiency can not be clearly shown.

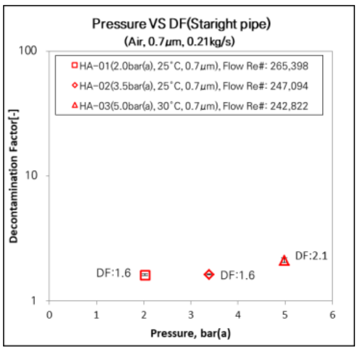


Fig. 4. DF with system pressure in straight pipe

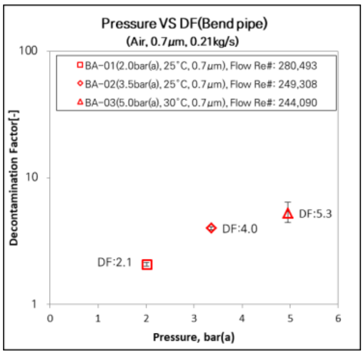


Fig. 5. DF with system pressure in bend pipe

The test results of the system temperature on the aerosol retention are presented in Fig. 6 (Straight pipe) and Fig. 7 (Bend pipe). In the straight pipe section, the results show no tendency of the DF variation in terms of the variation of the system temperature.

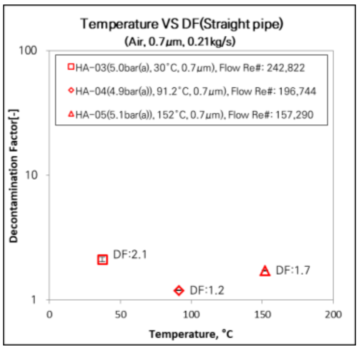


Fig. 6. DF with system temperature in straight pipe

However, the test result seems like that the temperature increased with the decrease of the DF. The system temperature can affect to several fluid properties such as density, viscosity, and Reynolds number. In addition, it also causes thermophoresis deposition. In fact, the temperature effects cannot be clearly found due to the combination of the several deposition mechanisms such as thermophoresis, inertial impaction and turbulent deposition.

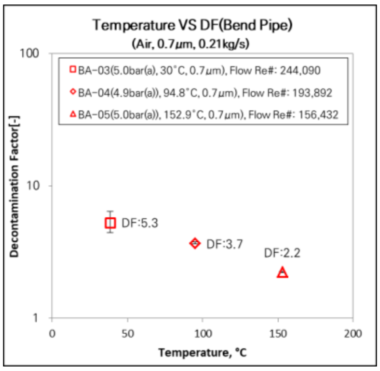


Fig. 7. DF with system temperature in bend pipe

The effect of the Reynolds number on the aerosol retention inside a pipe was examined under the thermal-hydraulic condition of 5bar(a), 30℃ of the system pressure and the temperature. The mass flow rates of the main carrier gas were about 0.21kg/s (HA/BA-03), 0.10 kg/s (HA/BA-06) and 0.05kg/s (HA/BA-07) with the Reynolds number of 242,822, 124,114 and 59,691, respectively. According to the previous studies, the DF increases with the increase of the Reynolds number. However, the results of the test condition in the straight pipe section show the DF among the three conditions maintained around the DF of 2. It can be inferred that too small Stokes number can minimize the effect of the sedimentation and inertial impaction leading to the cancelation of the Reynolds number effect or cause the change of the friction factor for the turbulent deposition due to the aerosol saturation on the inner surface of the straight pipe section under the high aerosol concentration condition.

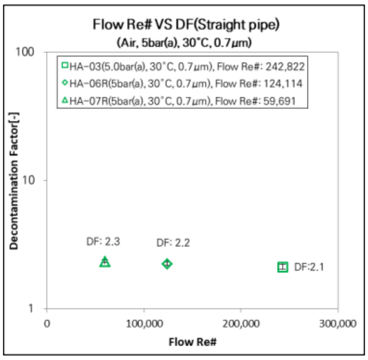


Fig. 8. DF with flow Reynolds number of the main carrier gas in straight pipe

On the other hand, the results in Fig. 9 explain that the DF increases with the flow Reynolds number increase. The DF was increased from 2.7 to 5.3 with the increase of the Reynolds number from 59,000 to 243,000, respectively.

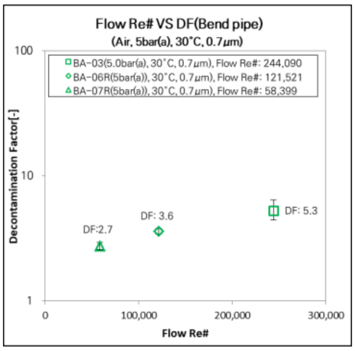


Fig. 9. DF with flow Reynolds number of the main carrier gas in bend pipe

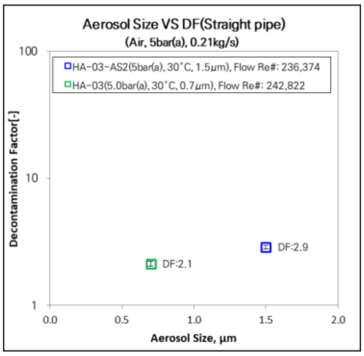


Fig. 10. DF with aerosol particle size in straight pipe

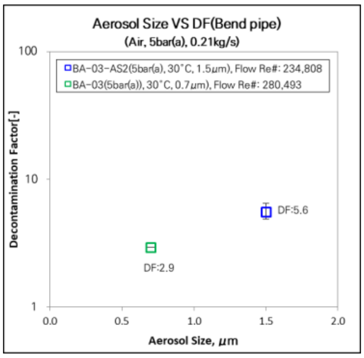


Fig. 11. DF with aerosol particle size in bend pipe

The effect of the aerosol size on the aerosol retention efficiency was investigated under the similar thermal-hydraulic conditions such as 5bar(a), 30℃ and 240,000 of the system pressure, temperature and the flow Reynolds number, respectively. These test condition planed to examine the effect of sub-micron size particle and micron size particle. In the both test section, the size effects can be clearly shown in Fig. 10 and Fig. 11. The DF in the straight pipe was from 2.1 to 2.9 which are equal to 53% and 65% of the aerosol retention efficiency, respectively. In case of the bend pipe section, the DF varied from 2.9 to 5.6 with the increase of the particle size from 0.7μm to 1.5μm.

4. Conclusion

In this study, the aerosol retention performance inside a piping system was experimentally examined under the various test condition. The quantitative DF of sub-micron SiO_2 particles were obtained based on the test parameters such as the system pressure, temperature, flow Reynolds number and aerosol particle size. In general, the results of this study showed that no finding of the relationship between the DF and the system pressure or temperature. The effect of the flow Reynolds number on the DF was partially proportional to each other. In the straight pipe test section, it was hardly to find the relationship between them, otherwise, the relationship between the flow Reynolds number and the DF can be clearly shown in the bend section. Also, the effect of the aerosol size variation on the DF was definitely confirmed under the test conditions. In total, the DF of about 2 in the straight pipe section and the DF range of between 2 and 5.6 in the bend pipe section were observed.

Table II: Aerosol retention behavior inside a piping system with test parameters

Research	Flow Re #	Particle Stk. #	Aerosol size
J. Bouilly et al. [15]	$\propto$ DF	-	-
S.R. Wilson et al. [16]	$\propto$ DF	$\propto 1/\mathrm{DF}$	$\propto$ DF
A.R. Mcfarland et al. [17]	$\propto$ DF	$\propto 1/\mathrm{DF}$	$\propto$ DF
M. R. Sippola and W.W. Nazaroff [18]	Partially $\propto$ DF	$0.01 \sim 1 \propto 1/\mathrm{DF}$ (Sharply) $1 \sim 7 \propto 1/\mathrm{DF}$ (Gradual)	$\propto$ DF
Liu and Agarwal [9]	$\propto$ DF	-	$\propto$ DF
T.M. Peters and D. Leith [19]	$\propto$ DF	$\propto$ DF	$\propto$ DF
This study	Partially $\propto$ DF	$\propto 1/\mathrm{DF}$(Gradual)	∞ DF

Table II summarizes the aerosol retention behavior in terms of the test parameters obtained from previous experiments and this study. Most of the previous experiments had an agreement that when the aerosol particle size is increased, the DF is also increased. However, the effects of flow Reynolds number and particle Stokes number on the deposition efficiency on the deposition efficiency were partially agree among the studies. It can be inferred that these differences could be caused by the variation of the test conditions.

It is expected that results obtained from this study will be used as benchmark data to develop the aerosol retention models for pool scrubbing phenomena, and these data will be a basis to develop the strategy to handle to release radioactive aerosols into the environment during postulated accidents in a nuclear power plant. In the future, it could be necessary for covering wider range and for finding clear correlations among test parameters experimentally.

5. Acknowledgements

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6. References

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