MELCOR Analysis of LACE-ESPAÑA Experiments to Determine the Efficiency of Pool Scrubbing Effect of CFVS

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We analyzed LACE-ESPAÑA experiments which had the objective of determining the overall decontamination factor (DF) exercised by water pools for soluble aerosols of cesium iodide (CsI) using MELCOR 1.8.6. The objective of this study is to figure out which factors dominate the efficiency of the pool scrubbing effect, and to establish a foundation of a regulatory utilization for evaluating the performance of wet-type Containment Filtered Venting System (CFVS, or FCVS). We conducted 20 computations for the analysis; for 10 experiments of LACE-ESPAÑA, two types of aerosol inputs – a Count Median Diameter (CMD) and an Aerodynamic Mass Median Diameter (AMMD) - were used. DFs acquired from computational results were relatively conservative, but there were extremely non-conservative ones. When the size of aerosol distribution had larger median diameter, decontamination effects were better, but the tendency was not a strong one. When the particle fraction of aerosol which had a diameter larger than 1 μm increased, DFs also increased. This tendency strengthened when α, which was defined as the mass fraction of particles having a diameter of less than 1 μm, was below 0.1. In addition, for larger particles of aerosol and higher injection rate of bubble regime, DF increased when steam fractions of injection gas increased.

I. INTRODUCTION

Containment Filtered Venting System (CFVS, or FCVS) for nuclear power plants is used for following purposes; providing means for controlling accidents of plants, and limiting a release of radioactive materials to the environment (Ref. 1). The load of radioactive aerosol from nuclear accident would be hundreds of kilograms. In order to filter radioactive materials, various types of filters are used such as metallic filters or pebble beds for a dry type CFVS or water pools for a wet type CFVS. The water pool of CFVS could retain radioactive materials of an aerosol form from nuclear accidents by 'pool scrubbing' phenomenon (Ref. 2).

The efficiency of the filtration of the wet type CFVS relies on the efficiency of the pool scrubbing. Typically, it is believed the aerosol particles which are sub-micron sized are tend to penetrate which means particles are not tend to be retained to filters. The aerosol particle grows because of their hygroscopicity, agglomeration and coagulation. For this reason, the size of aerosol in the containment building would be considered to have the diameter larger than 1 μm. However, the particle which has the size under 1 μm cannot be excluded, because such particle could exist in dry super-heated conditions or under saturated condition with water droplets (Ref. 3).

The objective of this study is to figure out which factors dominate the efficiency of the pool scrubbing using computational code, and to establish a foundation of a regulatory utilization for assessing the performance of wet-type CFVS. We analyzed LACE-ESPAÑA experiments which was conducted by CIEMAT, Spain, and has the objective of determining the overall decontamination factor (DF) exercised by water pools for soluble aerosols of cesium iodide (CsI). MELCOR 1.8.6 was used to analyze, which is the computational code developed by Sandia National Laboratories for evaluating global phenomena of severe accidents of the light water reactor.

II. METHODS

II.A. DESCRIPTION OF LACE-ESPAÑA EXPERIMENTS

The objective of LACE-ESPAÑA experiments was to determine DFs for CsI, which is soluble aerosol, at the suppression pool of boiling water reactors (BWR) (Ref. 4). The experiments were conducted under relatively high conditions of temperature and pressure (110 °C of pool temperature and 3 bar-abs of pressure). Although the facility represented the suppression pool of BWR, it is considered to be able to be applied for evaluating CFVS because of experimental conditions of high temperature and pressure. Fig. 1 shows schematic diagram of LACE-ESPAÑA experimental facility. Aerosol sources which have various size were injected to the pool horizontally with various injection speeds and steam fractions. The experiments were mostly conducted using single-orifice aerosol vent, but one multi-orifice test was also conducted. TABLE 1 and 2 show fixed parameters for LACE-ESPAÑA experiments and flow rates, respectively.

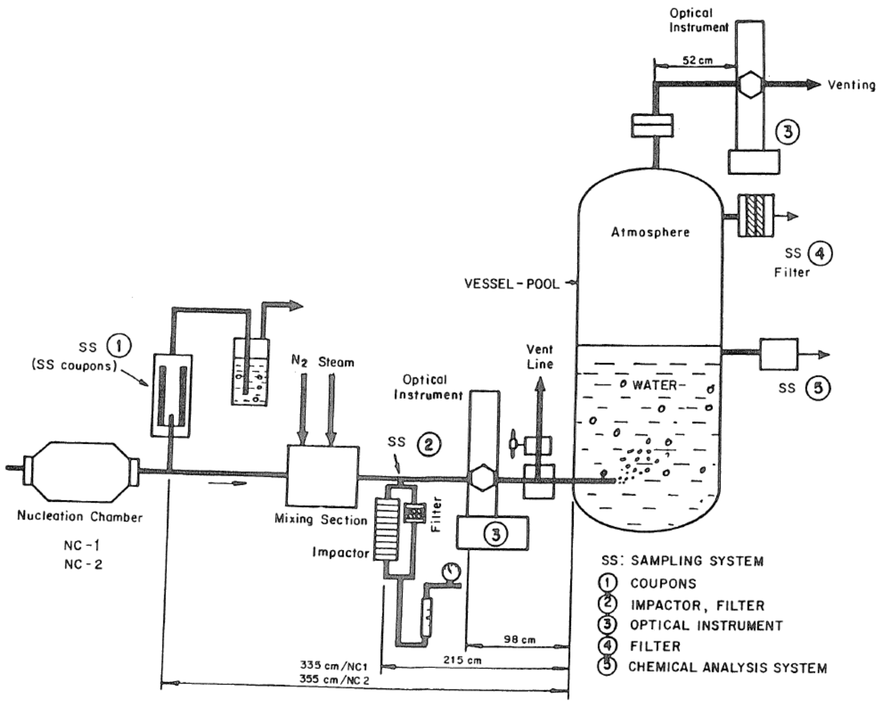

Fig. 1. Schematic Diagram of Facility of LACE-ESPAÑA

TABLE 1. Fixed Parameters for the LACE-ESPAÑA

Parameter	Description	Parameter	Description
Total height of the vessel-pool	5.0 m	Composition of the mixture	Non-condensable gas/Aerosol/Steam
Diameter	1.5 m	Injection temperature	150 °C
Volume of water	5.0 m^3	Type of aerosol	Soluble, CsI
Pool water depth	3.0 m	Discharge position	Horizontal
Pool temperature	110 °C	Injection time	1 hour (3,600 sec)
Volume of the atmosphere	3.1 m^3	Type of non-condensable gas in the mixture and entrained	Nitrogen (N-52)
Pressure of the atmosphere	3 bar-abs	Composition of the atmosphere	Nitrogen (N-52)
Injection depth	2.5 m	Steam	Superheated
Discharge Geometry (Single orifice)	10 mm	Multiple orifices	9 (3x3) of single orifices

TABLE 2. Flow Rates and Steam Fractions for LACE-ESPAÑA Experiments

Category	ID	Flow Rate (kg/s)		Steam Fraction (Volume)
		Nitrogen	Steam	
Smaller Particle, Bubble regime	RT-SB-12/13	9.53E-04	7.50E-05	0.11
	RT-SB-08/09	6.30E-04	2.47E-04	0.38
	RT-SB-04/05	4.18E-04	3.72E-04	0.58
Larger Particle, Bubble regime	RT-SB-14/15	9.14E-04	1.03E-04	0.15
	RT-SB-10/11	7.70E-04	2.64E-04	0.35
	RT-SB-06/07	4.46E-04	5.05E-04	0.56
	RT-SB-02/03	1.58E-04	7.04E-04	0.87
Smaller Particle, Jet regime	RT-SC-01/02	5.03E-03	3.69E-04	0.10
Larger Particle, Jet regime	RT-SC-P/01	4.83E-03	4.01E-04	0.11
Smaller Particle, Multiple orifices	RT-MB-01/02	7.18E-03	5.99E-04	0.11

II.B. DESCRIPTION FOR MELCOR CALCULATION

This study was conducted using MELCOR 1.8.6. The code consists of various packages that deal with numerous physical phenomena. For pool scrubbing effect, MELCOR uses SPARC-90 code which can evaluate aerosol deposition by Brownian diffusion, gravitational settling, and inertial impaction at the entrance of pool, and evaporate forces for the rising bubble (Ref. 5).

TABLE 3 shows input data of the aerosol size distributions for MELCOR calculations. It is known that the size of aerosol particles can be expressed in a lognormal distribution (Ref. 6). MELCOR input for aerosol size distribution was written in RNASxxx record which is the record used for descripting information of aerosol source, and lognormal distribution data using AMMD and CMD can be written for the record. We used both AMMD and CMD data for the aerosol size distribution input since both kinds of median diameters were given in experiments. Median diameters was acquired after the end of each experiment with geometric standard deviation (GSD). For each experiment, two kinds of particle size distributions, were obtained with different methods. The distribution data using AMMD was acquired by means of a least squared lognormal distribution from sectional mass fraction data of experiments, and the sectional mass fraction data was obtained using cascade impactor. Also, the distribution data using CMD was obtained using optical instrument. The parameter "α" which was defined as the mass fraction of particles having a diameter of less than 1 μm, was given in experiments.

Fig 2 shows a visualization for a MELCOR nodalization for LACE-ESPAÑA. Three control volumes (CV) were prepared for a mixing section, a vessel and environments, and two flow paths were prepared for the CVs. Each calculation started at -2000 seconds in order to conduct a thermal-hydraulic steady-state calculation. At 0 second, aerosol injection started at CV 300 and carried to CV 800 with nitrogen and steam, with the flow rate shown in TABLE 2. The calculation ends at 3,600 seconds. DFs in this study was calculated as in Eq (1), and normally, DF is defined as the ratio of the injected mass to the non-retained released mass.

$$\mathrm{DF} = \frac{Injected\ Mass\ [kg]}{Released\ Mass\ [kg]} = \frac{(Injected\ CsI)\,[kg]\ at\ 3{,}600\ sec}{(\mathrm{Injected\ CsI - CsI\ retained\ in\ pool})\,[kg]\ at\ 3{,}600\ sec} \tag{1}$$

TABLE 3. Input Data of Size Distribution for LACE-ESPAÑA Experiments

Category	ID	Input for Size Distribution				α*
		AMMD (μm)	GSD	CMD (μm)	GSD	
Smaller Particle, Bubble regime	RT-SB-12/13	3.0	2.3	1.06	1.67	0.14
	RT-SB-08/09	3.5	1.4	1.12	1.50	0.43
	RT-SB-04/05	3.4	5.4	0.88	1.61	0.21
Larger Particle, Bubble regime	RT-SB-14/15	5.8	3.5	0.94	1.42	0.17
	RT-SB-10/11	7.2	1.6	1.03	1.80	0.02
	RT-SB-06/07	4.2	3.3	1.07	1.66	0.02
	RT-SB-02/03	5.0	3.8	1.08	1.59	0.08
Smaller Particle, Jet regime	RT-SC-01/02	1.7	2.2	0.85	1.42	0.25
Larger Particle, Jet regime	RT-SC-P/01	5.6	3.6	1.04	1.52	0.18
Smaller Particle, Multiple orifices	RT-MB-01/02	4.1	1.8	0.72	1.32	0.06

* α: Particle fraction < 1μm

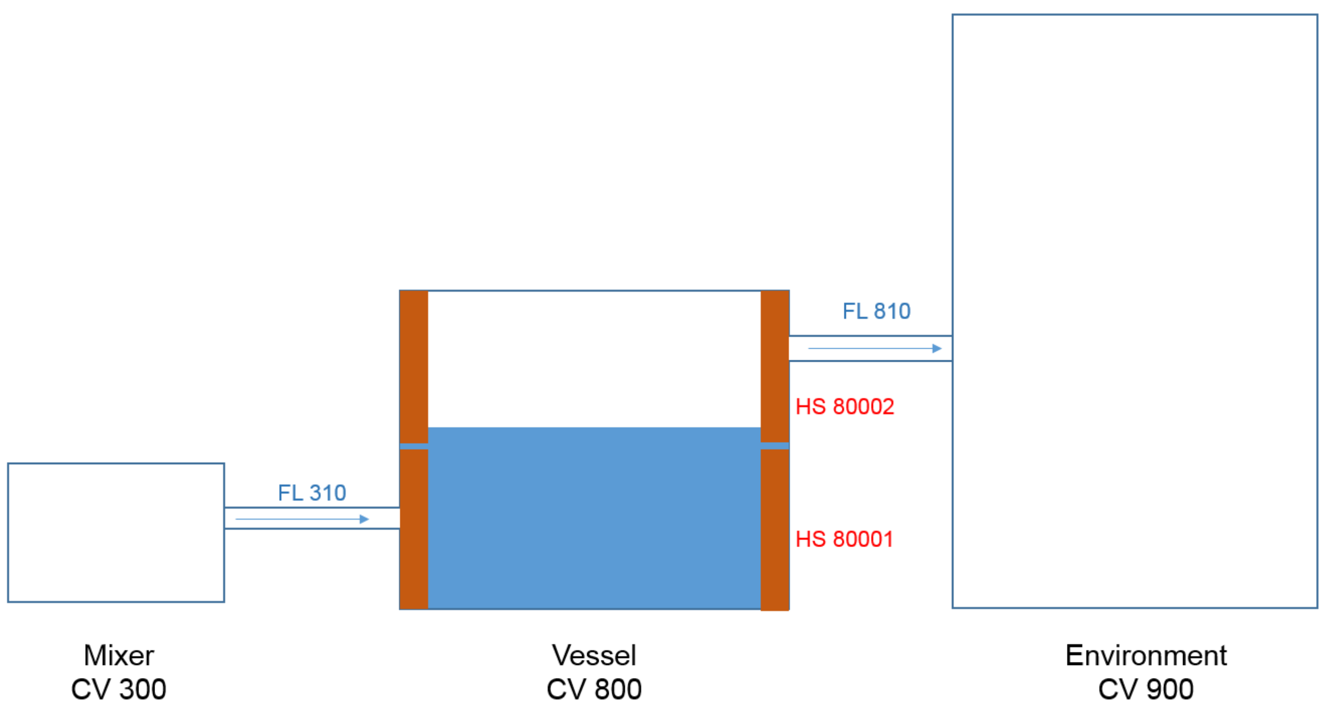

Fig. 2. MELCOR Nodalization for LACE-ESPAÑA

III. RESULTS AND DISCUSSION

TABLE 4 shows DFs from experimental results and those obtained by computational calculations. The calculation was not conducted in the case of using CMD for RT-SB-00/01 because there is no available CMD data for the case and obtained two AMMDs in the experiment were for a binomial distribution. In General, DFs of computational calculation were lower than those of experimental results. This implies that MELCOR brings normally conservative results when the code deals with pool scrubbing effect of radioactive aerosols. DFs from CMD-using calculations showed relatively higher values than those from AMMD, but better agreement with experimental results. However, it should be noticed that one moderately-large and four extremely-large values were obtained, which are not only large but also non-conservative.

Fig. 3 shows a relationship between steam fractions and calculated DFs. For larger particles and bubble injection regime cases (with red dots), a positive relationship was observed between steam fractions and DFs. For the other cases, relationships between steam fractions and DFs were not found.

Fig. 4 shows comparison between CMDs and AMMDs of aerosol sources, and calculated DFs in a log scale of Y-axis. For cases using CMDs, which has all below 1.12 μm of CMD, a strong level of a positive relationship was observed with CMDs and. On the other hand, a relationship was not found among results in the case of using AMMD.

Fig. 5 shows comparisons between GSD of size distribution data and calculated DFs in a log scale of Y-axis. It could be seen that DFs increased under 2 of GSDs. GSDs with CMD were distributed in the range of 0-2, whereas those with AMMD were distributed in the range of 1-6. GSD could be expressed in the terms of a spread degree of a distribution. If an aerosol distribution has a large GSD, the fraction of aerosol increases with relatively smaller diameter, for example, under 1 μm, even though a median diameter from an aerosol size distribution is large enough. On the other hand, although the aerosol size distribution has a relatively smaller median diameter, if GSD is small enough, there could be a chance to have an increase in particle fraction whose diameter is larger than 1 μm.

Fig. 6 shows comparison between α and calculated DFs. Lower α means lower particle fraction which has particle diameter under 1 μm. The tendency of increases in DFs was observed when α value were lower, except one case (RT-SB-08/09 with α=0.43). Higher DFs were observed when the fraction of large particle increases, which means lower α value.

TABLE 4. DFs from Experiment and Computational Calculations

Category	ID	DF			
		Experimental Results	Experimental Results, Avg.	MELCOR Results using CMD	MELCOR Results using AMMD
Smaller Particle, Bubble regime	RT-SB-12/13	444-702	573	127	34
	RT-SB-08/09	16-20	18	135	25996
	RT-SB-04/05	168-169	168.5	80	12
Larger Particle, Bubble regime	RT-SB-14/15	52-53	52.5	52	20
	RT-SB-10/11	677	677	160	361,432
	RT-SB-06/07	419-858	638.5	222	28
	RT-SB-02/03	569-922	745.5	649	73
Smaller Particle, Jet regime	RT-SC-01/02	116-128	122	26	14
Larger Particle, Jet regime	RT-SC-P/01	491-526	508.5	85	22
Smaller Particle, Multiple orifices	RT-MB-01/02	1,273-2,913	2,093	7,337	305,530

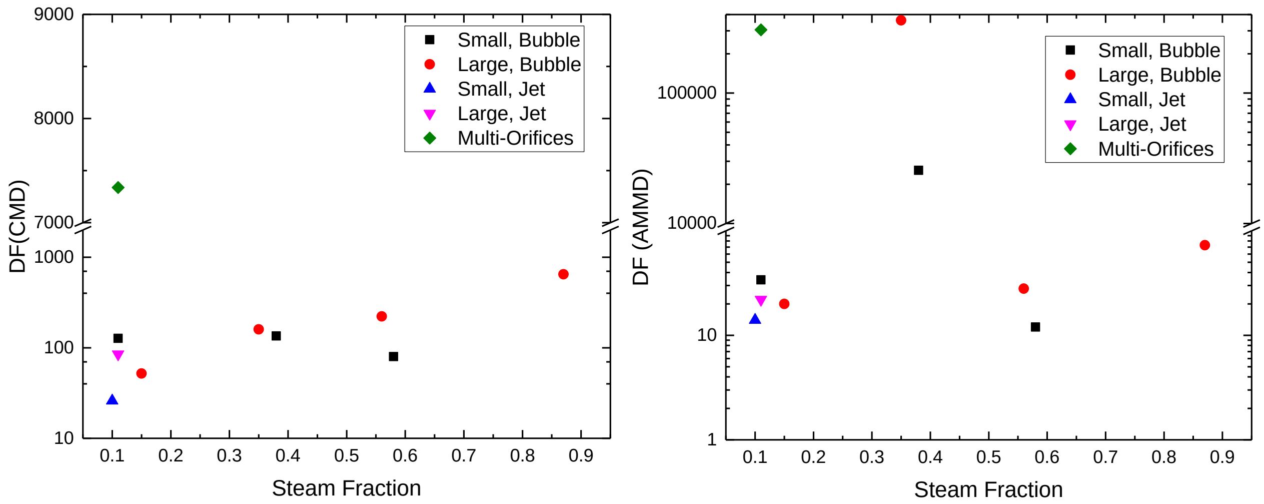

Fig. 3. Steam Fraction and DFs, using CMD (left) and AMMD (right) for Input Data of Size Distribution

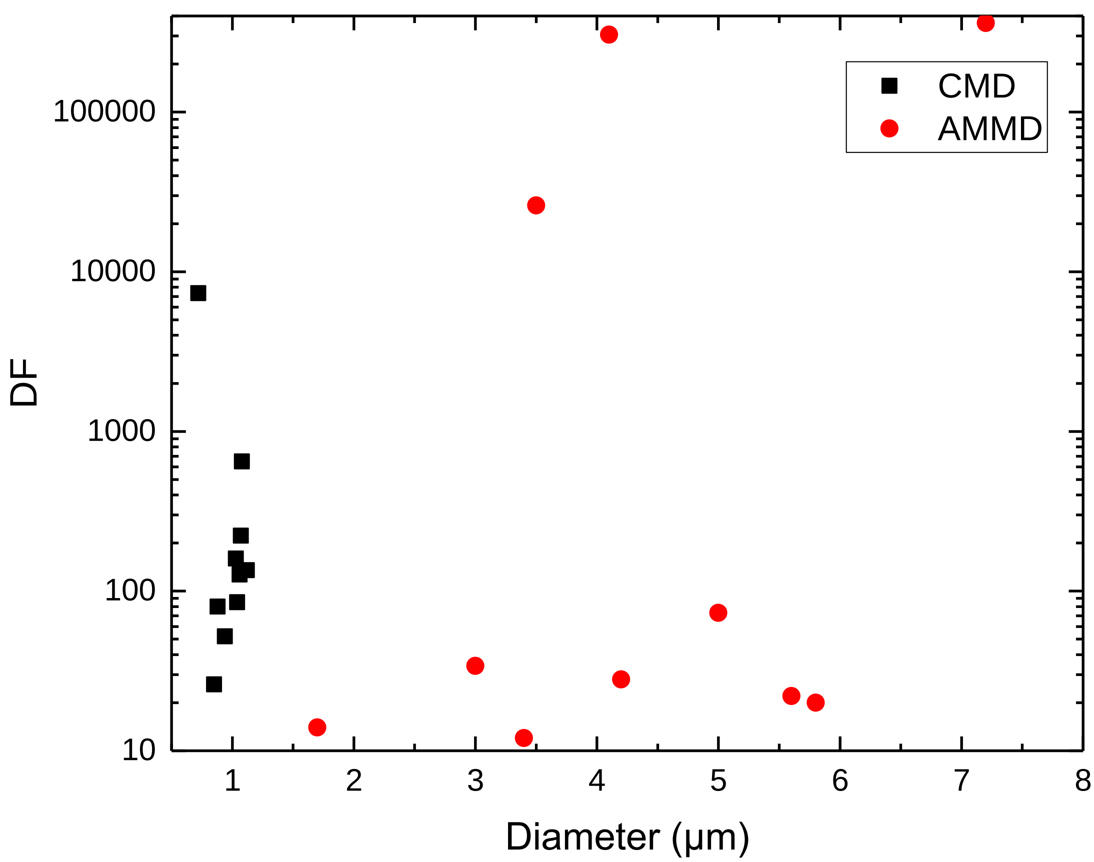

Fig. 4. Comparison between Median Diameters and DFs

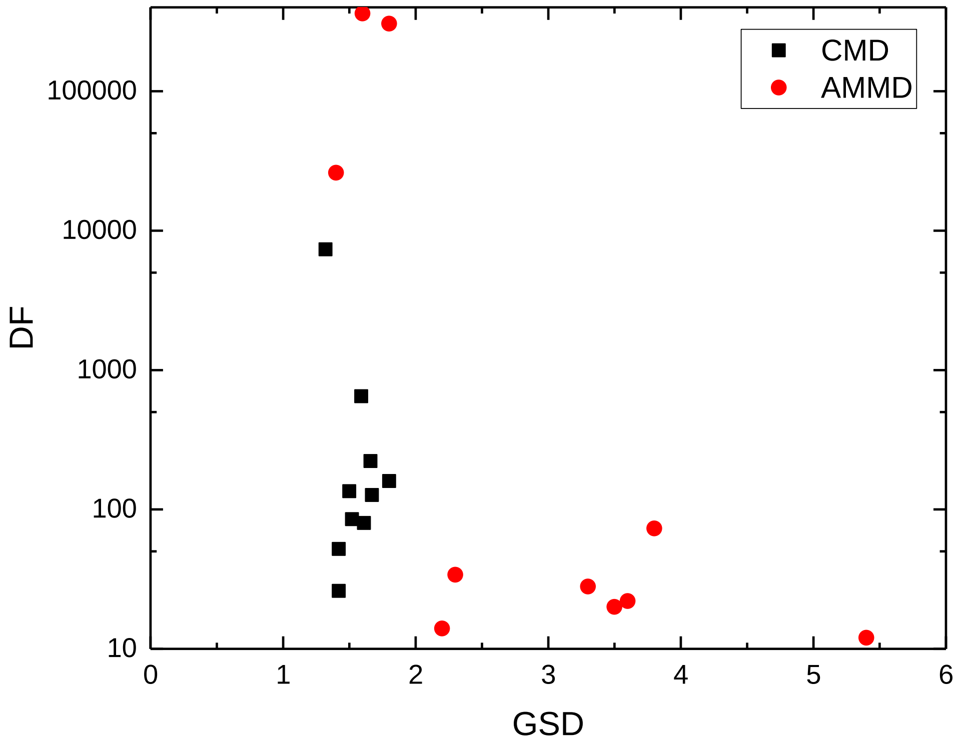

Fig. 5. Comparison between GSDs and DFs

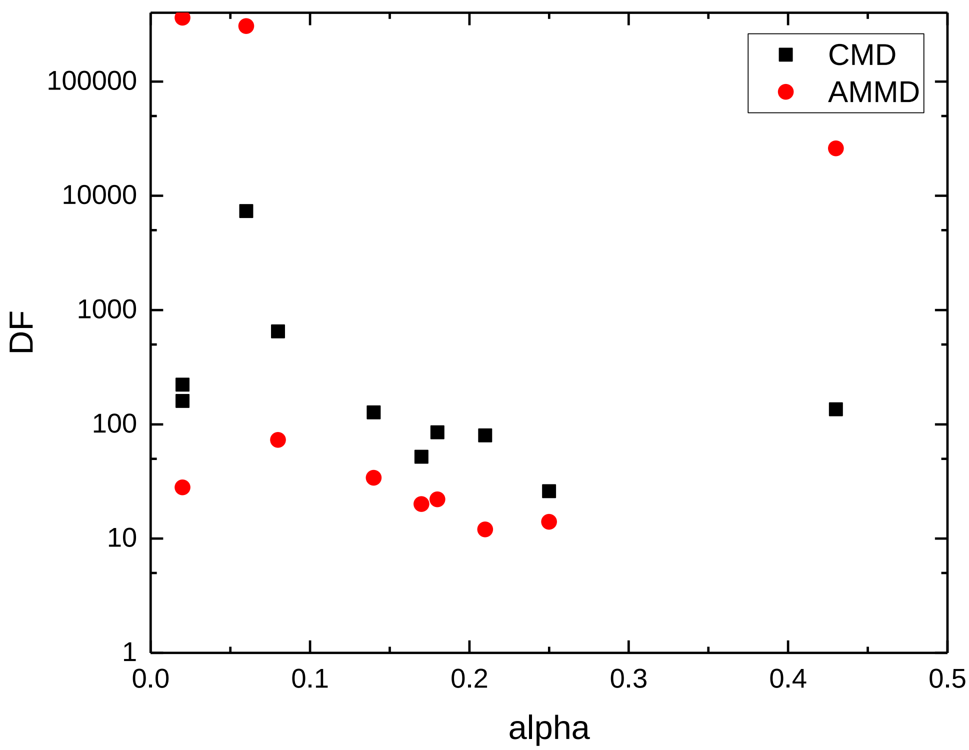

Fig. 6. Comparison between α and DFs.

IV. CONCLUSIONS

MELCOR calculations were conducted to evaluate a pool scrubbing effect of radioactive CsI aerosol for 10 experiments of LACE-ESPAÑA. The objective of study was to find dominant factors of MELCOR for DFs for pool scrubbing process of CFVS, and to utilize it for a regulatory purpose. The calculation results showed relatively conservative ones, however, some of results brought non-conservative DFs of a very high degree. For this reason, there should be a careful approach to utilize the code for the regulatory purpose. Major findings for this can be summarized as follows;

1. Using CMD, a strong positive relationship is found with median diameters and DFs. However, the tendency is not found for the cases using AMMD.
2. When the particle fraction of aerosol which has a diameter larger than 1 μm increases, DFs also increases. This tendency is clear when alpha was below 0.1
3. For larger particles of aerosol and higher injection rate of bubble regime, DF increases when steam fractions of injection gas increases.

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REFERENCES

1. Dosam Kim et al., *Review on the requirements of containment filtered venting system performance*, KINS/RR-1108, Korea Institue of Nuclear Safety (2014)
2. Yongjin Cho et al., *State of the art for Fission Product Pool Scrubbing – Phenomena and Experiments*, KINS/RR-1257, Korea Institue of Nuclear Safety (2015)
3. OECD/NEA, *Status Report on Filtered Containment Venting*, NEA/CSNI/R(2014)7, OECD/NEA (2014)
4. M. J. Marcos Crespo et al., *LACE-ESPAÑA Experimental Programme on the Retention of Aerosol in Water Pools*, CIEMAT (1994)
5. R. O. Gauntt et al., *MELCOR Computer Code Manuals Vol. 1: Primer and Users Guide Version 1.8.6*, SAND 2005-5713, Sandia National Laboratories (2009)
6. Hinds, *Aerosol technology: Properties, behavior, and measurement of airborne particles (2nd ed.)*, New York, John Wiley & Sons. (1999)