Nuclear Engineering and Design 303 (2016) 58–67

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Development of an aerosol decontamination factor evaluation method using an aerosol spectrometer

Taizo Kanai*, Masahiro Furuya, Takahiro Arai, Yoshihisa Nishi

Central Research Institute of Electric Power Industry Tokyo, Japan

HIGHLIGHTS

- Aerosol DF of each diameter is evaluable by using optical scattering method.
- Outlet aerosol concentration shows exponential decay by the submergence.
- This decay constant depends on the aerosol diameter.
- Aerosol DF at water scrubber is described by simple equation.

ARTICLE INFO

Article history:
Received 1 December 2015
Received in revised form 31 March 2016
Accepted 6 April 2016

ABSTRACT

During a severe nuclear power plant accident, the release of fission products into containment and an increase in containment pressure are assumed to be possible. When the containment is damaged by excess pressure or temperature, radioactive materials are released. Pressure suppression pools, containment spray systems and a filtered containment venting system (FCVS) reduce containment pressure and reduce the radioactive release into the environment. These devices remove radioactive materials via various mechanisms. Pressure suppression pools remove radioactive materials by pool scrubbing. Spray systems remove radioactive materials by droplet–aerosol interaction. FCVS, which is installed in the exhaust system, comprises multi-scrubbers (venturi-scrubber, pool scrubbing, static mixer, metal–fiber filter and molecular sieve). For the particulate radioactive materials, its size affects the removal performance and a number of studies have been performed on the removal effect of radioactive materials.

This study has developed a new means of evaluating aerosol removal efficiency. The aerosol number density of each effective diameter (light scattering equivalent diameter) is measured using an optical method, while the decontamination factor (DF) of each effective diameter is evaluated by the inlet outlet number density ratio. While the applicable scope is limited to several conditions (geometry of test section: inner diameter 500 mm × height 8.0 m, nozzle shape and air-water ambient pressure conditions), this study has developed a numerical model which defines aerosol DF as a function of aerosol diameter (d) and submergences (x).

1. Introduction

During the Fukushima-Daiichi accident, radioactive materials were released into the environment. FCVS allows for over-pressure release through multi-scrubbers (venturi-scrubber, bubbling-scrubber, metal–fiber filter and molecular sieve) and reduces the radioactive release. FCVS is a key countermeasure for severe accidents. CsI and CsOH are major radioactive materials, which are released as aerosols. NUREG-1465 shows how radioactive iodine is released as CsI (aerosol) 95%, I_2 (gas) 4.85% and CH_3I (gas) 0.15% (Soffer et al., 1995). Accordingly, aerosol removal is the key factor for preventing radioactive contamination and aerosol decontamination performance tests are conducted by some test programs, typical examples of which are as follows: The Advanced Containment Experiments (ACE) by the Electric Power Research Institute (EPRI), Battel Columbus Laboratories (BCL) experimental programme, the Japan Atomic Energy Research Institute (JAERI) programme, the Pool Scrubbing Effect on Iodine Decontamination (POSEIDON and POSEIDON-II) by PSI and so on (Kanai et al., 2014; Guntay, in press; Escudero Berzal et al., 1995; Bowsher, 1987; Hillary et al., 1981; Eckhardt et al., 1990; Hakii et al., 1990).

* Corresponding author.
E-mail addresses: t-kanai@criepi.denken.or.jp (T. Kanai), furuya@criepi.denken.or.jp (M. Furuya), t-arai@criepi.denken.or.jp (T. Arai), y-nishi@criepi.denken.or.jp (Y. Nishi).

http://dx.doi.org/10.1016/j.nucengdes.2016.04.011

Nomenclature

C	Aerosol concentration [cm^{-3}]
CV	Coefficient of variation [%]
d	Test vessel diameter [m]
d	Aerosol diameter [μm]
DF	Decontamination Factor [–]
h	Test vessel height [m]
M	Aerosol mass concentration [$\mu g/cm^3$]
x	Submergence [m]

Greek symbol

α	95% confidence interval (Minimum) coefficient
β	Decay constant
ε	Error
σ	Standard Deviation

Subscripts

0	Submergence is 0 m
C	Count
IN	Inlet
MF	Metal–fiber filter
MIX	Static Mixer
N	Nozzle
n	Channel number of aerosol spectrometer
Total	Total FCVS decontamination performance
W	Water
x	Submergence [m]

Acronyms and abbreviations

ACE	Advanced Containment Experiments
BCL	Battel Columbus Laboratories
CMD	Counting Median Diameter
CRIEPI	Central Research Institute of Electric Power Industry
DF	Decontamination Factor
DOP	DiOctyl Phthalate
EPRI	Electric Power Research Institute
FCVS	Filtered Containment Venting System
GSD	Geometrical Standard Deviation
HEPA	High Efficiency Particulate Air Filter
JAERI	Japan Atomic Energy Research Institute
MD	Median Diameter
MMD	Mass Median Diameter
POSEIDON	Pool Scrubbing Effect on Iodine Decontamination
CV	Coefficient of variation
SEM	Scanning Electron Microscope

The aerosol removal performance in FCVS depends on several conditions (aerosol diameter, submergence depth, water temperature, gas flow, steam flow rate, pressure, operating time and so on). Under these conditions, the aerosol particle size is considered to have a key impact on aerosol removal performance. To evaluate aerosol removal, the measurement method is also an important factor, while mass and counting methods are widely used as general filter test methods. The mass method is used for pre-filter and the counting method for fine filters, with considerable differences in the results obtained from mass- and counting method results. Weight is also important when evaluating radioactivity filtration performance. In the previous FCVS test programme, the mass method was widely used to evaluate aerosols. In practice, the aerosol characteristics (size, distribution and so on.) differ for each accident scenario and aerosol behavior can vary greatly in size (Allelein et al., 2009). Aerosol size distribution is important to evaluate the behavior of radioactive materials in severe accidents. Moreover, the aerosol size distributions at the outlet of former stage become inlet conditions for the next stage and the aerosol size distribution at the FCVS outlet is also important to evaluate the aerosol environmental diffusion. The importance of the aerosol particle size has been taken up in ACE and PSI programmes. Aerosol particle-size distribution is measured using multi-stages cascade impactors in ACE and PSI programmes. However, the particle-size classification of the impactor is not high (about 4 ch/dicade). Hence, price evaluation of aerosol DF of each size is difficult by this method.

FCVS performance test facilities in CRIEPI, Japan include id.500 mm × 8.0 m high test section and a changeable inner structure (nozzle, mixer and metal–fiber filter). The steam boiler, air compressor and aerosol generation system can all reproduce actual FCVS conditions, while the thermal follow dynamics, nozzle effect, metal–fiber filter and so on are also important factors dictating the FCVS aerosol removal performance. However, this study focuses on evaluating the aerosol decontamination performance by a wet scrubber using high-precision real-time aerosol measurement systems. The particle-size classification performance of this aerosol measurement system is up to 64 channels/decade (This study: 32 channels/decade) and the DF of each aerosol size is available using this measurement system.

2. Experimental setup

Fig. 1 shows a schematic diagram of the CRIEPI aerosol test facility. Table 1 shows the CRIEPI test facility performance and the test conditions of this experiment. The test section is made of stainless steel, with an inner diameter of 500 mm × height 8.0 m. The design pressure and temperature of the test section are 1.8 MPa eand 230 °C, respectively. Compressed air is generated by the air compressor (at a maximum flow rate of 3.0 m^3/min (234 kg/h)), while the steam mass flow rate peaks at 1600 kg/h at 0.7 MPa. No steam boiler is used in this study. Thermal hydraulic parameters are as follows, ambient pressure and temperature, air-water condition, air-flow rate is 78-194 kg/h (1000–2500 l/min, Normal), stagnant pool, nine submergences (1.5, 1.75, 2.0, 2.25, 2.5, 2.75, 3.0, 3.25 and 3.5 m). The gas volume of the air-flow rate of 2500 l/min is almost equivalent to the actual FCVS condition (pressure: 0.7 MPa, steam mass flow 20 kg/s). An injection nozzle shape affects the aerosol DF, venturi and impact nozzles remove liquid and aerosol interaction in the high-velocity flow field (Jacquemain et al., 2014). To evaluate the aerosol DF by water scrubber (submergences), a uniform high gas flow rate at a low gas velocity is required for the nozzle. An orifice assembly (hole diameter 5 mm × 100 holes) is used in this experiment. For an air-flow rate of 2500 l/min, the gas velocity is about 21 m/s.

An aerosol is generated by redistributing the compressed particle method. Fig. 2 shows a schematic of the aerosol generator. This aerosol supplier features continuously high volumes of aerosol under high-pressure conditions. CsI and CsOH are the major radioactive materials released as aerosols in nuclear power plant severe accident. These materials are soluble and deliquescent, meaning their size changes with water during scrubbing, sampling and analytical processes. It is difficult to conduct measurements using water-soluble particles. Insoluble barium sulfate ($BaSO_4$) powder is widely used as an aerosol simulant material. $BaSO_4$ powder is filled in the cylinder, pushed by the piston, scraped by the rotating blade and mixed with the air. The aerosol supply is continuously controllable by piston speed and various aerosols can be generated by changing the powder material.

The outlet aerosol is sampled in front of the metal–fiber filter. Air containing the powder is introduced into the pressure buffer tank, diluted by a dilution system (Palas: VKL10) and measured by the aerosol spectrometer. The dilution factor is determined by