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Comparative Study on One-Dimensional Models for Particle Collection Efficiency of a Venturi Scrubber

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Abstract. A wet type filtered containment venting system of a nuclear power plant uses venturi scrubbers submerged in a water pool to enhance the efficiency of collecting particulate aerosols from a gas effluent discharged from a containment after severe accidents. This paper describes a comparative study of three typical one-dimensional semi-empirical models on their predictive capability for particle collection efficiency of the venturi scrubbers. Laboratory and pilot scale experimental conditions are used for the model predictions with major parameters of particle size, gas velocity and flow rate. Among these three models, Yung's model is found best performing for the range of the physical parameters considered.

Keywords: FCVS, aerosol, venturi scrubber, particle, collection efficiency, impaction parameter

1 Introduction

A venturi scrubber submerged in a water pool, as schematically shown in Fig. 1, is used to enhance the collection of radioactive particles in filtered containment venting systems (FCVS) of nuclear power plants after severe accidents [1]. If an off-gas stream is guided through a contraction, the particle (aerosol or dust) capturing performance is significantly improved by impaction of particles in the gaseous stream into water droplets due to large relative velocities [2]. The whole process comprises such phenomena as droplet break-up and coalescence, particle adhesions to the droplets and water film, and so on [3,4].

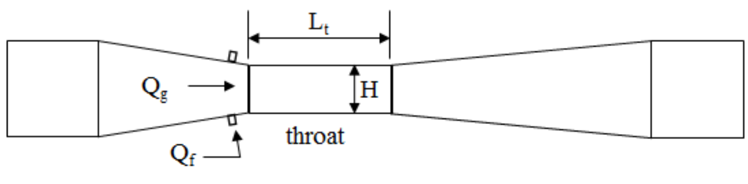

Fig. 1. Schematic of a typical venturi scrubber.

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A plenty of theoretical works are reported as reviewed by Ali et al. [5]: semi-empirical or mechanistic and one-dimensional (1D) or multi-dimensional. Primary interests of the mechanistic and/or multi-dimensional modeling are radial particle/droplet interactions and dispersions [3,6,7]. However, limited data set prohibits validation of these complicated models and thus 1D semi-empirical models using macroscopic factors such as particle/droplet sizes, drag coefficient, impaction parameter and flow velocities are still utilized to predict the collection efficiencies of the current fleet venturi scrubbers [8-10]. Major assumptions in 1D semi-empirical models are (1) incompressible flow; (2) no liquid film on the wall; (3) uniform droplet size; (5) small liquid fraction at any cross-section; and (7) single particle size.

However, limited studies are available for 1D models' predictive capabilities: Rundnick et al. [11] provided statistics on discrepancies between the models [8-10] and their own data and stated that Boll's model [9] overpredicts the efficiency due to underestimation of water droplet size. At any rate, Rundnick et al. [11] did not show any parametric comparisons and used their data only. Charisiou et al. [12] made only model-to-model comparisons. The purpose of the present work is thus to parametrically compare three typical 1D semi-empirical models [8-10] against laboratory-scale data from Calvert et al. [8] and Brink and Contant [13]. Comparison is also made with a 2D model [6] and the best performing model is deduced after application to pilot-scale FILTRA-MVSS data from Nilsson et al. [14].

2 Mathematical Models and Method of Work

Particle collection by venturi scrubber is mostly done by impact of particles colliding with water droplets, which is described by following impaction parameter:

$$K_i = \frac{C_C \rho_p d_p^2 (u_{fg} - 1)}{9 \mu_g d_d u_f} \quad \textbf{(1)}$$

where C_C is the Cunningham slip correction factor [8], ρ_p is the particle density, d_p is the particle diameter, μ_g is the gas viscosity, d_d is the water droplet diameter, u_{fg} is the gas-to-water droplet (two-phase) velocity ratio given by u_g/u_f.

Calvert et al. [8] provided one of the simplest models for the collection efficiency without considering gas velocity variation along the channel as following:

$$E_f = 1 - \exp\left[\frac{Q_f \rho_f}{Q_g \rho_g C_{di}} f(K_i, \mathrm{f}) \right] \quad \textbf{(2)}$$

where Q_f is the water flow rate, Q_g is the gas flow rate, ρ_f is the water density, ρ_g is the gas density, C_{di} is the interfacial drag coefficient at the flow inlet, and $f(K_i$, f) is the lengthy function of the impaction parameter K_i and f standing for two-phase velocity ratio used as a tuning parameter (best value recommended is 0.25 [8]).

Boll [9] considered variations of flow velocities by using momentum differential equations. The collection efficiency can be obtained after integrating the equation along the throat assuming linear variation of the velocity ratio, u_{fg}, as following:

$$E_f = 1 - exp\left[-1.5\eta_t \frac{Q_f}{Q_g}\frac{L_t}{d_d}(u_{fg} - 1)\right] \quad \textbf{(3)}$$

where L_t is the throat length, which does not appear in Eq. (2) and η_t is a function of the inertia impaction parameter given by Eq.(1).

Yung et al. [10] modified the Calvert's model [8] by considering axially varying two-phase velocity ratio which depends on water droplet diameter:

$$E_f = 1 - \exp\left[\frac{Q_f \rho_f}{Q_g \rho_g C_{di}} f(K_i, u_{fg})\right] \quad \textbf{(4)}$$

where $f(K_i, u_{fg})$ is the lengthy function of the gas-to-liquid velocity ratio, u_{fg} [8], and C_{di} is the drag coefficient given by Goel and Hollands correlation [15]. The velocity ratio, u_{fg}, in Eq.(4) is the value averaged along the axial flow direction expressed as following:

$$u_{fg} = 2\left[1 - x^2 + x^2\sqrt{x^2 - 1}\right] \quad \textbf{(5)}$$

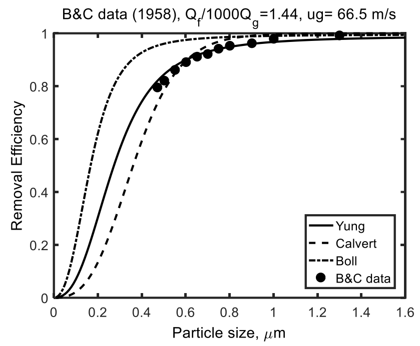
where x is the correlation parameter greater than one [8], which is a function of several parameters including water droplet diameter [16]. In Calvert's and Boll's models, two-phase velocity ratio is independent of droplet size. In Yung's model, however, the velocity ratio depends on droplet size through the parameter x in Eq.(5).

In the next section, computations from the foregoing three models are performed after computer programming by using MATLAB language. The data used [8, 13, 14] are for long-throat venturi scrubbers with flows of air at atmospheric conditions. Major parameters are particle size, gas velocity and flow rate.

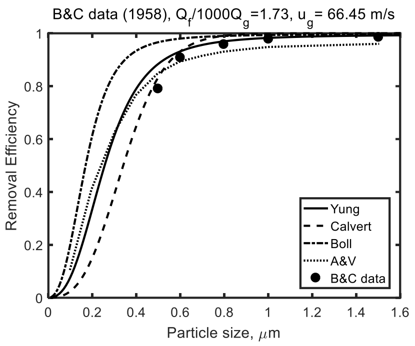
3 Result and Discussion

Figure 2(a) shows the predicted results from the three models for Brink and Contant data [13] for the gas-to-liquid flow ratio (in terms of $Q_f/1000Q_g$) of 1.44. The venturi is of large rectangular type with the throat dimension of 6 in x 34 in x 12 in (height x width x length). The gas velocity is 66.5 m/s and the particle diameter is in the range of 0.47~1.3 μm. The collection efficiency was from 0.79 to 0.99. The experimental conditions are applied to each model for particle diameters from 0 to 1.6 μm. Boll's model overpredicts the data while the Calvert's model is relatively good. Yung's model is in best agreement with the data within about 3 %.

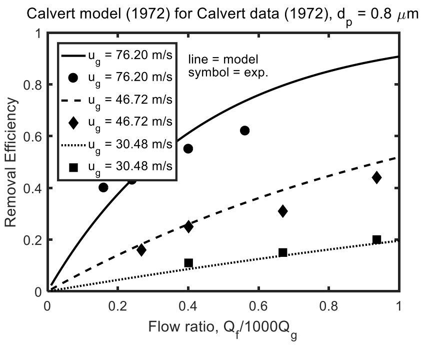
Figure 2(b) displays the comparison of the three models with the Brink and Contant data [13] for the gas-to-liquid flow ratio of 1.73 and 2D analysis result [6], who calculated collection efficiency in the range of 0.1~0.96 for the particle diameter from 0.097 to 1.5 μm. Yung's model is in better agreement with the data than the 2D calculation [6] for particle sizes larger than 0.6 μm. These overpredictions of Calvert's and Boll's models result from independence of two-phase velocity ratio from water droplet size and coincide with the result of Rundnick et al. [11].



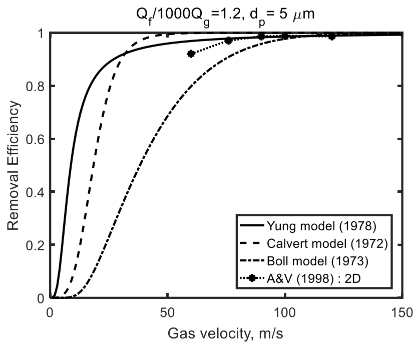
(a) 1D models for $Q_f/1000Q_g = 1.44$



(b) 1D vs. 2D models for $Q_f/1000Q_g = 1.73$



(c) Yung's model vs. Calvert's data



(d) 1D vs. 2D models for large particles

Fig. 2. Comparison of removal efficiency from each model.

The collection efficiency is thus further estimated by using Yung's model for the other data from Calvert et al. [8] in accordance with parameters of flow rate ratio and the gas velocity for the particle diameter of 0.8 μm. The venturi is of long circular type with the throat dimension of 1 in x 4 in (diameter x length). The velocities of the gas are 30.48, 46.72 and 76.20 m/s, and the liquid-to-gas flow ratio is in the range of 0.15~0.95. The agreement is good as shown in Fig. 2(c) with the accuracy comparable to Fig. 2(b).

Figure 2(d) shows the efficiencies from the three 1D models compared with a 2D model of Ananthanarayanan and Viswanathan [6]. The liquid-to-gas flow ratio is 1.2 and the particle diameter is 5 μm. Yung's model is in best agreement with the 2D model for the gas velocity greater than 80 m/s. However, for slower velocity, 1D models overpredict efficiencies. This seems due to neglect of radial velocity profile in 1D models resulting in larger two-phase velocity ratio which is more pronounced for slow velocity and consequently gives greater impaction as can be noted in Eq.(1).

Based on these results, Yung's and Calvert's models are used to predict the pilot FCVS data from FILTRA-MVSS [16] where several decontamination factors (DF) are measured for CsOH, CsI and MnO particles. The throat length is 2.6 m and the diameter is 5 cm. The particle density assumed are 3 kg/m^3 for MnO and 5 kg/m^3 for CsOH and CsI [16]. As shown in Fig. 3, Calvert's model results in unphysically increasing DF for larger particles since the drag coefficient, C_{di}, in Eq.(2) is independent of velocity ratios and thus monotonically increases according to particle size. Yung's model, however, shows reasonably saturating DF for particles greater than 10 μm since the velocity ratio increases with increasing drag as noted in Eqs.(4) and (5) and the data points measured lie well on the curves predicted.

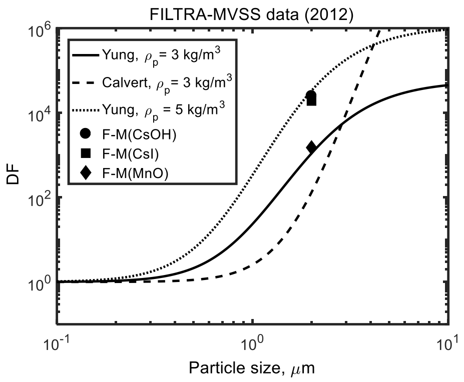


Fig. 3. Comparison of Calvert's [8] and Yung's model [10] with FILTRA-MVSS data.

4 Conclusion

A comparative study is performed on the predictive capabilities of three one-dimensional semi-empirical models for particle collection efficiency of venturi scrubbers. Compared with previous studies, the present study uniquely provides parametrical discussion on the typical models' predictive capabilities, which is hardly available from literatures. Two data sets are used for model predictions in accordance with major parameters of particle size, gas velocity and flow rate. The results show that Calvert's and Yung's models are relatively in better agreement with the data range considered but Boll's model is relatively poor. When Calvert's and Yung's models are compared with a FILTRA-MVSS pilot scale data, Yung's model reveals more physically reasonable and accurate predictions. This is mainly because Yung's model considers dependence of two-phase velocity ratio on water droplet size via interfacial drag. It is thus concluded that Yung's model has the best potential applicability to practical venturi scrubbers in filtered containment venting systems.

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