Applied Thermal Engineering 110 (2017) 150–161

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

# Numerical study of monodispersed particle deposition rates in variable-section ducts with different expanding or contracting ratios

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## HIGHLIGHTS

- The numerical model is validated with experimental results for uniform-section duct.
- Particle deposition rate keeps increasing with the increase of particle size in contracting duct.
- 20–30 μm particles have the maximum deposition velocities in expanding duct.
- "Particle free zone" appears in expanding duct but not exists in contracting duct.
- Particle deposition mechanisms in variable-section ducts are analyzed and discussed.

## ARTICLE INFO

*Article history:*
Received 3 June 2016
Revised 16 August 2016
Accepted 26 August 2016
Available online 28 August 2016

*Keywords:*
Particle deposition
Variable-section duct
CFD
Numerical simulation

## ABSTRACT

This paper presents the deposition rates of monodispersed particle in variable-section ducts with different expanding and contracting ratios. The Eulerian-Lagrangian approach based on Reynolds stress model (RSM) with turbulent fluctuation correction and discrete particle model (DPM) was adopted to investigate particle deposition behaviors in ducts. Particle deposition velocity profile in uniform-section duct was first predicted and validated well with the literature data. Then, particle deposition velocities, air flow field structures, particle trajectories and deposition mechanisms in variable-section ducts with different expanding and contracting ratios were investigated and analyzed in details. For expanding duct cases, particle deposition velocity first keeps constant, then greatly increases, finally decreases with the increase of particle size. The maximum particle deposition rate appears for 20–30 μm particles. As the growth of expanding ratio, the particle deposition velocities are significantly reduced for $d_p > 5$ μm while almost not affected for $d_p < 5$ μm. For contracting duct cases, particle deposition velocity keeps increasing when particle size increases. Moreover, particle deposition velocities are greatly increased for $d_p < 30$ μm but very closed for $d_p > 30$ μm, when the contracting ratio increases. The modification of deposition distance, the variation of air velocity along the streamwise direction as well as air flow structures are the main mechanisms to change the particle deposition characteristics, compared with uniform duct case. Besides, the "particle free zone" appears for large particles in expanding duct cases while it doesn't exist for contracting duct cases.



## 1. Introduction

Aerosol particle transport and deposition in building ventilation ducts are crucial for indoor air quality (IAQ) [1–3]. In the building ventilation system, variable cross-section ducts are usually common, such as expanding and contracting ones. Particle deposition rate and mechanism in varying-section ducts may be very different from those in uniform duct, as the geometrical configuration and flow field structures are greatly modified. However, according to authors' knowledge, very limited researches have been conducted on particle deposition in expanding or contracting ducts. Thus, it is necessary to carefully investigate this issue.

This study was focused on deposition behaviors of monodispersed particle. In the past several decades, a large number of researches have been carried out on monodispersed particle deposition behaviors in uniform ducts, including experimental studies [4–8], theoretical analysis [9–12] and numerical simulations [13–24]. It was found that particle deposition rate profile for vertical duct case can be divided into turbulent particle diffusion regime, eddy diffusion-impaction regime and inertia-moderated regime with the increase of particle relaxation time [4–7]. In the

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http://dx.doi.org/10.1016/j.applthermaleng.2016.08.167
1359-4311/

**Nomenclature**

| | |
|---|---|
| $C_0$ | mean particle concentration |
| $D_1$ | uniform duct width |
| $D_2$ | outlet width of expanding duct |
| $D_3$ | outlet width of contracting duct |
| $F_S$ | Saffman's lift force |
| $f$ | fanning friction factor |
| $h$ | duct height |
| $J$ | number of particles deposited per unit time and unit area |
| $k$ | turbulent kinetic energy (T.K.E.) |
| $\bar{p}$ | time-averaged pressure |
| $Re$ | Reynolds number |
| $S$ | ratio of particle-to-fluid density |
| $U_{mean}$ | mean velocity of air |
| $U_{free}$ | freestream velocity of air |
| $u_g$ | velocity of fluid |
| $\bar{u}_i$ | time-averaged velocity |
| $u_p$ | velocity of particle |
| $u'_{rms}$ | streamwise fluctuating velocity of air |
| $V_d$ | particle deposition velocity |
| $V_d^+$ | dimensionless particle deposition velocity |
| $v'_{rms}$ | wall-normal fluctuating velocity of air |
| $w'_{rms}$ | spanwise fluctuating velocity of air |
| $u^*$ | frictional velocity of air |
| $y^+$ | dimensionless distance from the wall |

*Greek symbols*

| | |
|---|---|
| $\varepsilon$ | dissipation rate of turbulent kinetic energy |
| $\rho_g$ | density of fluid |
| $\rho_p$ | density of particle |
| $\zeta$ | normal distributed random number |
| $\mu$ | dynamic viscosity of air |
| $v$ | kinetic viscosity of air |
| $\tau_p^+$ | dimensionless particle relaxation time |
| $\lambda_e$ | expanding ratio of duct inlet and outlet diameter |
| $\lambda_c$ | contracting ratio of duct inlet and outlet diameter |

first regime, deposition behaviors of particles are mainly determined by turbulent eddy and Brownian diffusions. In the second one, particle deposition is controlled by the motions of turbulent eddies and particle inertia. In the last one, the particle inertia is the main mechanism of deposition. Considering Brownian diffusion, turbulent diffusion and gravity settling, the "three-layer" model was developed to predict deposition rate of particles on smooth surface by Lai and Nazaroff [10]. Further, this model was revised to successfully predict particle deposition rate in smooth and rough uniform ducts by Zhao and Wu by considering turbophoresis [11,12]. Except for experimental and theoretical studies, a large number of numerical simulations based on the CFD (computational fluid dynamics) have been conducted to investigate particle deposition in uniform duct [13–24]. There are two main numerical methods on this issue, i.e. the Eulerian-Eulerian and the Eulerian-Lagrangian approaches. The former one considers particles as continuous phase and establishes transport equations as fluid phase. Zhao and Chen [13] successfully predict particle deposition velocity in uniform ventilation duct by the Eulerian-Eulerian method. The latter one obtains the spatial particle positions and instantaneous particle velocities by tracking the trajectories of each particle. It was found that the RSM (Reynolds stress model) with correction of turbulent velocity fluctuation can accurately predict particle deposition rate in uniform duct by Tian and Ahmadi [14], Gao et al. [15], because RSM considers turbulent anisotropy. Moreover, Zhang and Chen [16] also accurately simulated particle deposition behaviors in uniform ventilation duct by $\overline{v'^2} - f$ turbulent model with a modified Lagrangian method.

Nevertheless, studies on monodispersed particle deposition in variable-section duct was very limited. Haber et al. [25] and Lee and Lee [26] investigated particle deposition in expanding and contracting alveolus by CFD methods. The results showed that particle deposition is enhanced by turbulent motions in the near-wall regions. Moreover, particle deposition behaviors in S-connector and duct bend were experimentally studied by Sippola and Nazaroof [27–29] in details. It was also found that particle deposition rate is significantly increased compared with uniform duct case. However, particle deposition in variable-section ducts with different expanding and contracting ratios has never been investigated. The deposition characteristics and mechanisms in variable-section ducts remain unclear. Therefore, this study aims to investigate the deposition behaviors and mechanisms of monodispersed particles in variable-section ducts by CFD simulation. The effects of different expanding and contracting ratios of the duct on particle deposition rate and air flow fields would be studied in details, and the results will be compared with the ones of uniform duct case.

## 2. Numerical models

### 2.1. RSM model and DPM model

In present study, RSM (Reynolds stress model) was adopted to predict turbulent air flow fields in variable-section ducts, as its accuracy for particle deposition has been proved by many researches [14,15]. At the same time, DPM (discrete particle model) was employed to simulate particle deposition behaviors in ducts. Correction of wall-normal turbulent velocity fluctuation was conducted for both the uniform- and variable-section duct flows to ensure the accuracy of simulation.

For air flow in ducts, RSM model was adopted in the simulation. The Reynolds-Averaged Navier-Stokes equations and the Reynolds stress transport equation were resolved to predict turbulent air flow fields. Moreover, the turbulent flow fields in the near-wall regions were modeled by the two-layer zonal model with enhanced wall function [20]. More details of RSM model and two-layer zonal model can be found in the authors' previous studies [2,3].

For particle motion, DPM (discrete particle model) was employed to track the trajectory of each particle. Dilute gas-particle flow was considered in this study, thus the effect of particle behaviors on air flow fields and inter-particle interaction were ignored in the simulation. Zhao and Chen [30] found that the Basset, the virtual and the pressure gradient forces are small enough to be ignored when air to particle density ratio is quite small. Therefore, the drag, the gravity, the buoyancy, the Brownian and the Saffman's lift forces were considered in this simulation. The governing equation of particles can be written by,

$$\frac{du_p}{dt} = \frac{1}{\tau}\frac{C_D Re_p}{24}(u_g - u_p) + \frac{g(\rho_p - \rho_g)}{\rho_p} + \zeta\sqrt{\frac{\pi S_0}{\Delta t}} + \frac{2\rho K_c v^{0.5}}{\rho_p d_p (S_{lk} S_{kl})} s_{ij}(u - u_p) \quad (1)$$

The drag coefficient $C_D$ is computed as follows,