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Particle flow behavior of distribution and deposition throughout 90° bends: Analysis of influencing factors

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ABSTRACT

This paper experimentally investigates the particle concentration distribution and deposition in three-dimensional 90° bends considering three potential influencing factors: inlet mass concentration C_m, Reynolds number Re and wall material. Particle penetrations were found to decrease moderately within 11% with the increase of C_m under current conditions, but deposition velocity would increase by 1.29–2.87 times. The inlet particle concentration will not affect the outlet concentration distribution and particle penetration for the particles of $St = 5.15 \times 10^{-4}$. For larger particles, however, higher C_m, St and Re cause higher concentration near the outer wall of bend outlet, lower concentration near the inner wall and even 'particle free zone'. For the outlet concentration distribution, apexes and concave points are observed, which may be formed by the rebounding particles. Furthermore, concentration polarization factor is introduced to analyze the outlet nonuniformity. Accordingly, Re is found to be a higher weighting factor compared with C_m. Compared to penetration, deposition velocity is more sensitive to wall materials, for example, with an increase factor up to 1.45. Furthermore, a rough estimation method and an empirical model are suggested to establish the correlation among dimensionless outlet concentration, St and 'particle free zone'.

1. Introduction

Particle deposition and distribution in bends is particularly significant for many engineering and environmental applications, including pneumatic conveying (Song et al., 1996; Yang & Kuan, 2006), collecting pollutant samples (Pui et al., 1987), particle treatment in industrial exhaust ducts (Peters & Leith, 2004), solving indoor air quality (IAQ) problems (Chao & Tung, 2001; Li et al., 2007) and controlling particle contaminants for occupants (Jin et al., 2007), especially epidemic ones (Yang et al., 2009). Although particle deposition in ventilation duct has been proved to contribute crucially to filter the contaminants, the deposition and distribution in bend are far from fully understanding.

Particle deposition is influenced by a large amount of factors and changes in a range of one to two orders of magnitudes (Yu et al., 2008; Zhang & Chen, 2009). Disturbed particle flow in bends becomes more complicated for various turbulent flow conditions and particle-wall impactions (Sippola, 2002; Zhang et al., 2010). Raised important factors include particle bulk concentration and its distribution (Zhao & Chen, 2006), Dean number (Lin et al., 2009) and wall materials (Tian et al., 2008; Zhang & Ahmadi, 2000). However, the influences of these factors onto particle distribution and deposition have not been fully studied in bend flows.

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Previous studies of particle deposition in ventilation bends focus mainly on averaged penetration and deposition velocity, by both experimental methods (Lai, 2002; McFarland et al., 1997; Peters & Leith, 2004; Pui et al., 1987; Sippola & Nazaroff, 2005; Wilson et al., 2011) and numerical modeling (Berrouk & Laurence, 2008; Breuer et al., 2006; Zaichik et al., 2010). Recent experimental investigations show that depositions are obviously changed by different particle concentration distributions (Lin et al., 2004; Zhao & Wu, 2007, 2009). This is because the concentration distribution alters the particle flux onto a surface. However, the investigations were primarily conducted in chambers and rooms, and the concentration distribution of duct bend should attract more attention. Concentration distribution can also provide the deposition distribution location which the mean deposition values do not reveal.

In practical ventilation environment, the inlet bulk particle concentration varies from time to time under different influencing factors (Zhao & Wu, 2007, 2009). As a result, particle deposition will change with these factors, like inlet concentration. On the other hand, the deposited particles and rebounding particles could influence the concentration distribution at the bend outlet when the inlet concentration varies. The disturbed particle flow in bends will be non-uniform, and thus enhance the deposition on the downstream surfaces of straight ducts (Sippola, 2002; Sippola & Nazaroff, 2005). However, reviewing the literature shows that the interaction between concentration distribution and particle deposition in bends is undiscovered.

Dean number (*De*), as an integration of two dimensionless parameters, e.g. Reynolds number (*Re*) and bend curvature ratio, would be a potential factor to affect particle concentration distribution and deposition. Lin et al. (2009) studied the nanoparticle deposition numerically in curved pipes. The particle deposition over the entire edge of the bent pipe is found to become uniformly-distributed as the *De* increases. Wilson et al. (2011) investigated the effect of high Reynolds number of $Re = 10{,}250–30{,}750$ on aerosol deposition, and their results showed that a distinct enhancement in deposition efficiency is detected for $0.1 < St < 0.4$ when *Re* increases. These recent literature reveal that, however, the Dean number or Reynolds number effect on concentration distribution and concentration-deposition interaction is rare.

To construct the ventilation ducts, series of wall materials can be used according to ASHRAE handbooks (ASHRAE, 2009). Wall material contains significant information of wall characteristics including surface roughness (Tian et al., 2008; Zhang & Ahmadi, 2000) and property of particle-wall collision (Tu et al., 2004). Nevertheless, experimental studies of the wall materials in bend particle flow are seldom found. As a whole, different wall materials are valuable to be investigated.

To further discuss bend particle flow, based on our previous study (Sun et al., 2013), this article aims to: (1) experimentally study the particle concentration spatial distribution in three-dimensional 90° bends; (2) investigate the interaction among particle concentration distribution, penetration and deposition velocity; and (3) analyze potential influencing factors including inlet mass concentration, Reynolds number and wall material.

2. Experimental method

2.1. Definitions

The aerosol deposition efficiency, η, can be defined as

$$\eta = (1-P)100\% = \frac{C_i - C_o}{C_i} \tag{1}$$

where P is aerosol penetration, C_o and C_i are average aerosol number concentration at the bend outlet and inlet respectively. These average concentrations are calculated over all the sampling time period, sampling positions and repeated experiments at each section in this work. Measured penetration through bends are illustrated against particle bend Stokes numbers, *St*, expressed as

$$St = \frac{\tau_p U_{ave}}{(D_h/2)} \tag{2}$$

where U_{ave} is the average air velocity, τ_p is the particle relaxation time, and D_h is the hydraulic diameter of the duct.

The particle deposition velocity expresses the rate of the deposition process, given as

$$V_d = \frac{J_0}{C_{ave}} \tag{3}$$

where J_0 is the deposition flux onto a surface per unit square meter per unit time and C_{ave} stands for the average particle number concentration.

The Reynolds number (*Re*) in the ducts is calculated as

$$Re = \frac{\rho_a U_{ave} D_h}{\mu} \tag{4}$$

where ρ_a is air density and μ is air dynamic viscosity. Based on the Reynolds number, bend Dean number is determined as

$$De = \frac{Re}{\sqrt{R_o}} \tag{5}$$