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Penetration efficiency of nanoparticles in a bend of circular cross-section*

YIN Zhao-qin (尹招琴), LIN Jian-zhong (林建忠), LOU Ming (娄明)
Institute of Fluid Measurement and Simulation, China Jiliang University, Hangzhou 310018, China,
E-mail: yinzq@cjlu.edu.cn

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Abstract: In order to quantify the losses of nanoparticles in a bend of circular cross-section, the penetration efficiency of nanoparticles of sizes ranging from 5.6 nm to 560 nm in diameter is determined as a function of the Dean number, the Schmidt number and the bend angle. It is shown that the effect of the Dean number on the penetration efficiency depends on the particle size. The Dean number has a stronger effect on the penetration efficiency for small particles than for large particles. There exists a critical value of the Dean number beyond which the penetration efficiency turns from increasing to decreasing with the increase of the Dean number, and this critical value is dependent on the particle size and the bend length. The penetration efficiency increases abruptly when the Schmidt number changes from 7 500 to 25 000. Finally, a theoretical relation between the penetration efficiency and the Dean number, the Schmidt number and the bend length is derived.

Key words: nanoparticle, penetration efficiency, bends, measurement, Dean number, Schmidt number

Introduction

The particle deposition in bends is important in various scenarios ranging from a ventilation system and an aerosol experiment to human circulation systems[1-4]. Nanoparticles are more diffusible and toxic and would suffer greater losses in their number than larger particles[5,6]. Deposited particles can change the particle number distribution, the size distribution, the total mass concentration and the mean particle size within the bends. Better understanding of the deposition process is important to the applications of the nanoparticle technology.

Even though the lengths of the flow paths within the bends are usually short, the strong secondary flow inside the bends affects both the particles and the fluid that transports the particles from the core of the flow toward the walls[7], and redistributes the particles across the bend cross-section, greatly enhancing the particle diffusional deposition inside the bends.

For nanoparticles in bends, the numerical[5] and experimental results[8-10] show that smaller nanoparticles (of diameter less than 50 nm) deposit on the wall surface more easily. Wang et al.[9] studied the nanoparticles of diameters ranging from 5 nm to 15 nm in 90° bends, and found that the curvature ratio and the Dean number (De) have effects on the nanoparticle penetration efficiency. Yook and Pui[10] studied experimentally the penetration efficiency with particle diameters ranging from 3 nm to 50 nm in coils with the Dean number in the range $21 < De < 1\,799$, and indicated that the penetration efficiency increased with the increase of the Dean number and the particle size. Lin et al.[11] observed that the effects of the Schmidt number, the bending radius and the Reynolds number on the relative deposition efficiency are different.

Several factors can cause particles to deposit[12,13]. For nanoparticles, the diffusion instead of the inertia is the main factor in the particle deposition. The Brownian diffusion is an important factor for particles smaller than 100 nm, while both the Brownian and the turbulence diffusions are important for particles larger than 100 nm[9,14]. Therefore, the particle, flow and bend characteristic parameters must be used to describe the property of the particle deposition. The particle

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Biography: YIN Zhao-qin (1976-), Female, Ph. D., Associate Professor
Corresponding author: LIN Jian-zhong,
E-mail: mecjzlin@zju.edu.cn

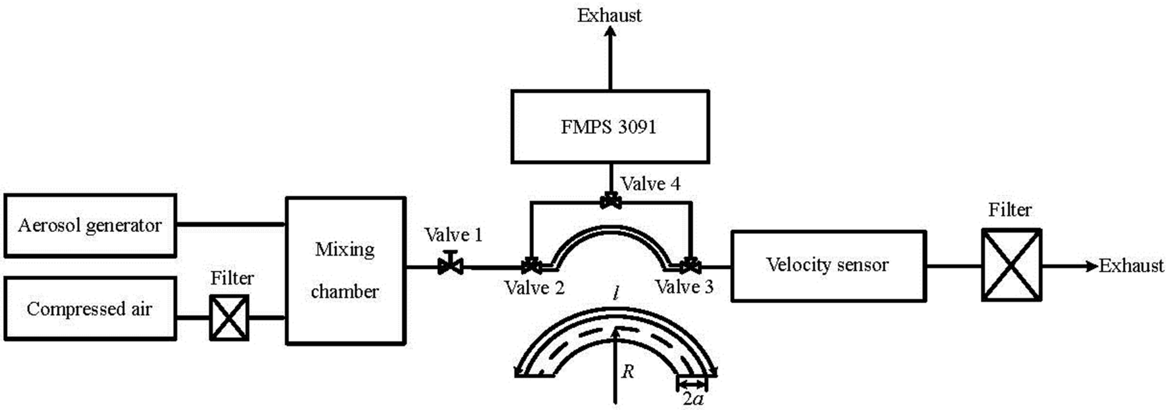

Fig.1 Schematic diagram of the experimental setup

Stokes number (St) is an important parameter for the particle motion in the Stokesian regime. For nanoparticles, the particle Stokes number is about 10^{-5} in orders of magnitude. So the Schmidt number was used to describe the particle deposition[8,15]. The Schmidt number is a dimensionless number that characterizes the ratio of the mass diffusion and convection processes of the nanoparticles. The strength of the secondary flow in a bend is characterized by the Dean number. For a bend flow, the Dean number plays a role of the "Reynolds number", i.e., $De = Re/\sqrt{R/a}$ where $Re = 2Ua/\nu$ is the flow Reynolds number, ν is kinematic viscosity of the air, U is the mean axial velocity in the bend, R and a are the radius of the bend and the tube, respectively. So the Schmidt number, the Dean number and the bend angle are the main parameters to describe the nanoparticle deposition.

Even though a large number of results about the particle deposition in bends were obtained, most of them were about micro particles in the 90° bends or coils[16,17]. The effects of the Dean number, the Schmidt number and the bend angle on the penetration efficiency of the nanoparticles in a bend remain an unexplored topic of research. With the bend being always the important part of the corrosion and the jam, it is necessary to understand the mechanism of the nanoparticle deposition in the bend. Therefore, the aim of this paper is to study the effects of above factors on the penetration efficiency of nanoparticles, and to derive a theoretical relation between the penetration efficiency and the Dean number, the Schmidt number and the bend length.

1. Experimental method

Measurements of the size and number distributions of nanoparticles are usually made by using instruments such as the electrical low pressure impactors (ELPI), the scanning mobility particle sizers (SMPS), the ultrafine particle condensation counters (UPCC). Most of these instruments have low sampling frequencies relative to that required to characterize the nanoparticle transmission in bends[18]. For example, for the SMPS, it takes 30 s to 180 s to analyze a single scan. In this paper, therefore, the fast mobility particle sizer (FMPS, Model3091, TSI Inc.) system is chosen to measure the size and number distributions of nanoparticles. A sampling frequency of 1 Hz is taken in each measurement. The particles of sizes ranging from 5.6 nm to 560 nm can be measured in 32 channels[19].

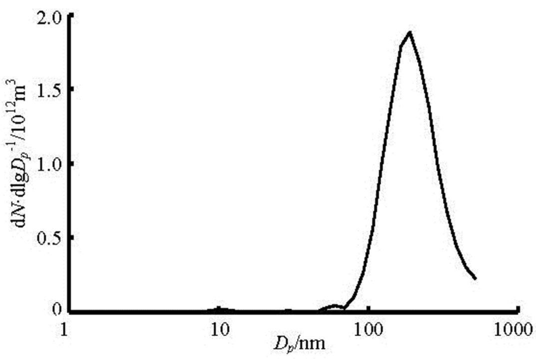

Fig.2 Particle size distribution

A schematic diagram of the experimental setup is shown in Fig.1. Particles and compressed air are mixed in a pressure chamber. The flow required for the bend is regulated using a valve downstream of the mixing chamber. In order to obtain a fully developed flow profile, each bend has an inlet straight section of a sufficient length. The valves 2, 3, 4 are three way valves used to regulate the fluid flow. When the fluid flows through the valves 1, 2, 4 and FMPS3091, the entrance parameters are measured. While the fluid flows through the valves 1, 2, the bend, the valve 4 and FMPS3091, the exit parameters are measured. The inner radius of the bend (a) is 0.006 m. The sample flow rate is 0.01 m^3/min, corresponding to the