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Particle loss in a critical orifice

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Abstract

Particle deposition in different regions of a critical orifice assembly was studied numerically and experimentally. The investigated orifice is an O'Keefe E-9 (O'Keefe Control Co.) orifice whose diameter is 0.231 mm and critical flow rate is 0.455 slpm. The orifice assembly has an inlet tube (inner diameter = 10.4 mm, length = 90 mm) and outlet tube (inner diameter = 6.2 mm, length = 60 mm). In the numerical study, axisymmetric, laminar flow field of the orifice assembly was obtained first by solving the Navier–Stokes equations. The diffusion loss of nanoparticles was then calculated by solving the convection–diffusion equation. Inertial impaction and interception loss of 2–10 μm particles was calculated by tracing particle trajectories in the flow field. In the experimental study, monodisperse NaCl (20–800 nm in aerodynamic diameter) and fluorescein-containing oleic acid (2–10 μm in aerodynamic diameter) particles were used to test particle loss in both diffusion- and inertial impaction-dominated regimes. The numerical results were compared with the experimental data and good agreement was obtained with the maximum deviation smaller than 10.4%.

Keywords: Critical orifice; Aerodynamic lens; Inertial impaction; Aerosol sampling and transport; Particle deposition

1. Introduction

Orifices are widely used to control the gas flow rate. They can also be used as a pressure reducing device for high purity gas sampling (Lee, Rubow, Pui, & Liu, 1993; Pui, Romay-Novas, Wang, & Liu, 1987; Pui, Ye, & Liu, 1988; Wang, Wen, & Kasper, 1989; Wen, Kasper, & Montgomery, 1988), or used in a particle focusing apparatus (Das & Phares, 2004; Lee, Yi, & Lee, 2003; Liu, Ziemann, Kittelson, & McMurry, 1995). In these applications, it is desirable to have particle loss in the orifice as small as possible so that particle concentration can be measured accurately. Lee et al. (1993) reviewed particle deposition mechanisms in orifice-type pressure reducers including inertial impaction at the front side and the back side of the orifice, and on the chamber (or tube) wall downstream of the orifice. They also illustrated that the loss of nanoparticles (<100 nm) also occur due to diffusional mechanism.

Deposition loss due to inertial impaction of particles on the front surface of the orifice with abruption contraction or a contraction half-angle θ of 90° was first studied by Pich (1964). He derived a model based on laminar flow assumption

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to predict particle deposition efficiency, η, by using an approximate analytical flow field. The model of Pich (1964) is

$$\eta = \frac{2S}{1+G} - \frac{S^2}{(1+G)^2}, \quad (1)$$

where

$$S = 2A + 2A^2[\exp(-1/A) - 1],$$
$$A = St_o\sqrt{G},$$
$$G = \sqrt{A_o/A_i}/(1-\sqrt{A_o/A_i}).$$

A_o and A_i are the area of the orifice and the inlet tube (m^2) and St_o is the Stokes number which is defined as

$$St_o = \frac{\rho_p D_p^2 U_i C_c}{9\mu D_o}, \quad (2)$$

where ρ_p is the particle density (kg/m^3), D_p is the particle diameter (m), U_i is the average velocity at the inlet tube (m/s), C_c is the Cunningham slip correction factor, μ is the air dynamic viscosity (N s/m^2) and D_o is the orifice diameter (m).

Assuming the air flow was laminar and fully developed, Ye and Pui (1990) developed an empirical equation for the deposition efficiency on the front side of an orifice with abrupt contraction as

$$\eta = 1 - \exp(1.721 - 8.557F + 2.227F^2), \quad (3)$$

where the variable F and the contraction ratio R were defined as

$$F = \sqrt{St_o}/(R)^{0.31}, \quad (4)$$

$$R = D_i/D_o. \quad (5)$$

In Eq. (5), D_i is the inner diameter of the inlet tube. In their study, the contraction ratio R was in the range of 2–10 and the Reynolds number was in the range of 100–200, which was based on the inlet tube diameter (D_i) and the average velocity at the inlet tube (U_i). Chen and Pui (1995) extended the work of Ye and Pui (1990) and considered the effect of six different contraction half-angles, namely 15°, 30°, 45°, 60°, 75° and 90°, on the inertial particle deposition efficiency. The Reynolds number was fixed at 1000 while R was varied from 2.0 to 5.0. Deposition efficiency for contraction half-angle $\theta > 75°$ was found to be the same as that in Ye and Pui (1990).

For $\theta < 60°$, the following empirical equation for the deposition efficiency on the front side of the orifice was obtained:

$$\eta = [0.882 + 0.0272H^{0.5} - 8.272H^{0.5}\exp(-3.627H^{0.5})]^2, \quad (6)$$

where the dimensionless variable H is defined as

$$H = St/St_{50}, \quad (7)$$

St_{50} is the Stokes number corresponding to 50% deposition efficiency, which is related to R and θ as

$$St_{50} = 0.235R^{0.61}(\sin\theta)^{-1.119}. \quad (8)$$

Sato, Chen, and Pui (2002) investigated particle deposition on the front surface of the orifice at low pressure experimentally and numerically. In their experiment, the pressure at downstream of the orifice ranged from 0.20 to 0.28 Torr, the contraction ratios R were fixed at 2, 3 or 5, and the Reynolds number based on D_i and U_i was 3. In the numerical simulation, R was also fixed at 2, 3 or 5 while the flow Re was controlled at 0.1, 0.3, 3, 10 and 30. After comparing their own experimental data and numerical results, they found the deposition efficiency could be correlated as

$$\eta = \exp(-0.5376/H - 0.1824/H^{7.019}). \quad (9)$$

In contrast to laminar flow assumptions in previous studies, Muyshondt, McFarland, and Anand (1996) studied particle deposition efficiency experimentally and numerically in the turbulent flow regime (Re = 1120–113, 000 based