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Investigation of the effect of nozzle shape on supersonic/hypersonic impactors designed for size discrimination of nanoparticles

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ABSTRACT

In this study the flow field and the nanoparticle collection efficiency of supersonic/hypersonic impactors with different nozzle shapes were studied using a computational modeling approach. The aim of this study was to develop a nozzle design for supersonic/hypersonic impactors with the smallest possible cut-off size d_{50} and rather sharp collection efficiency curves. The simulation results show that the changes in the angle and width of a converging nozzle do not alter the cut-off size of the impactor; however, using a conical Laval nozzle with an L/D_n ratio less than or equal to 2 reduced d_{50}. The effect of using a cap as a focuser in the nozzle of a supersonic/hypersonic impactor was also investigated. The results show that adding a cap in front of the nozzle had a noticeable effect on decreasing the cut-off size of the impactor. Both flat disks and conical caps were examined, and it was observed that the nozzle with the conical cap had a lower cut-off size.

1. Introduction

Inertial impactors are used extensively for the collection and size measurement of aerosol particles. As airflow passes through the orifice or nozzle of impactors, the pressure decreases and airflow increases and accelerates the particles to high speeds. The generated aerosol jet then impinges against a surface, and the airflow direction changes sharply. While small particles follow the flow streamlines, particles with sufficient inertia deviate from the airflow streamlines and are trapped on the impactor plate. Because normal impactors cannot separate and capture nanoparticles from gas streams, supersonic/hypersonic impactors must be used. In these high-speed impactors, the pressure decreases drastically, which leads to an increase in the gas mean free path and decrease in the drag force. Thus, nanoparticles moving at supersonic speeds do not follow the flow streamlines and are trapped on the impactor plate. The impinging of the supersonic jet on the impactor plate generates a strong bow shock in front of the plate. The nanoparticle collection efficiency of the impactor thus strongly depends on the airflow field of the impinging jet. The pressure ratio of the impactor, the distance between the nozzle exit and the impactor plate, the diameter of the impactor plate and the nozzle geometry are among the parameters that control impactor efficiency.

de la Mora, Rao, and McMurry (1990) provided a comprehensive study of the inertial impaction process of fine particles at moderate Reynolds numbers in transonic gas flow regimes. The authors used nozzles with rapidly converging walls, embodied by a thin-plate orifice at the end. The separation of submicron particles in supersonic impactors was experimentally studied by Kanaoka, Chutmanop, and Kitada (2001). To obtain supersonic velocities at low-pressure condition, they used a Laval nozzle. The authors reported achieving a cut-off size of 0.04 μm at a Mach number of approximately 2.8. Tafreshi et al. (2002) presented a novel so-called focuser nozzle design to enhance the focusing capabilities of aerodynamic lenses by placing a cap in front of the cylindrical nozzle to produce a sudden change in flow passage and divert the particles from their streamlines toward the nozzle axis. Middha and Wexler (2003) modified the geometry of the focuser presented by Tafreshi et al. (2002). They showed that the particles can be focused even more effectively if the cap and plate assembly have a conical shape instead of a flat one. Both of these focuser designs were studied in the present work.

Zare, Abouali, and Ahmadi (2007) presented a new computational method for the accurate prediction of nanoparticle trajectories in low-pressure supersonic/hypersonic impactors with a thin-orifice nozzle shape. In their work, a new correlation for the distance between the bow shock and the impactor plate, δ, was

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Nomenclatures

D_c	cap diameter
D_n	nozzle throat diameter
d_{50}	cut-off size of impactor
F_D	drag force per unit mass
F_B	Brownian force per unit mass
L	distance between nozzle and impactor plate
L_c	gap between cap and thin orifice
L_D	distance between nozzle and bow shock
P_0	nozzle inlet stagnation pressure
P_b	nozzle back pressure
Th_n	width of the nozzle
t	time
$\mathbf{V_P}$	particle velocity vector
$\mathbf{x_p}$	particle position vector
δ	distance between bow shock and impactor plate
η	$(L/D_n)/\sqrt{P_0/P_b}$

developed. The authors also studied the effect of impactor plate size and showed that the sharpness of the collection curves deteriorates when a smaller plate is used.

Using a computational approach, Abouali, Saadabadi, and Emdad (2011) investigated the flow field and cut-off characteristics of supersonic/hypersonic impactors with a thin-orifice nozzle shape for a wide range of pressure ratios, P_0/P_b, nozzle-to-plate distances L/D_n and nozzle diameters. They also suggested an expression for the critical Stokes number, St_{50}, as a function of the flow properties at the nozzle inlet.

The presented literature survey shows that in previous experimental and numerical studies, only a simple nozzle shape, a thin or slightly thick orifice, was used as the impactor nozzle. In fact, no previous studies have focused on finding the most appropriate shape of the nozzle of a supersonic impactor for the optimal separation of nanoparticles.

In the present study, the effect of nozzle shape on the airflow and separation of nanoparticles in low-pressure inertial impactors was investigated. Axisymmetric, compressible Navier–Stokes equations, coupled with the energy equation, were solved by a finite volume code. Analyses of particle trajectories were performed using a Lagrangian approach. A computer code previously developed by Nikbakht, Abouali, and Ahmadi (2007) and Abouali, Nikbakht, Ahmadi, and Saadabadi (2009) was used to solve the governing equation of particle motion including drag and Brownian forces. The validation of the computational model with experimental data for an impactor with a thin orifice was previously reported (Abouali, Saadabadi, & Emdad, 2011). Impactors with different nozzle shapes and different caps were investigated, and the corresponding cut-off particle sizes were obtained. The airflow field and collection efficiency curves were also evaluated and compared with those of a thin-orifice nozzle impactor.

2. Model description and boundary conditions

In this study, supersonic/hypersonic impactors with different nozzle configurations were modeled. Fig. 1 shows the schematic of an axisymmetric model of an impactor with a thin orifice. The flow enters the computational domain with a stagnation pressure of $P_0 = 1$ atm and stagnation temperature of $T_0 = 300$ K. A constant pressure boundary condition, $P = P_b$, at the outlet boundary is used. This value for the back pressure corresponds to a pressure ratio of 400 used in the experiments of de la Mora, Hering, Rao, and McMurry (1990). The impactor walls and impactor plate are treated as solid-wall boundaries.

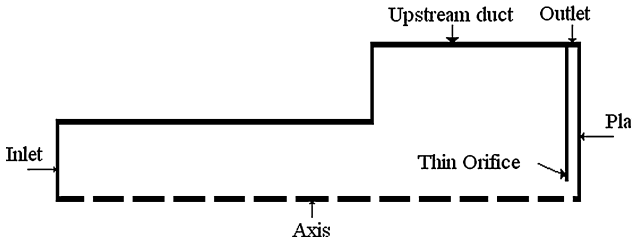

Fig. 1. Schematic of an impactor with thin nozzle orifice.

Impactors with various L/D_n ratios were studied, where L is the distance from the nozzle outlet to the impactor plate, and D_n is the diameter of the nozzle, a fixed value of 0.27 mm was assumed. Although the geometry of the impactors, boundary conditions of the computational domain and throat diameter of the nozzle are the same as those considered in all cases studied, the nozzle shape is different.

This study examined the following nozzle configurations:

A. **Thick orifices**, which are cylindrical nozzles with a width equal to the nozzle diameter or twice the diameter, as shown in Fig. 2(a).
B. **Conical converging nozzles**, whose width is equal to the nozzle throat diameter and which exhibit converging angles of 10° and 45°. Fig. 2(b) shows these nozzles for impactors with $L/D_n = 1$.
C. **Conical Laval nozzles**. Fig. 2(c) shows the schematic of a conical Laval nozzle. To avoid generating shock waves inside the nozzle, the angle of the diverging section was calculated based on the characteristic line method. For a nozzle with minimum width, the expansion angle downstream of the throat is equal to one-half of the Prandtl–Mayer function for the design's exit Mach number. The angle of the diverging section is 37°, and the angle of converging section was selected to be equal to the diverging section. The width of the nozzle is $Th_n \approx 4.65D_n$. In these nozzles, the exhaust flow diverges, and the flow direction is not entirely axial at the exit area.
D. **Capped nozzles**

(D-1) **Disk-cap nozzle**. As mentioned in the introduction, Tafreshi et al. (2002) presented a focuser for aerodynamic lenses to enhance the focusing of particle clusters. We adopted the same configuration for the impactors considered in this study by placing a cap in front of the orifice nozzle to capture more particles in the impactor plate. The geometry of the disk-cap nozzle is shown in Fig. 2(d.1). The geometrical parameters of the nozzle shown in Fig. 2(d) include the cap diameter (D_c) and the gap between the cap and the thin orifice (L_c). The cap was considered to have a thickness of 0.1 mm. We performed simulations for different sizes of the cap and gap: $D_c/D_n = 1$, 2.8, 5, 10 and $L_c/D_n = 0.1$, 0.15.
(D-2) **Cone-cap nozzle**. The modification presented by Middha and Wexler (2003) was also employed for capped nozzles in this study, and a conical cap and nozzle assembly were simulated. Various sizes of cap and gap: $D_c/D_n = 2$, 5 and $L_c/D_n = 0.1$, 0.15 were studied numerically. A cone half-angle of 60° was considered.

It should be noted that the proposed use of nozzle types B and D is quite new in the application of supersonic impactors. Furthermore, nozzle type C has not been used before under the extremely low-pressure conditions of supersonic impactors. In addition, no