Using Divergent Nozzle with Aerodynamic Lens to Focus Nanoparticles

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***Abstract*—**ANSYS Fluent will be used to simulate Computational Fluid Dynamics (CFD) for an efficient lens and nozzle design which will be explained in this paper. We have designed and characterized an aerodynamic lens and a divergent nozzle for focusing flow that transmits sub 25 nm particles through the aerodynamic lens. The design of the lens and nozzle has been improved using CFD for particle trajectories. We obtained a case for calculating nanoparticles (25 nm) flowing through the aerodynamic lens and divergent nozzle. Nanoparticles are transported by air, which is pumped into the aerodynamic lens through the nozzle at 1 atmospheric pressure. We have also developed a computational methodology that can determine the exact focus characteristics of aerodynamic lens systems. Particle trajectories were traced using the Lagrange approach. The simulation shows the ability of the aerodynamic lens to focus on 25 nm particles after using a divergent nozzle.

***Keywords*—**Aerodynamic lens AL, divergent nozzle DN, ANSYS Fluent, Lagrange approach.

I. Introduction

PARTICLES in the air can be focused in a small area of high concentration, and the resulting narrow particle flow is useful in observing particles with different sizes. Particle focusing cannot be increased with a reduced size of the pipe. However, the particle flow size can be reduced if a small diameter pipe is used [9]. Therefore, we used a pipe with a length of 100 mm, and the diameters of the inlet and outlet of the pipe are 35 mm as shown in Fig. 1. We used a single lens with a divergent nozzle instead of multi-lenses [7]. Inside the pipe, an aerodynamic lens was installed as the first technique used herein to focus particles, which has 3-mm diameter with 1.6-mm thickness. Improving further the effectiveness of focusing particles was our next attempt by using a divergent nozzle, which was installed after the aerodynamic lens. The divergent nozzle is a cross section becomes larger in the direction of flow. It is used to minimize gas flow to sonic speed; however, there is a decrease in cross-sectional area. The radius of the divergent nozzle is 15 mm. Particles dispersed sparsely in air flow can be focused into a small area of highly increased focusing [9]. Therefore, for measuring the particle size and particle trajectories, we need to install a Faraday Cup (FCE) (Fig. 2) inside the pipe [1] to send the particle charge, size, shape, and number to the differential mobility analyzer (DMA) to analysis the results [5], [6], (Fig. 3) shows a DMA) which is using in classifying and generating particles. Moreover, DMA is classifying and measuring nanoparticles between 1 nm to 1000 nm in diameter, based on their electrical mobility. The DMA could be used with a Faraday Cup Electrometer (FCE) to measure the size distribution of nanoparticles [8], see Fig. 4. Therefore, we should consider the length of the section between the aerodynamic lens AL and Faraday Cup FCE inside the pipe. Thus, after several readings of the simulations, we obtained that the suitable the length of the section between the lens (x = 0) and FCE is 16 mm which could provide good results because the sonic speed is achieved when x = 16 mm and focusing on particles occurs only at sonic speed, as shown in Fig. 5.

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The performance of an aerodynamic lens and a divergent nozzle operating at atmospheric pressure is analyzed numerically. Then, the results will be validated computationally.

II. Background

The most common method these days about the focus of nanoparticles is to use an aerodynamic lens, which can be a single lens or multi-lenses [7] installed inside a pipe [2], [3]. Most research efforts with aerodynamic lenses focus on the generation and use of particle beams under low pressure. Recently, the theoretical analysis of the aerodynamic lens began. A formula for the design of the aerodynamic lens for flowrate, pressure, and particle size has been given by several studies [4].

In this research, we explain the main parts used for our research that was used to focus on nanoparticles. This model consists of a pipe whose length is 100 mm. The pipe includes two openings, namely the inlet, and outlet, with a diameter of 35 mm for both so that the direction of air flow is from left at the inlet to the right at the outlet. The novelty in this research is the use of a diverging nozzle in conjunction with a single aerodynamic lens instead of using multi-lenses [7] to focus nanoparticles as shown in Fig. 6.

III. Theory

A. Fluid Flow through the Aerodynamic Lens

In this research, an aerodynamic lens operates with air flowing via the orifice when the Mach number is equal to 1. For this case, the maximum air flowrate with $\gamma = 1.4$, $R =$

$287\frac{J}{kg.K}$ is:

$$\dot{m}_{max} = \frac{0.532\, A^{*}\, P_0}{\sqrt{T_0}} \quad (1)$$

In (1), $\dot{m}_{max}$ is in $(\frac{kg}{sec})$, A* is in m^2, T_0 is in (K), P_0 is in (Pa) and P_0 and T_0 are the total pressure and temperature, respectively, at the pipe inlet. By indicating that the flow of the volume is simply the mass flow divided by the fluid density, ρ, the flowrate of the volume can be expressed as:

$$\dot{m}\left(\frac{m^3}{sec}\right) = \dot{m}_{max}\,(\frac{Kg}{sec})/\rho(\frac{Kg}{m^3})$$

$$\dot{m} = \frac{\dot{m}_{max}}{\rho}\left(\frac{m^3}{sec}\right)$$

Since the air in the surrounding conditions is an ideal gas, $\rho = \frac{P}{RT}$, thus:

$$\dot{m} = 0.532R\left(\frac{P_0}{P}\right)\left(\frac{T}{T_0}\right) A^{*}\sqrt{T_0}\,. \quad (2)$$

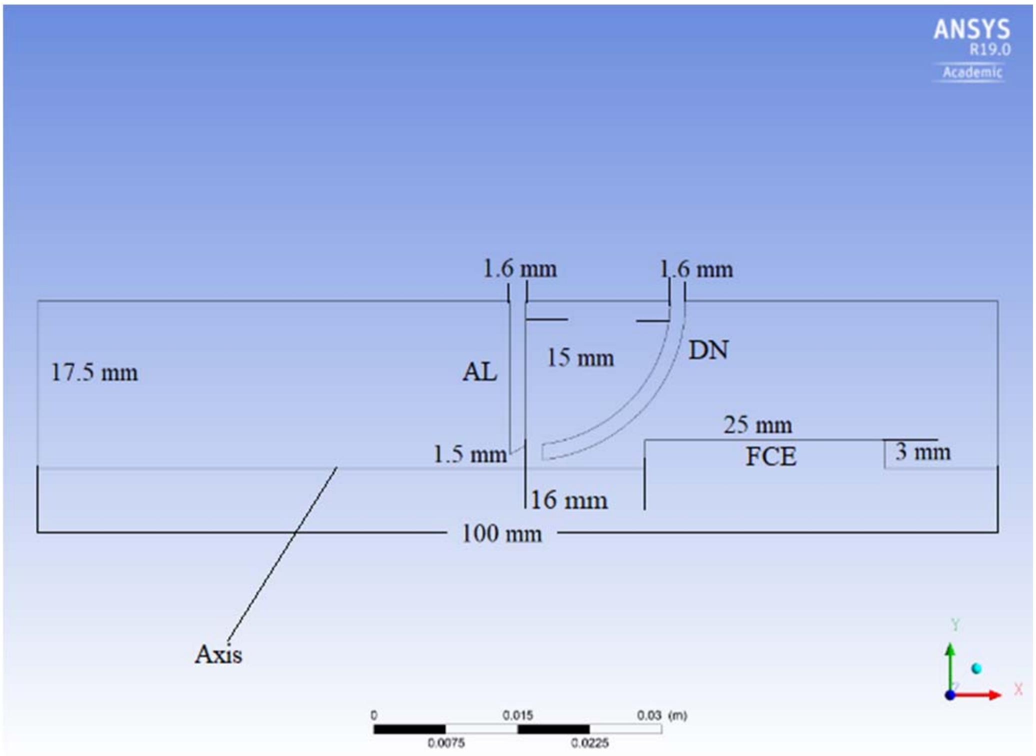


Fig. 1 The nozzle diameter 15 mm (divergent nozzle), where x = 0 at the orifice

Fig. 2 Faraday Cup Electrometer

Fig. 3 Differential mobility analyzer

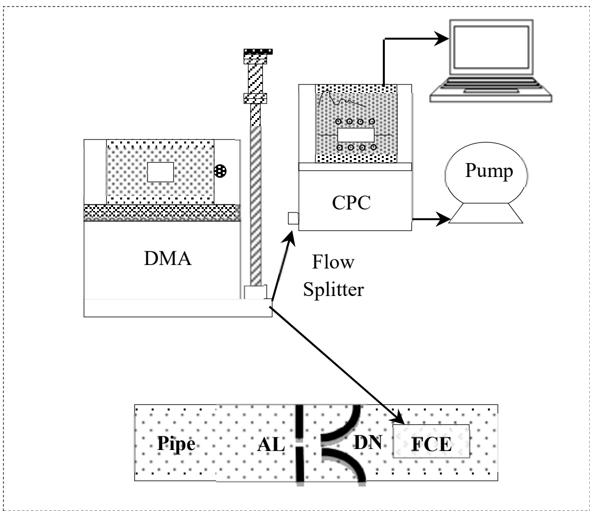


Fig. 4 Experimental apparatus for measuring nanoparticle penetration in an aerodynamic lens

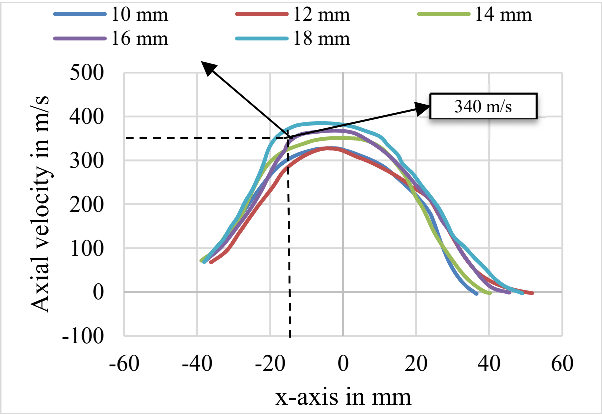


Fig. 5 The axial velocity along the x-axis with the length of the section between the lens (x = 0) and FCE being x = (10 mm, 12 mm, 14 mm, 16 mm and 18 mm)

Equation (2) is the flowrate of the volume $\left(\frac{m^3}{sec}\right)$ via any cross section of the pipe. Note that since pressure and temperature change throughout the pipe, the volume flowrate is not the same for each cross section. The flowrate of the volume is not constant, but the mass flowrate is constant all the time. In the use of the aerodynamic lens for sampling, it is important to know that the volume flowrate not at the throat of the orifice, but into the inlet of the orifice. It is possible to simplify (2) further when the flow velocity at the orifice inlet is slow. At standard conditions ($P = 101352\,Pa, T = 298\,K$) sonic velocity is ($340\,m/sec$). Therefore, for interest flows in sampling lines, (2) will be:

$$\dot{m} = 28.4\,A^* \sqrt{T_0} \tag{3}$$

Equation (3) provides that, when operating under critical conditions, the flowrate of the volume is constant for an existing orifice (A^* constant), unless the ambient temperature changes significantly.

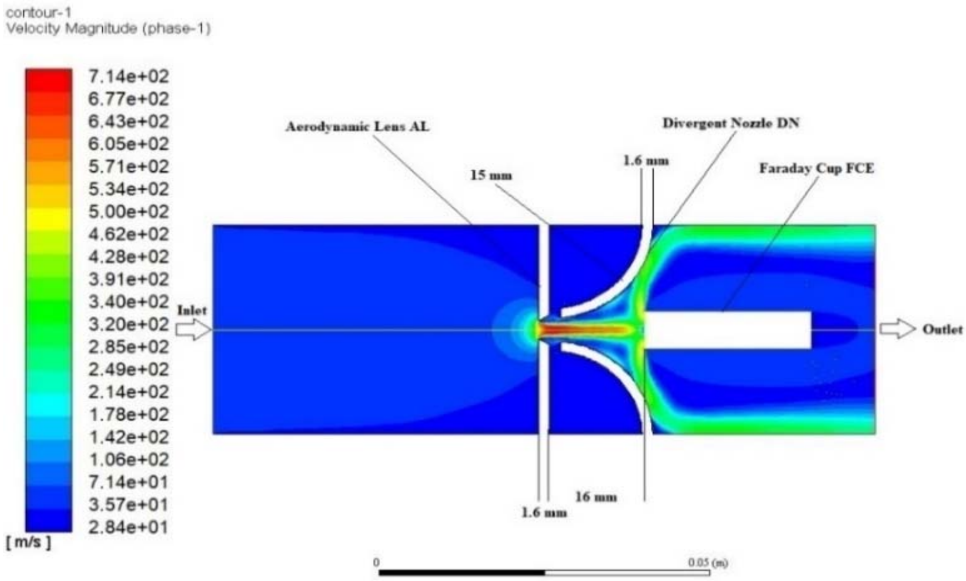


Fig. 6 The main parts used for our study

B. Fluid Flow through the Divergent Nozzle

The divergent nozzle is a cross section becomes larger in the direction of flow. It is used to minimize gas flow to sonic speed; however, there is a decrease in cross-sectional area decrease. When the gas passes the orifice, the speed increases to the supersonic sound (Mach number < 1). When the gas enters a divergent section, its speed decreases, with the mass flowrate constant. However, when the gas passes through the divergent nozzle, the speed drops to the sonic (Mach number = 1). Therefore, for the aerodynamic lens AL - divergent nozzle DN, the calculation from the inlet to the throat is usually an extension of the sonic conditions, and from the throat to the divergent nozzle, the flow is rapidly expanded.

If the static pressure of the nozzle outlet is higher than the surrounding pressure, it means that the solution has been found, and the calculation has been completed. The aerodynamic lens - divergent nozzle is designed to reach the speed that equates to the sonic speed. Aerodynamic lens - divergent nozzle design came from the speed zone relation:

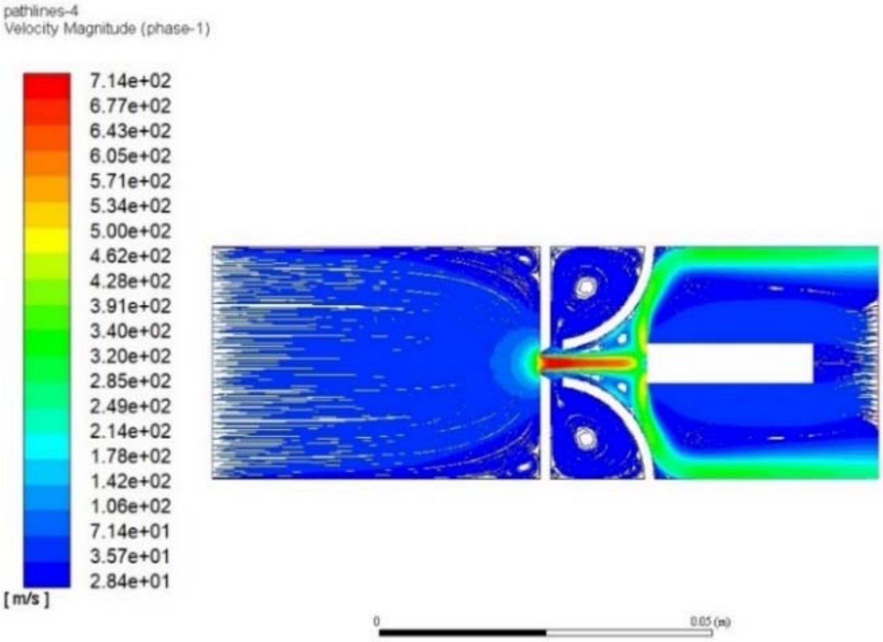
$$\left(\frac{dA}{dV}\right) = -\left(\frac{A}{V}\right)(1 - M^2)$$

M is the Mach number, A is the area, and V is the velocity. For fluid flow measurements, orifice plate and divergent nozzle simplify the use of differential pressure (ΔP) sensors to determine the flowrate. In these cases, the flow is associated with $\Delta P = (P_1 - P_2)$ by (4):

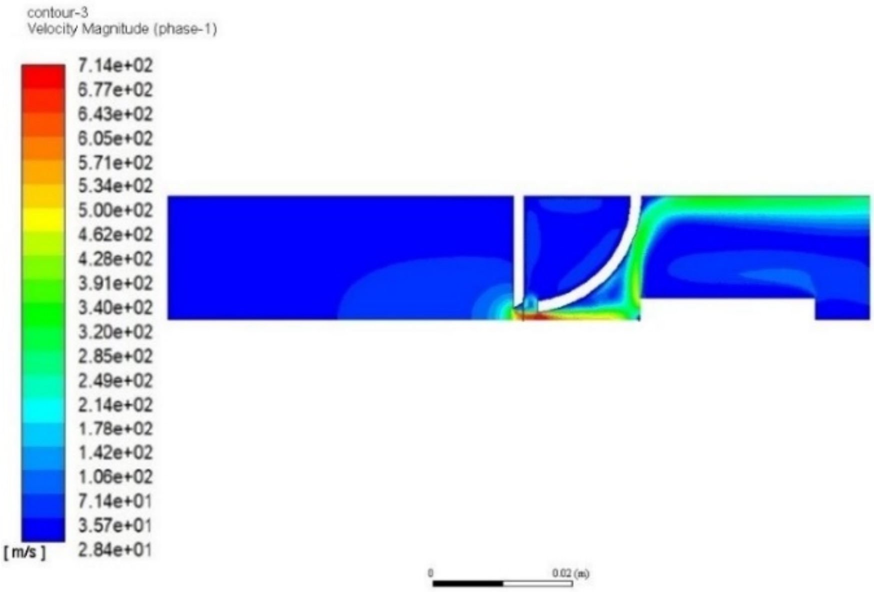
$$\dot{m} = \left[C_D \frac{\pi}{4} d^2\right]\left[\frac{2(P_1 - P_2)}{\rho(1 - d^4)}\right]^{\frac{1}{2}} \tag{4}$$

where $\dot{m}$ is the flowrate of the volume in $\frac{m^3}{s}$, C_D is the discharge coefficient, and dA is the area ratio $= \frac{A_2}{A_1}$, P_1 and P_2 are in Pa, ρ is the fluid density in $\frac{kg}{mm^3}$, d is the orifice diameter (in mm), D is the upstream and downstream pipe diameter (in mm) , and $\beta = \frac{d}{D}$ diameter ratio.

One important point is to obtain sonic speed; it should maintain appropriate compression ratios across the divergent nozzle. Therefore, to obtain sound speed only in the throat or aperture, the pressure ratio $\left(\frac{P_{throat}}{P_{inlet}}\right) = 0.528$ should be maintained [1]. The orifice size is selected to choke the flow and set the mass flowrate across the system [10]. The velocity of the flow up to the sound speed in the aperture means that the Mach number equals one in the lens. Expanding the supersonic flow reduces the static pressure and temperature from the aperture to the outlet. Therefore, the amount of expansion, also, determines the out pressure and temperature [10].



(a)



(b)

Fig. 7 The gas streamlines of air via a sharp plate with the diverging nozzle (a, b)

IV. Results and Discussion

A. Aerodynamic Lens

There is a design for the aerodynamic lens suggested by us using a single sharp orifice with a divergent nozzle which is installed after the lens to avoid any recirculation and avoid instability in fluid flowing through the pipe through the lens and nozzle. The gas streamlines of air across a sharp plate orifice with a diverging nozzle are shown in Fig. 7.

Fig. 7 shows a severe flow recirculation downstream of the aperture. The recirculation area fills the entire space between the aperture and the divergent nozzle in the figure above, leaving the periodic flow pattern and thus destroying the particle focusing. After reading the simulation in this study by using ANSYS Fluent, the results show us there is a recirculation that occurred between the sharp orifice and the divergent nozzle.

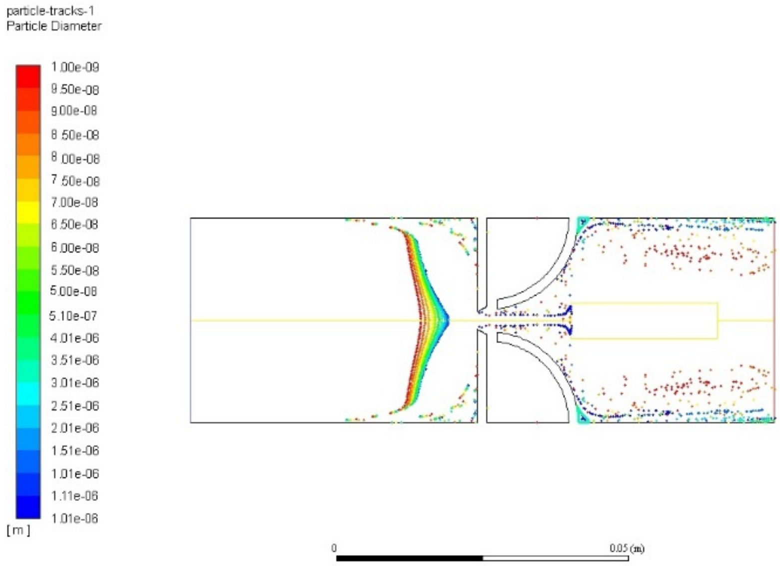


Fig. 8 Particle diameter

Measured particle velocities were determined to range from $375 - 155\frac{m}{s}$ for particles of size $7 - 23\,nm$, respectively, and followed the trend of force law with strong correlation 0.9884, see Fig. 8 and 9.

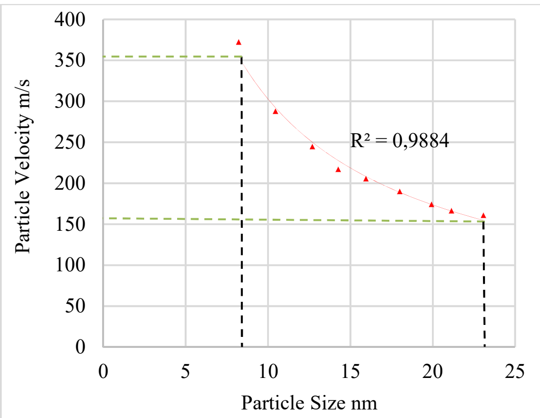


Fig. 9 Particle size with the measured particle velocities

B. Divergent Nozzle

Most researchers have used multi-lenses [7] to measure and focus nanoparticles due to instability and shock deformation. Therefore, in this research, we reduced economic costs by using one lens, and we explained the theories, analyses, and methods to reach the measurement of the smallest size of particles. We also demonstrated the success of our approach by simulating the model to validate the results; Fig. 10 shows the contour of the velocity phase by using a divergent nozzle.

First, we used one aerodynamic lens to focus the nanoparticles by compressing the particles across the orifice hole and assembling them into a single trajectory to detect nanoparticles; also to measure their size after focusing. However, because of the high speed of gas - particles, which reached higher than the sonic speed, this caused the instability in the orifice hole and the shock deformation in the orifice due to the high velocity of particles led to particle loss and lack of focusing especially for the small particles. Therefore, in our research, to avoid the instability and the deformation of the shock in the orifice, we have installed a divergent nozzle with the aerodynamic lens, see Fig. 11. A divergent nozzle is a form that provides less resistance to flow and has a higher discharge coefficient. Moreover, it does not have a cone to restore pressure. Fig. 11 shows a divergent standard nozzle. A divergent nozzle is installed between the edges of the pipe that carry the fluid after passing through the lens. For the stability, the best length of the section between the aperture and the divergent nozzle is 16 mm as approved in simulations by using ANSYS Fluent — Notes pressure on the upstream and downstream (P1 and P2) using a differential pressure sensor to calculate the flowrate, see Fig. 12.

As shown in Fig. 13, the predicted axial velocity profile which is generated from the CFD simulated by using multi-lenses [7] was found to correspond with CFD simulated results by using a divergent nozzle with the aerodynamic lens (the measured axial velocity) at the center of the pipe.

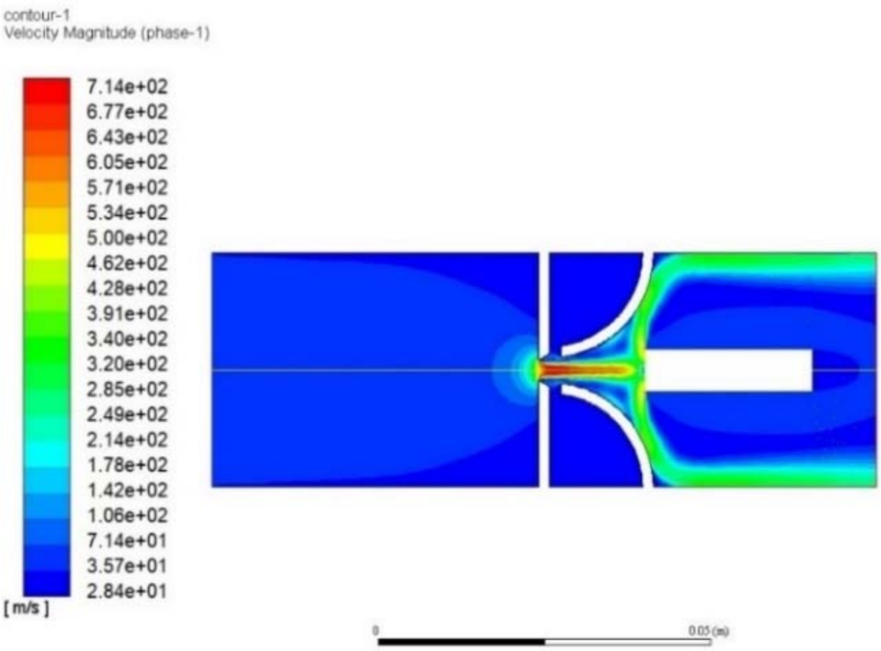


Fig. 10 The contour of the velocity phase by using DN

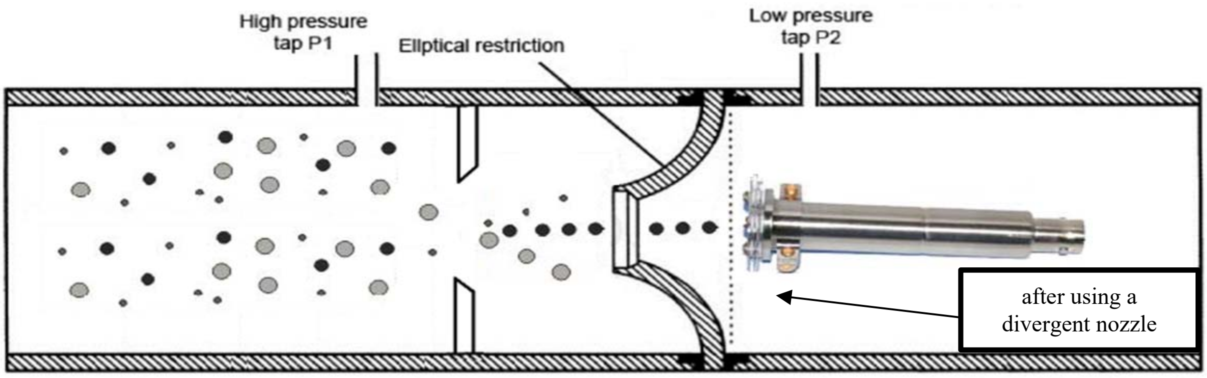


Fig. 11 The geometry of an aerodynamic lens and a divergent nozzle

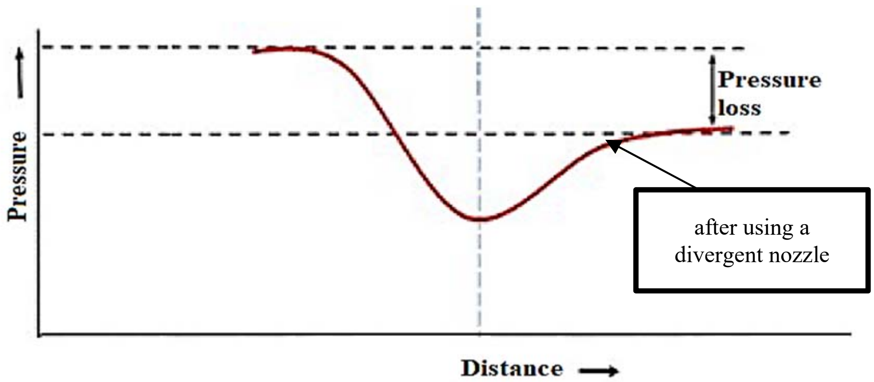


Fig. 12 The diagram shows the relationship between pressure and the distance after using a divergent nozzle

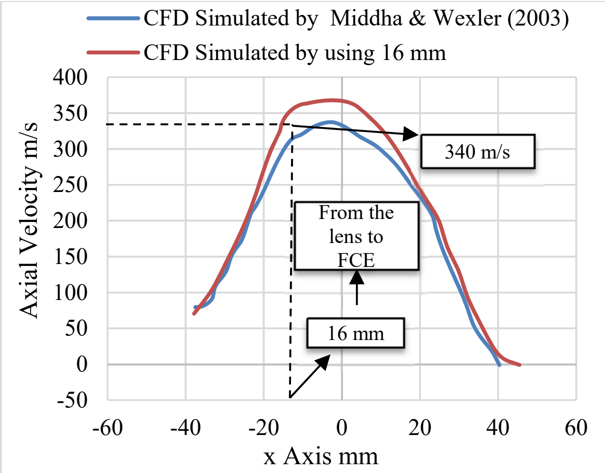


Fig. 13 Comparison of the CFD Results for mean axial velocity

V. Conclusion

This paper represented the first systematic effort to measure the size of nanoparticles using the aerodynamic lens with a divergent nozzle. Computational simulations were used. This study developed a system of the aerodynamic lens with a divergent nozzle to focus sub 25 nm. Moreover, computational simulations showed that the possibility to focus and measure particles larger than 25 nm but the inability to focus or measure particles smaller than 5 nm. The present study presented that aerodynamic lens with a divergent nozzle system performs better method systems for nanoparticles with a focus on multiphase flow than multi-lenses [7]. Therefore, this study confirmed that the possibility of using one lens to focus small nanoparticles while maintaining the speed equal to the sonic speed at which we can focus on nanoparticles.

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