**Nano-Particle Deposition in Laminar Annular Pipe Flows**

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**Abstract**

The transport and deposition of nano-particles in annular pipe flows under laminar conditions were studied. The Lagrangian particle tracking method was used to simulate the Brownian diffusion of ultrafine solid particles in a three-dimensional domain. The effects of nano-particle size, flow rate, inner and outer pipe diameters, pipe length, and temperature were studied. The computational models for the deposition of nano-particles in tubular, as well as annular pipe flows, were validated. Furthermore, using the CFD simulations and the Lagrangian particle tracking results, a new correlation for evaluating the deposition fraction of nano-particles in annular pipe flows was developed. The presented results could provide guidelines for evaluating nano-particle transport and deposition in annular pipes.

**Keywords:** Nano-particle; Deposition; Lagrangian particle tracking; Laminar flow; Annular pipe flow.

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| **Nomenclature** | | | |
|  | Cunningham correction factor |  | local fluid velocity |
|  | pipe diameter |  | particle velocity |
|  | deposition efficiency (%) |  | average velocity |
|  | Boltzmann constant |  |  |
|  | pipe length | **Greek symbol** | |
|  | mass deposition rate |  | zero-mean, unit-variance independent Gaussian random number |
|  | inlet mass flow rate |  | gas density |
|  | inner radius of the annular pipe |  | particle density |
|  | outer radius of the annular pipe |  | air mean free path |
|  | pipe radius |  | fluid viscosity |
|  | the spectral intensity function |  | kinematic viscosity |
|  | absolute temperature of the fluid |  | time-step for particle integration |

1. **Introduction**

Dispersion and deposition of aerosol particles have attracted the attention of many researchers due to their wide applications in medical, environmental, and industrial fields [[1](#_ENREF_1), [2](#_ENREF_2)]. These include particle separation devices, solid particle formation, transport and deposition in combustors and post-combustion devices, indoor and outdoor environments, inhalation drug delivery, and particle deposition in respiratory airways [[3-8](#_ENREF_3)]. Furthermore, due to the ever-increasing production of nano-particles and the potential for their adverse health effects, there has been considerable interest in understanding the transport and deposition of nano-scale particulate matter [[9-11](#_ENREF_9)].

Nano-particle deposition in tubular pipe flows was investigated earlier in the literature[[12](#_ENREF_12)]. A few studies have developed theoretical and empirical expressions for particle deposition in smooth tubes due to their Brownian diffusion. Thomas [[13](#_ENREF_13)] developed an analytical expression for a range of particle diameters. Ingham developed a model for calculating the deposition efficiency in a fully developed flow in a cylindrical tube and for the entrance region of a cylindrical tube [[14](#_ENREF_14), [15](#_ENREF_15)] for Poiseuille, plug, and a combination of Poiseuille and plug fluid flow. For laminar parabolic flow conditions, Yeh and Schum [[16](#_ENREF_16)] derived an analytical equation for evaluating the deposition rate of particles. Cohen and Asgharian developed an empirical expression for the deposition efficiency of particles larger than 10nm [[17](#_ENREF_17)]. Most of these studies have used the mass convection-diffusion equation for the concentration of particles and found analytical correlations for deposition efficiency.

In addition to the analytical approaches, there are several studies in the literature that employed the Eulerian-Lagrangian particle tracking method for evaluating the deposition efficiency of nano-particles [[18](#_ENREF_18)]. The original model for the Lagrangian Brownian simulation model was introduced by Li and Ahmadi [[19](#_ENREF_19), [20](#_ENREF_20)] and Ounis et al. [[21](#_ENREF_21)]. Zamankhan et al. [[22](#_ENREF_22)] studied the airflow and deposition of nano-particles in a realistic human nasal cavity. They verified the model by comparing the predicted nano-particle deposition efficiency for the entrance region of the pipe to the empirical equations of Cohen and Asgharian [[17](#_ENREF_17)], Ingham [[15](#_ENREF_15)], and Martonen et al. [[23](#_ENREF_23)] for the developing laminar regime. Inthavong et al. [[24](#_ENREF_24), [25](#_ENREF_25)] investigated the deposition of nano-particles in the nasal cavity and tracheobronchial airway. In their study, they simulated nano-particle deposition in fully developed tubular pipe flow for different particle diameters and Reynolds numbers using the commercial software FLUENT. They verified the Lagrangian Brownian model with the analytical equations for uniform flows. They also noted the effectiveness of the Lagrangian approach due to the inclusion of the effect of finite inertia.

Longest and Xi [[26](#_ENREF_26)] employed the model of [[19-21](#_ENREF_19)] for simulation of nano-particle deposition in upper airways. They simulated nano-particle deposition in laminar developing and fully developed flows and compared the results to the Eulerian particle transport model and also the analytic equation of Ingham [[14](#_ENREF_14)]. They note the computational cost of the Lagrangian approach. There have been additional studies in the literature that investigated nano-particle deposition and dispersion in tubular cylinders using the Lagrangian approach [[27](#_ENREF_27), [28](#_ENREF_28)].

In contrast to a large number of studies on tubular pipe flows, the Brownian diffusion of nano-particle in annular pipe flow has rarely been reported in the literature despite its applications in after-treatment systems, electrostatic precipitators and separation devices [[12](#_ENREF_12), [18](#_ENREF_18), [29-32](#_ENREF_29)]. For example, in dielectric barrier or corona discharge reactors, the duct configuration is an annular pipe where a high voltage is applied for reducing the gaseous pollutants and for depositing the particulate pollutants. It should be noted that most of the previous studies were concerned with the turbulent flow regime rather than the laminar flow condition [[33](#_ENREF_33)].

Chang et al. [[34](#_ENREF_34)] studied the effect of Brownian diffusion and thermophoresis on the deposition of solid glass aerosols in the annular flow with fixed thermal gradients between two cylinders, experimentally and numerically. They suggested that the dominant mechanism of particle deposition is due to the thermophoresis effect. Tsai et al. [[35](#_ENREF_35)] investigated the deposition of nano-particles in the range of 38 to 500 nm in a tube considering electrostatic, thermophoretic, and Brownian diffusion experimentally and numerically. The presented experimental results were in good agreement with the analytic correlation for both laminar and turbulent flows. They showed that in the absence of the thermophoretic effect in laminar tube flow, electrostatic deposition, as well as the Brownian diffusion, should be considered. The brief survey of literature shows that there are little if any computational modeling studies of particle deposition in annular pipes using Lagrangian particle tracking approach.

As discussed in the introduction section, there are many studies on nanoparticle deposition and dispersion in tubular pipes; however, deposition studies on annular pipes are rather limited despite their numerous applications. Thus, in this study, a Lagrangian particle tracking method was used to evaluate the deposition of nano-particles in annular as well as tubular pipe flows under the fully developed laminar flow condition. The deposition efficiencies for different flow rates, pipe and annulus lengths, pipe diameters, and wall and fluid temperatures for a range of particle sizes were evaluated. The model was also validated by comparing the predicted deposition efficiencies for different flow rates, pipe diameters and pipe lengths in tubular as well as annular flows with the analytic equations reported in the literature. Furthermore, a new analytic expression for evaluation of particle deposition in annular pipe flows was developed. The new correlation for the deposition efficiency as a function of diffusion parameter may find applications in the after-treatment and separation devices in addition to the electrostatic precipitators.

1. **Methods**
   1. *Flow system*

For generating fully developed tubular and annular flows, the exact solutions for laminar velocity profiles were imposed at the pipe inlet. Then, the governing continuity and momentum equations in a three-dimensional domain are solved. The parabolic velocity profile for the fully developed laminar tubular flow is given as [[36](#_ENREF_36)],

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| (1) |  |

For annular flow, the fully developed velocity profile is given as [[37](#_ENREF_37)],

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| --- | --- |
| (2) |  |

where

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| (3) |  |

* 1. *Transport equation of particles*

The one-way coupled assumption is used, and the trajectories of mono-disperse submicron particles ranging in diameter from 5 nm to 100 nm are calculated using the Lagrangian method by integrating an appropriate form of the particle equation of motion. In this range of particle diameters, the transport of nano-particles is mainly due to the Brownian excitation, and gravity and lift forces are comparatively small. The appropriate equations for spherical particle motion can be expressed as [[19-21](#_ENREF_19)],

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| --- | --- |
| (4) |  |

In Eq. (4), the subscript denotes the ith directions. Here, is the Cunningham correction factor to the Stokes drag law and is given as [[1](#_ENREF_1)],

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| --- | --- |
| (5) |  |

Where the air mean free path is equal to 65 nm under normal condition.

The amplitude of the Brownian force is given as [[19-21](#_ENREF_19)],

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| (6) |  |

Where is a zero-mean unit variance Gaussian random number and the spectral intensity of the noise is,

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| (7) |  |

It should be noted that an isothermal condition is assumed, and the temperature of the air and particles, as well as the duct boundaries, are all equal. Therefore, there is no temperature gradient, and as a result, no thermophoresis force is acting on nano-particles [[38](#_ENREF_38)]. As noted before, the gravity and lift forces are also negligible for the studied range of nanoparticles diameter (5-100 nm) [[39](#_ENREF_39)].

* 1. *Geometry and mesh structure*

In the present study, two geometries are simulated: a tubular pipe and an annular pipe. The tubular pipe is only used for validating the computational model within the Ansys-Fluent code. For this purpose, pipe diameters of 4.5 and 9 mm, as well as two different flow rates with pipe lengths of 1, 3, and 5 cm, are studied. For the annular pipe, three different cases are employed. The different studied geometries are listed in Table 1. Fig. 1 displays a schematic view of the annular pipe studied.

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| **Table 1**  Different studied geometries of the annular pipe | | | |
| Geometry | Outer diameter | Inner diameter | Length |
| Case 1 | 2.25 mm | 1.125 mm | 0 to 6 cm |
| Case 2 | 4.5 mm | 2.25 mm | 0 to 6 cm |
| Case 3 | 9 mm | 4.5 mm | 0 to 6 cm |

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| C:\Users\Acer\Desktop\Aerosol science\geometry.jpg  Particle injection |
| **Fig. 1.** A schematic view of the annular pipe. |

Different meshes consisting entirely of hexahedral control volume are generated in ICEM CFD 15.0. Figs. 2-a and 2-b display the created meshed at the cross-section of the tube for tubular and annular pipes, respectively. These meshes are generated after a mesh sensitivity study. The mesh study is discussed in the following section.

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| a) | b) |
| **Fig 2.** A cross-sectional view of computational mesh for a) tubular pipe, and b) annular pipe. | |

As is seen from Fig. 2, mesh near the wall is denser to provide a more accurate evaluation of the deposition efficiency [[40](#_ENREF_40)].

* 1. *Boundary condition*

As mentioned before, the deposition efficiency is calculated in a fully developed flow. Therefore, the boundary condition of a fully developed laminar flow profile at the inlet, and the outflow boundary condition at the outlet are imposed. A no-slip condition is also used as the wall boundary condition. Spherical particles are released uniformly at a cross-section in the flow field. Particles were released at a plane 2 mm from the inlet to prevent any spurious results by particles exiting the inlet upon immediate release [[24](#_ENREF_24), [41](#_ENREF_41)]. Note that since the flow is fully developed, there is no difference where the particles are released along the pipe. But the length of the pipe from the injection point to the end of the pipe is important.

The inlet particle flux profile was generated by using Eqs. (1) and (2), respectively, for the tubular and annular pipe to generate the mass flow profile (for each particle size) in the injection plane. Then, the deposition efficiency is calculated based on the ratio of the mass deposition rate to the inlet mass flow rate. That is,

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| (8) |  |

1. **Results and discussion**
   1. *Flow field simulation*

As mentioned previously, for flows driven by a pressure gradient, fully-developed laminar tubular and annular flow profiles given, respectively, by Eqs. (1) and (2) were imposed as boundary conditions at the inlet. A second-order upwind scheme was used for solving the momentum equation. Figs. 3-a and 3-b, respectively, show the velocity distribution at three cross-sections along the tubular and annular pipes, which include the imposed inlet conditions. It is seen that for both tubular and annular pipes, the velocity profiles for the three locations collapse into single curves, indicating that the computational model maintains the fully developed laminar velocity profile in the entire pipe and annulus.

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| a) | b) |
| **Fig. 3.** Comparison of velocity proﬁles at three cross-sections. a) Tubular pipe. b) Annular pipe. | |

It should be noted that the velocity profiles along the flow direction are shown in Fig. 3, while the velocity magnitudes in other directions are negligible.

* 1. *Model testing and sensitivity analysis*

Grid convergence testing for the annular pipe, based on the deposition of nano-particles, is first performed. Figs. 4-a and 4-b display the calculated deposition efficiencies for 10 and 40 nm particles for different meshes for a pipe length of 6 cm. The grids contain approximately 500,000 – 2,600,000 cells. In all cases, the height of the ﬁrst near-wall grid point was 0.005 of the pipe radius, and the grid size increase ratio is 1.1 [[42](#_ENREF_42)]. Note that further refinement was also tested using a mesh with the distance of the first grad from the wall set to 0.0025 pipe radius; however, no noticeable effect in the results was observed. The simulation results for different grid sizes shown in Fig. 4 indicate that the grid size has only a limited effect on the total deposition efﬁciency, especially when considering the two last grids. One reason is that all the grids are approximately the same in the near-wall region, which is the most critical region for particle deposition. For the annular pipe, a mesh size of approximately 1.4M grid points is considered for this study to provide grid-independent particle deposition results.

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| 1. 10 nm | 1. 40 nm |
| **Fig. 4.** Effect of mesh sizes on the deposition efficiency in the 6 cm pipe for the particle size of a) 10 nm and b) 40 nm. | |

For the velocity distribution, the grid independency analysis was also performed, and it was shown that the selected mesh provides grid-independent velocity results. Note that the velocity distributions described in the previous section were also obtained using the selected meshes.

It should be emphasized that the number of nodes in the flow direction in all the models is constant. Furthermore, different length scales in the discrete phase model of ANSYS-Fluent code were also tested, and a length scale of m was selected. This parameter controls the integration time step size in the FLUENT code for solving the particle equation of motion. Note that the same procedure for grid independency analysis was also performed for the tubular pipe.

Since the Brownian motion is a random process, the predicted deposition efficiency for a specific number of injected particles was slightly different. Therefore, to provide a more accurate result, the simulation for deposition efficiency for each case was performed five times. For the annular pipe in case 1 (listed in Table 1) and the fluid velocity of 1 m/s, Fig. 5-a displays the calculated deposition efficiencies of 5 nm particles for various tests. Note that in this figure, the number of particles is 50,000.

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| a) | b) |
| **Fig. 5.** Effect of a) multiple runs and b) the number of injected particles on the deposition efficiency for 5 nm particle diameter and pipe length of 5cm. | |

To provide accurate results, in addition to having multiple runs, the number of simulated particles is also important and should be checked. The results should be independent of the particle numbers. By increasing the number of simulated particles, fluctuations in calculated deposition efficiency are decreased. Fig. 5-b displays the variation of estimated deposition efficiency for different numbers of particles, ranging from 20,000 to 70,000. This figure shows that by increasing the number of particles to more than 50,000, the deposition efficiency is roughly constant. Therefore, the value of 50,000 or larger was selected as the total number of simulated particles. Also, the deposition efficiencies were averaged over five runs. So, effectively 250,000 particles were used in the averaging. Note that for case 3 in Table 1, due to the large area of the pipe, 200,000 particles were simulated for each run (a total of 1,000,000 particles over 5 runs.).

* 1. *Deposition in fully-developed tubular pipes*

The computational model for trajectory analysis of nano-particles was first verified for deposition efficiency in a straight tubular pipe, and then the model was applied to the annular pipe flows. In order to validate the simulation approach, a series of simulations were performed for two different pipe diameters and two flow rates for different pipe lengths. The predicted deposition fraction for all cases was compared with the analytical equation of Ingham [[14](#_ENREF_14)]. Accordingly, for fully-developed laminar pipe flow, the deposition efficiency is given as

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| --- | --- |
| (9) |  |

where

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| --- | --- |
| (10) |  |

Fig. 6 displays the simulated deposition efficiency of 5 nm to 100 nm particles for a tubular pipe with a diameter of 4.5 mm and different lengths. Here the inlet fluid velocity is 1 m/s. It is seen that the simulation results show excellent agreement with the empirical equation of Ingham.

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| **Fig. 6.** Deposition efficiencies versus particle diameter for fully developed tubular flow for various pipe lengths for an inlet fluid velocity of 1 m/s and pipe diameter of 4.5 mm. |

Similar verification tests were performed by varying the inlet fluid velocity and pipe diameter, respectively, in Figs. 7 and 8. It can be seen that present model predictions are still in good agreement with the model prediction of Ingham [[14](#_ENREF_14)].

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| **Fig. 7.** Deposition efficiencies versus particle diameter for fully-developed tubular flow for various pipe lengths for an inlet fluid velocity of 2 m/s and pipe diameter of 4.5 mm. |

As shown in Figs. 7 and 8, with increasing the length of the pipe, the deposition efficiency enhances due to the higher surface area of the tubular pipe and higher residence time of the nano-particles in the pipe. With increasing the surface size, the probability of the impacts of nanoparticles on the wall enhances, resulting in a higher number of deposited particles. In addition, the particles have more time to deposit on the walls before leaving the domain for a longer tube. For a nano-particle diameter, due to the higher effect of Brownian diffusion, the deposition efficiency is higher, as seen in Figs. 6-8 [[43](#_ENREF_43)].

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| **Fig. 8.** Deposition efficiencies versus particle diameter for fully-developed tubular flow for various pipe lengths for an inlet fluid velocity of 1 m/s and pipe diameter of 9 mm. |

* 1. *Deposition in fully-developed annular pipes*

Deposition efficiencies for different particle diameters and various pipe lengths are displayed in Fig. 9 for case 2 of Table 1. The deposition efficiency always increases as the pipe length increases due to the higher residence time of the particles in the pipe. Similar to the tubular pipe, the deposition efficiency decreases rapidly with the increase of particle diameter. Also, when a logarithmic scale is used, the slopes of the deposition efficiency lines for various pipe lengths are roughly constant.

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| **Fig. 9.** Deposition efficiencies versus particle diameter for fully-developed annular flow for various pipe lengths for case 2 of Table 1 for an inlet fluid velocity of 1 m/s. |

In annular pipes, particles are deposited on both inner and outer walls. However, due to the larger surface of the outer wall, more particles are deposited on the outer wall. Figs. 10-a and 10-b display the variation of number in the deposited particles as a function of pipe length for the inner wall, outer wall, and both walls of the pipe for particle diameters of 5 nm and 100 nm, respectively, for case 2 in Table 1.

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| 1. 5nm | 1. 100nm |
| **Fig. 10.** The variation of the number of deposited particles as a function of pipe length for a) 5 nm particles and b) 100 nm particles for case 2 in Table 1. | |

Fig. 11 displays variations of deposition efficiencies for different inlet fluid velocities for various particle diameters for a pipe length of 5 cm for case 2 in Table 1. It is seen that increasing the airflow velocity reduces the deposition efficiency. The reason is that the particle residence time in the pipe decreases as the velocity increases and since the Brownian diffusion is the primary deposition mechanism, the deposition of the nano-particles on the walls decreases. It is seen that the difference between the deposition efficiencies for fluid velocities of 0.5 and 1 m/s are almost equal to the difference for fluid velocities of 1 and 2 m/s.

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| **Fig. 11.** Deposition efficiencies versus particle diameter for fully-developed annular flow for various inlet fluid velocities for case 2 of Table 1 for a pipe length of 5 cm. |

Fig. 12 shows the variation of particle deposition efficiency versus particle diameter for different cases tabulated in Table 1 for an inlet fluid velocity of 1m/s and a pipe length of 5cm. For case 1 (smallest annulus), higher deposition efficiency is achieved compared to the other studied cases with larger diameters. The reason is in the annulus with the smallest gap, the particles are closer to the walls, and the probability that the particles can reach the walls by Brownian motion is higher compared with the other cases. Therefore, the deposition efficiency in case 1 is higher compared to case 2, which is also higher than case 3 (largest Annulus).

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| **Fig. 12.** Deposition efficiencies versus particle diameter for fully-developed annular flow for geometries listed in Table 1 for an inlet fluid velocity of 1m/s and a pipe length of 5cm. |

When the temperature changes, the fluid properties and the intensity of Brownian force vary. Therefore, the deposition efficiency also changes. Fig. 13 displays the effect of temperature on particle deposition efficiency for the annular pipe of case 2 of Table 1 for the pipe length of 5 cm. It should be noted here that the condition is still isothermal but for different constant temperatures. Increasing the temperature increases the diffusion coefficient, which results in a higher random movement of nano-particles, and therefore increases the Brownian force. On the other hand, an increase in temperature increases the viscosity of the air, which decreases the particle diffusion coefficient and therefore decreases the Brownian excitations. Overall, as shown in Fig. 13, an increase in the temperature leads to the increase of the deposition efficiency for all particles with different diameters.

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| **Fig. 13.** Effect of temperature on the deposition of nano-particles for fully-developed annular flow for case 2 of Table 1 for an inlet airflow velocity of 1 m/s and a pipe length of 5cm. |

To provide a better understanding of the effect of temperature, Fig. 14 displays the deposition efficiency values for different particle diameters with constant properties of the air for different air temperatures for case 2 in Table 1. As shown, increasing the temperature alone has a considerable effect on the particle deposition efficiency due to higher Brownian diffusion effects.

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| **Fig. 14.** Effect of temperature on the deposition of nano-particles for fully-developed annular flow for case 2 of Table 1 for an inlet fluid velocity of 1 m/s and a pipe length of 5cm under the assumption of constant air properties. |

It should be noted that the particle density does not influence the deposition efficiency for the range of nano-particles studied; therefore, the variation of particle density was not considered. Ingham’s expression given by Eq. (9) also shows that deposition efficiency is not a function of particle density [[14](#_ENREF_14)].

* 1. *A new correlation for deposition efficiency of nano-particles in annular pipes*

For evaluating the deposition of nano-particles in annular pipe flow due to the Brownian diffusion, Winiwarter [[44](#_ENREF_44)] developed an analytic solution by solving the convection/diffusion equation for fully-developed annular pipe flows. The resulting deposition efficiency is given as,

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| --- | --- |
|  | (11) |

where is the dimensionless diffusion parameter defined as,

|  |  |
| --- | --- |
|  | (12) |

Here is the hydraulic diameter. The expression for the diffusion parameter given by Eq. (10) is very similar to that defined in Eq. (12); however, for the annulus, the hydraulic diameter is used instead of the pipe diameter. Coefficients and eigenvalues depend on the ratio of inner diameter (d1) to the outer diameter (d2) of the annular pipe. The first few terms and in the series have been evaluated in the literature [[44-46](#_ENREF_44)]; however, after the fourth terms, the parameter approaches zero for a different d1/d2 ratio [[44](#_ENREF_44)]. Therefore, in this paper the first four terms of Eq. (13) are used for estimating DE. For Kerouanton et al. [[46](#_ENREF_46)] suggested that a annular pipes with a d1/d2 ratio greater than 0.25, has approximately the same efficiency as a flat rectangular duct. In the case of the flat rectangular channel, Ingham [[47](#_ENREF_47)] developed an asymptotic solution forwhich is given as:

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| --- | --- |
|  | (13) |

Fig. 15 compares the calculated deposition efficiency versus the dimensionless diffusion parameter with Winiwarter Eq. (11) and Ingham Eq. (13). This figure shows that the present simulation results are in good agreement with the earlier analytical expressions. The largest difference between the present simulation and the Ingham equation is about 1%. The maximum difference of about 3% is seen in comparison with the Winiwarter expression, which occurs for small particle sizes. Furthermore, as shown in Fig. 15 and was also noted in [[46](#_ENREF_46)], the Winiwarter equation is not a good predictor of the deposition efficiency at the beginning of the fully-developed annular pipe flow, which should start from zero at the pipe inlet.

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| **Fig. 15.** Comparison of deposition efficiency as predicted by the present model with analytical equations for a range of dimensionless diffusion parameter |

It should be noted that the analytical correlation of Winiwarter given by Eq. (13) for estimating particle deposition efficiency in annular pipes was obtained by only considering the diffusion process. The present Lagrangian approach, however, includes the effect of particle inertia in addition to the Brownian diffusion effects. The influence of particle inertia becomes more important as particle diameter increases. As noted before, the Winiwarter correlation also is not a good predictor of the deposition efficiency of fully-developed annular pipe flows near the inlet.

Therefore, using the MATLAB software, the present simulation results are curve fitted, and a new correlation for predicting the deposition efficiency of nano-particles in annular pipe flows for is developed. The new correlation as a function of is given as,

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|  | (14) |

Fig. 16 compares the present simulation results with the fitted curve given by Eq. (14). It is seen that there is an excellent agreement with the R-square value of 0.9984 for the range of studied diffusion parameter .

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| Fig. 16. Curve ﬁtting procedure to develop a new correlation |

Fig. 17 compares the new correlation with the analytical expressions of the Ingham and Winiwarter equations. It is seen that the new correlation is very close to the Ingham equation for the rectangular annular pipe, which is equivalent to the circular annular pipe for

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| **Fig. 17.** Comparison of the new correlation for the deposition efficiency with the Ingham and Winiwarter expressions. |

1. **Conclusions**

In this paper, the Lagrangian particle tracking method was used to predict the deposition of nano-particles in annular pipe flows under laminar flow conditions. For nano-particles, Brownian diffusion is the main deposition mechanism. Commercial Ansys-Fluent 15 software was employed to solve the governing equations of fluid and particle motions. The model was verified by simulating nano-particle transport in tubular flows and comparing the results with the analytical equation. A detailed study on the effects of various parameters such as particle size, pipe length, pipe diameter, air temperature, and the flow rate was performed. The results show the ability of the Lagrangian approach for evaluating the deposition of nano-particles in annular pipe flows due to the Brownian motion. The simulation results obtained by the Lagrangian particle tracking method were curve fitted, and a new correlation was developed for calculating the deposition of nano-particles in annular pipe flows as a function of the dimensionless diffusion parameter.

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