

Use of an Eulerian/Lagrangian Framework to Improve the Air Intake System of an Automobile with Respect to Snow Ingress

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ABSTRACT

A simulation approach to predict the amount of snow which is penetrating into the air filter of the vehicle's engine is important for the automotive industry. The objective of our work was to predict the snow ingress based on an Eulerian/Lagrangian approach within a commercial CFD-software and to compare the simulation results to measurements in order to confirm our simulation approach. An additional objective was to use the simulation approach to improve the air intake system of an automobile. The measurements were performed on two test sites. On the one hand we made measurements on a natural test area in Sweden to reproduce real driving scenarios and thereby confirm our simulation approach. On the other hand the simulation results of the improved air intake system were compared to measurements, which were carried out in a climatic wind tunnel in Stuttgart. An estimation of the snow particle size and the snow mass flux on the two test sites was measured by a Snow Particle Counter (SPC). Our investigation shows that an Eulerian/Lagrangian approach can be used to predict the snow ingress. By using snow properties from the test sites as well as from literature, we observed a good agreement between the simulation results and the experiments. Our results also show that it is possible to improve the air intake system by using an Eulerian/Lagrangian framework. However, there are limitations due to the model applied for the particle-wall interactions and due to the fact that the snow particle density and especially the snow particle shape are not known from the test area.

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INTRODUCTION

In cold and snowy regions vehicles can experience an engine power loss. In such regions (e.g. northern Europe) roads are often covered with snow during the wintertime and the driving speed is typically between 50 km/h and 80 km/h. On such a road snow particles, which have a volume median diameter of approximately 300 μm , can be rolled up by vehicles. When vehicles are driven in a row, snow particles can be rolled up by the vehicles in front and penetrate into the air filter body of vehicles behind. Within the air filter body of the engine the particles are separated from the air flow by the air filter. On a longer journey the air filter body can collect a lot of snow in this way. Depending on the amount of snow within the air filter body the vehicle can experience a power loss. Even an engine stop is possible. To prevent this, automobile manufacturers carry out measurements in snowy conditions and improve the air intake system if necessary. Our objective was to use a numerical simulation model to predict the amount of snow, which is penetrating into the air filter body and to apply this simulation model to improve the air intake system regarding snow.

In literature there are investigations from Takamura and Saito [1] and us [2] which focus on this topic. Takamura and Saito also used an Eulerian/Lagrangian approach to predict the snow ingress. In their investigations they assumed spherical snow particles which have no influence on the continuous phase (one-way coupling). In our previous work [2] we described our simulation method and investigated the influence of important parameters (for instance the particle shape or the wall-normal restitution coefficient). The focus of this paper is to validate the simulation approach from [2] and to introduce an improved air intake system. Compared to the simulation approach described in [2], we didn't use a constant value for the wall-normal restitution coefficient. A model from Villedieu et al. [3] was applied to estimate this parameter.

In the next section the numerical approach is explained. After that measurements on the test area in Sweden are presented. These measurements include the analysis of the snow mass flux, which penetrated into the air filter body of our test vehicle and the quantification of the particle size and the mass flux of the rolled up snow particles. Then our simulation results will be compared to the measurements. At the end an improved air intake system will be introduced.

NUMERICAL METHOD AND MODELS

The particle-laden flow was modeled by using an Eulerian/Lagrangian framework in STAR-CCM+ [4]. To calculate the multiphase flow an Eulerian framework was applied to the continuous phase (air) and a Lagrangian framework to the dispersed phase (snow particles). By using the Reynolds-averaged Navier-Stokes (RANS) equations in conjunction with the standard two-layer $k-\epsilon$ turbulence model the fluid flow was determined. Information about the two-layer approach can be found in [4] and [5]. Since the difference between the ambient temperature and temperature inside the air filter body is low in our case, the energy equation was not solved. For the wall treatment an all- y^+ model was selected. This treatment is suitable for fine and coarse meshes [4]. For the simulations, which will be presented, we assumed a one-way coupled flow. So the dispersed phase doesn't affect the continuous phase. Further information related to the phase coupling in our case can be found in [2]. In the following subsections the modelling of the dispersed phase will be explained.

Equation of Motion for the Dispersed Phase

In our simulations we used the parcel concept. A parcel represents a group of particles, which have similar properties [4]. By using the Lagrangian approach for the dispersed phase the trajectory of each representative particle (or parcel) is calculated. To calculate this trajectory Newton's second law has to be solved for each representative particle using the following equation

$$m_p \frac{d\mathbf{v}_p}{dt} = \mathbf{F}. \quad (1)$$

According to this law the change of the particle velocity $\mathbf{v}_p$ can be determined by evaluating the forces $\mathbf{F}$, which are acting on the particle. Combining eq. (1) and the differential equation

$$\frac{d\mathbf{x}_p}{dt} = \mathbf{v}_p \quad (2)$$

allows to calculate the current particle position $\mathbf{x}_p$. Yeoh and Tu [6] and Crowe et al. [7] discuss several forces, which act on the particle. These include: drag force, virtual mass force, Basset force, lift forces, body forces, buoyancy force and pressure gradient force. In many applications the drag force is the most important force [6]. In an accelerated flow or for an accelerated particle movement the virtual mass force and the Basset force occur [8]. Due to the low density ratio between the fluid and the particle these two forces were neglected in this work [9]. Lift forces are the Magnus force and the Saffman force. These forces occur due to particle rotation. Since particle rotation was not considered in our investigations these forces were neglected. For the simulations one body force, the gravitational force, was considered. Due to the high difference between the particle density and the fluid density the buoyancy force was neglected for the particles. The pressure gradient force arises because of a local pressure gradient [7]. To summarize, for our investigations we considered the drag force

$$\mathbf{F}_d = \frac{1}{2} \rho A_p c_d (\mathbf{v} - \mathbf{v}_p) |\mathbf{v} - \mathbf{v}_p|, \quad (3)$$

the gravitational force

$$\mathbf{F}_g = m_p \mathbf{g}, \quad (4)$$

and the pressure gradient force [4]

$$\mathbf{F}_p = -V_p \nabla p_{static}. \quad (5)$$

In eq. (3) ρ is the fluid density, A_p the cross-sectional area of the particle, c_d the drag coefficient and $\mathbf{v}$ the velocity of the fluid. In eq. (4) $\mathbf{g}$ is the gravitational acceleration and in eq. (5) V_p is the volume of a particle and ∇p_{static} is the gradient of the static pressure in the continuous phase. Using these forces the equation of motion results in

$$m_p \frac{d\mathbf{v}_p}{dt} = \mathbf{F}_d + \mathbf{F}_g + \mathbf{F}_p. \quad (6)$$

The ambient temperature in regions like northern Europe can be considerably low during the wintertime. For such low temperatures the air temperature within the air intake pipe is usually below 0°C. For this reason we didn't consider melting of the snow particles in our simulations.

Drag Force

To determine the drag force $\mathbf{F}_d$ we treated the particles as isolated. That means the drag force of a snow particle is not influenced by its neighboring particles. For the calculation of $\mathbf{F}_d$ the particle shape is important. As photographs from Nakaya [10] or Libbrecht [11] show, natural snow crystals can have different particle shapes. For example there are needles, dendrites, plates or columns. For our simulations rolled up snow particles are of interest. It is conceivable, that rolled up particles also contain fragments of a dendrite, a needle or any other snow crystal. Unfortunately there is no distribution of the particle shape available for these particles. So for our investigations we considered different basic shapes: a thin plate, a thick plate, a column and a needle (note that these shapes differ from those in [2]). Artificial snow particles (like those in the climatic wind tunnel in Stuttgart) often consist of frozen water droplets. Therefore, we also considered a spherical shape. To take the particle shape in the equation of motion into account, the drag coefficient c_d has to be specified. For spherical particles a correlation from Schiller and Naumann [12] has been used to specify the drag coefficient c_d

$$c_d = \begin{cases} \frac{24}{Re_p} (1 + 0.15 Re_p^{0.687}) & \text{for } Re_p \leq 1000 \\ 0.44 & \text{for } Re_p > 1000. \end{cases} \quad (7)$$

Re_p is the particle Reynolds number. This dimensionless quantity is defined as

$$Re_p = \frac{\rho D_p |\mathbf{v} - \mathbf{v}_p|}{\mu} \quad (8)$$

In eq. (8) D_p is the particle diameter and μ the dynamic viscosity.

To specify the drag coefficient of non-spherical particles we used an approach described by Loth [13]. To take the particle shape into account, there are two correction factors: f_{shape} and C_{shape} . The correction factor f_{shape} compares the drag coefficient of the particle to the drag coefficient of a sphere of equivalent volume in the Stokes regime ($Re_p \ll 1$)

$$f_{shape} = \frac{c_{d,St}}{c_{d,S,St}} \quad (9)$$

The correction factor C_{shape} compares the drag coefficient of the particle to the drag coefficient of a sphere of equivalent volume in the Newton regime ($Re_p \gg 1$ and an approximately constant drag coefficient)

$$C_{shape} = \frac{c_{d,Ne}}{c_{d,S,Ne}} \quad (10)$$

When these correction factors are known, the drag coefficient can be determined. For particles, whose relative cross-section to the flow is circular (e.g. a sphere or a needle, which has a broadside orientation), Loth suggests the following correlation

$$\frac{c_d}{C_{shape}} = \frac{24f_{shape}}{C_{shape}Re_p} \left(1 + 0.15 \left(\frac{C_{shape}Re_p}{f_{shape}} \right)^{0.687} \right) + \frac{0.42}{1 + \frac{42500}{\left(\frac{C_{shape}Re_p}{f_{shape}} \right)^{1.16}}} \quad (11)$$

Equation (11) is based on a correlation from Clift and Gauvin, which is used to calculate the drag coefficient of a sphere. By applying f_{shape} and C_{shape} the drag coefficient of a non-spherical particle can be calculated. For particles, whose relative cross-section to the flow is non-circular (e.g. a disk, which has a broadside orientation), Loth suggests a modified version of eq. (11)

$$\frac{c_d}{C_{shape}} = \frac{24f_{shape}}{C_{shape}Re_p} \left(1 + 0.035 \left(\frac{C_{shape}Re_p}{f_{shape}} \right)^{0.74} \right) + \frac{0.42}{1 + \frac{33}{\left(\frac{C_{shape}Re_p}{f_{shape}} \right)^{0.5}}} \quad (12)$$

The particle Reynolds number Re_p for non-spherical particles is based on the diameter of a sphere, which has the same volume as the particle. To determine the drag force F_d the cross-sectional area of a sphere of equivalent volume is used.

For the determination of the correction factors, the thin plate, the thick plate, the column and the needle were approximated by spheroids. The aspect ratio E (the ratio between the semi-axes) of the spheroid specifies the particle shape. To obtain a value for E for the different particle shapes we used data from Auer and Veal [14]. They investigated the diameter-thickness relationship for plate crystals, the length-width relationship for columnar crystals and the length-width relationship for needle crystals. Using the data from Auer and Veal [14] and a characteristic particle size of $300 \mu m$, values for E were determined. The values for E , f_{shape} and C_{shape} , which were used in our simulations, are shown in table 1. The values for f_{shape} and C_{shape} were approximated by the correlations given in [13].

Table 1. E , f_{shape} and C_{shape} for the non-spherical particles, which were used for the investigations.

	E	f_{shape}	C_{shape}
Thin plate	0.09	1.92	13.72
Thick plate	0.45	1.17	2.42
Column	2.50	1.15	1.56
Needle	8.33	1.65	2.99

Figure 1 shows the drag coefficient c_d as a function of the particle Reynolds number Re_p . These values were used to calculate the drag force F_d in eq. (3). As the figure shows the non-spherical particles can have a significant larger drag coefficient than a sphere. Considering that the drag force is the most important force, it can be recognized, that the particle shape is very important for the simulations. In our numerical investigations Re_p is relevant from close to zero up to approximately 500.

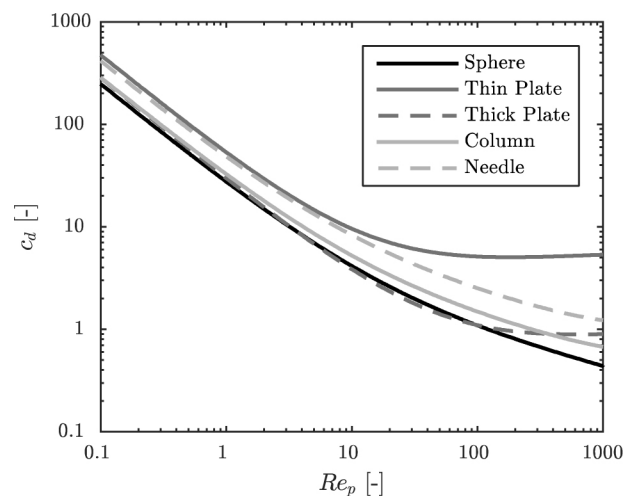


Figure 1. Drag coefficients for a sphere, a thin plate ($E = 0.09$), a thick plate ($E = 0.45$), a column ($E = 2.5$) and a needle ($E = 8.33$).

Wall-Impact Behavior

As explained by Sommerfeld [15] particle-wall collisions can influence the particle motion considerably. Especially for larger particles this influence is significant. The motion of such particles is dominated by inertia. After a wall collision these particles maintain their direction for a while. Small particles follow the fluid flow well. For such particles the influence of a wall collision is low. After a wall collision these particles will be quickly accelerated to the flow field velocity.

Higa et al. [16, 17] investigated the wall-impact behavior of ice spheres. They classified the collisional behavior into two regimes. In the first regime the ice particles maintained their shape and no macroscopic cracks were visible after the collision. Within this regime the particle velocity before and after the collision were similar. In the second regime cracks and fragmentation occurred. Within this regime the particle velocity after the wall collision can be significant lower. Higa et al. separated these regimes by a critical impact velocity.

Hauk et al. [18] studied the collisional behavior of irregular and spherical ice particles. Depending on the particle size and the particle impact velocity they observed four different fragmentation cases: No fragmentation, minor fragmentation, major fragmentation and catastrophic fragmentation. They also introduced a map for the ice particle breakup. Depending on the particle size and the impact velocity this map allows to estimate if fragmentation or minor fragmentation occurs. According to their map and our boundary conditions (volume median diameter: 300 μm , maximum velocity: 80 km/h) no fragmentation or minor fragmentation occur in our case. Since we didn't expect major or catastrophic fragmentation, we neglected fragmentation in our simulations.

To calculate the particle velocity after a wall collision, an approach based on the momentum equations for the collision of a spherical particle with a wall [19, 15, 7] was used. For the collision we assumed that the particles rebound on a smooth surface. By solving the momentum equations for the collision and neglecting particle rotation, the following equations are obtained

$$\text{if } \left| \frac{v_{p,n}^{(1)}}{v_{p,t}^{(1)}} \right| \geq \frac{2}{7(1+e_n)\mu_k}$$

$$v_{p,n}^{(2)} = -e_n v_{p,n}^{(1)} \quad (13)$$

$$v_{p,t}^{(2)} = \frac{5}{7} v_{p,t}^{(1)} \quad (14)$$

$$\text{and if } \left| \frac{v_{p,n}^{(1)}}{v_{p,t}^{(1)}} \right| < \frac{2}{7(1+e_n)\mu_k}$$

$$v_{p,n}^{(2)} = -e_n v_{p,n}^{(1)} \quad (15)$$

$$v_{p,t}^{(2)} = (1 - \mu_k(1 + e_n) \tan(\theta)) v_{p,t}^{(1)} \quad (16)$$

In these equations $v_{p,n}$ is the component of the particle velocity normal to the wall and $v_{p,t}$ is the component of the particle velocity tangential to the wall. The superscript (1) refers to the velocity before the collision and the superscript (2) to the velocity after the collision. θ is the particle incidence angle. This angle and the velocity components are illustrated in [fig. 2](#). As these four equations show the coefficient of kinetic friction μ_k and the wall-normal restitution coefficient e_n have to be known to calculate the particle velocity after the wall collision. The coefficient of kinetic friction μ_k is defined as the ratio between the force of kinetic friction F_k and the normal force F_N (Coulomb's friction law)

$$\mu_k = \frac{F_k}{F_N} \quad (17)$$

Barnes et al. [20] investigated the coefficient of kinetic friction between an ice cone and different materials with smooth surfaces. He showed, that for high sliding speeds ($> 0.5 \text{ m/s}$), the coefficient of kinetic friction for a sliding ice cone on steel, glass or granite is about 0.05. This value was used for our simulations.

The restitution coefficient e_n relates the particle normal velocity component before and after the collision

$$v_{p,n}^{(2)} = -e_n v_{p,n}^{(1)} \quad (18)$$

To estimate e_n we used a model from Villedieu et al. [3]. In their model they introduced the ratio L

$$L = \frac{\frac{\pi \rho_p D_p^3 (v_{p,n})^2}{12}}{\pi e_\sigma D_p^2} = \frac{\rho_p D_p (v_{p,n})^2}{12 e_\sigma} \quad (19)$$

This ratio compares the normal kinetic energy to the surface energy of the particle (assuming a spherical shape). In [eq. \(19\)](#) ρ_p is the particle density and e_σ the surface energy per unit area. According to Vidaurre und Hallett [21] e_σ has a value of 0.12 J/m^2 at a temperature of -20°C . Villedieu et al. [3] classified the collisional behavior into three types:

1. For $L \leq 0.5$ a quasi-elastic rebound without fragmentation occurs. For this case $e_n = 1$ is assumed.
2. For $0.5 \leq L \leq 90$ an inelastic rebound occurs. Fragmentation is possible. The restitution coefficient is given by

$$e_n = \left(\frac{0.5}{L} \right)^{\frac{1}{3}} \quad (20)$$

3. For $L \geq 90$ a highly inelastic collision with major fragmentation occurs. This case is not relevant for our investigations.