

Modeling and Numerical Calculation of Snow Particles Entering the Air Intake of an Automobile

Christoph Huber and Bernhard Weigand
University of Stuttgart

Heinrich Reister and Thomas Binner
Daimler AG

ABSTRACT

A physically based model to predict the amount of snow which is entering the air intake of an automobile is extremely important for the automotive industry. It allows to improve the air intake system in the development state so that new vehicles can be developed in a shorter time.

Using an Eulerian/Lagrangian approach within a commercial CFD-software we set up a model and calculated the snow ingress into an air intake of an automobile. In our numerical investigations we considered different particle shapes when calculating the drag coefficient, different coefficients of restitution and different particle sizes. Furthermore two-way coupling was considered.

To obtain key parameters for the simulation, we measured the size of snow particles in the Daimler climatic wind tunnel in Sindelfingen by using a microscope and a measuring device from Malvern. Besides we used mechanical snow traps to determine the snow mass flux in the climatic wind tunnel and on a test area in Sweden.

The numerical results show that especially the wall-impact behavior, the particle size and the particle shape can have a significant influence on the snow ingress into the air intake. Because there are currently uncertain parameters in describing the wall-impact behavior and the distribution of the particle shape on the road further investigations are needed to predict the exact amount of snow particles entering the air intake of an automobile.

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INTRODUCTION

In cold regions such as Canada or Northern Europe the roads are often covered with snow during the wintertime. When vehicles are driven in a row, one behind the other, snow can be rolled up by the ones in front and can penetrate into the engine air intake pipe of the vehicles behind. Snow, which enters the air intake pipe, accumulates in the air filter. Depending on the amount of snow, which entered the pipe, an engine power drop or an engine stop can occur. Even a power drop can be critical because overtaking is limited. For this reason the air intake system of a vehicle has to be well designed, so that less snow enters the air intake pipe.

Using a physically based model to predict numerically the snow ingress of an automobile can help to develop new vehicles in a shorter time frame. Applying an Eulerian/Lagrangian approach this was done by Takamura and Saito [1]. For their investigation they assumed spherical snow particles which have no influence on the continuous phase.

Using also an Eulerian/Lagrangian approach to set up a simulation model, we consider the influence of the particles on the continuous phase (two-way coupling). Besides we consider different particle shapes when calculating the drag coefficient, different coefficients of restitution and different particle sizes. The results in our test case show that two-way coupling lowers the snow ingress slightly compared to a one-way coupled flow system and that especially the particle shape, the restitution coefficient and the particle size can influence the snow entering the air intake significantly. Furthermore it is shown that there are currently uncertain parameters in describing the wall-impact behavior.

In the next chapter information about snow properties and the snow mass flux of rolled up snow is given. After that we explain the numerical method and the models used. After this numerical results are presented.

SNOW PROPERTIES AND SNOW MASS FLUX

To obtain important information for setting up a simulation model for the snow ingress, we did research on snow properties and on the snow mass flux. Because a climatic wind tunnel is used during the development process of many new vehicles the artificially produced snow in the Daimler climatic wind tunnel was also investigated.

Literature Research about Snow Properties

We did research on natural snow crystals, on the particle size of rolled up snow on roads and on the wall-impact behavior of ice particles.

Particle Shape and Size

As photographs from Nakaya [2] or Libbrecht [3] show, snow crystals, which are falling from the sky, can have many different particle shapes, e.g. there are needles, dendrites, plates or columns. Auer et al. [4] investigated the size of over 1500 ice crystals in clouds. The size spectrum ranged from a few micrometer up to almost 1 cm. When these crystals fall from sky, they can accumulate and form snowflakes, which are even larger [5].

As Takamura and Saito [1] mentioned, it is likely, that snow, which has been rolled up by vehicles, differs from snow, which falls from sky. To measure the size of rolled up snow they used a snow particle counter (SPC). This is an optical sensor, which counts and determines the size of snow particles passing through a sampling area [6]. Their results show that most of the rolled up particles are between 50 μm and 400 μm . Hence the size of rolled up snow particles is similar to the size of blowing snow particles [7]. Using the data given by Takamura and Saito we calculated their corresponding volume median diameter. This variable specifies the diameter, below which 50 % of the cumulative particle volume is. In their case this value is approximately 300 μm . Concerning the particle shape of rolled up snow, there is, to the authors' best knowledge, no measurement.

Wall-Impact Behavior

The wall collision process can significantly influence the motion of particles. This collision process depends on many parameters. Some of them are [8]: Particle incidence angle, particle velocities before collision (translational and rotational), properties of the particle and the wall materials, particle shape and the surface roughness of the wall. For many of these parameters little experimental information is available.

Hauk et al. [9] investigated the impact behavior of irregular and spherical ice particles on a tiltable aluminum surface. The investigated particles ranged from a few micrometers up to 1600 μm . 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. For the last three cases it is possible, that small fragments stick to the

wall. They also observed the particle rotation after the wall collision. Many of the particles, which had no significant particle rotation before the impact, showed rotational movements after the impact.

When describing the energy loss of particles during a wall collision, two important coefficients are: the coefficient of kinetic friction μ_k and the wall-normal restitution coefficient e_n . 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):

$$\mu_k = \frac{F_K}{F_N} \quad (1)$$

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

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

In [fig. 1](#) these velocity components are visualized.

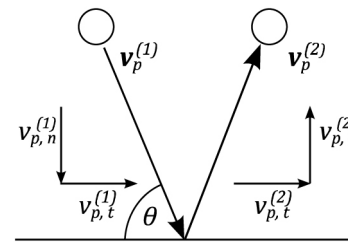


Figure 1. Particle velocity components during wall-collision and particle incidence angle.

In the literature survey from Güttler et al. [10], there is a list with experiments regarding the restitution coefficient of ice spheres. Some of these experiments were performed by Higa et al. [11, 12]. They classified the collisional behavior of ice spheres into three types: No-crack type, crack type and fragmentation type. According to their experiments e_n is roughly constant for low particle impact velocities. For such velocities there are in most cases no cracks visible after the collision and the restitution coefficient can reach almost 1. As soon as the impact velocity reaches a critical value, cracks appear and the value of the restitution coefficient decreases strongly with increasing impact velocity. At a certain impact velocity fragmentation occurs. For the last two types the restitution coefficient can get close to 0. Higa et al. also show that the restitution coefficient depends considerably on the particle diameter, the temperature and the surface condition (effects of frost). The experiments listed by Güttler are in the size range from $d_p = 2.8 \text{ mm}$ to $d_p = 400 \text{ mm}$. As Takamura and Saito showed, rolled up snow particles are in the order of 100 μm . To the authors' best knowledge there was no experiment performed with ice spheres or irregular (non-spherical) ice particles in the order of 100 μm .

As mentioned by Hobbs [13] ice has an unusual small coefficient of friction between itself and many solid materials. Barnes et al. [14] investigated the coefficient of kinetic friction between an ice cone and different materials with smooth surfaces. He shows, 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. For the combination of brass and ice μ_k is higher. For lower sliding speeds the material combination plays a more important role and μ_k can be significantly higher.

Measurement of the Particle Size in the Climatic Wind Tunnel

In the Daimler climatic wind tunnel in Sindelfingen snow is artificially produced by several two-fluid nozzles. These nozzles atomize water and generate small water droplets which will freeze and become solid. For this reason the artificial snow consists of frozen water droplets. In order to influence the size of the water droplets there is the possibility to vary the air pressure for the atomization. When making snow the two-fluid nozzles are located in the nozzle of the climatic wind tunnel. For all measurements presented in this paper the air temperature in the wind tunnel was set to -30°C , the wind speed to 50 km/h and the air pressure for atomization to 7 bar .

To measure the particle size in the climatic wind tunnel, we used a microscope and the measuring device Spraytec from Malvern Instruments Ltd. (see figure 2). By using the technique of laser diffraction the Malvern device determines the particle size. In the climatic wind tunnel vehicles are usually installed in a distance of 1.5 m from the exit of the wind tunnel nozzle. To determine the particle size at the vehicle front the Malvern Spraytec was located at that position. The height of the measuring area was approximately 0.5 m .

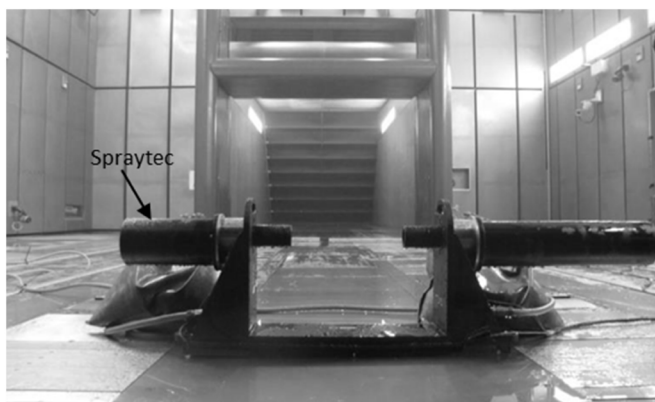


Figure 2. Measuring device Spraytec from Malvern Instruments Ltd. to determine the size of the artificially produced snow in the Daimler climatic wind tunnel.

The results are shown in figure 3. The solid line represents the particle size frequency distribution based on the volume and the dotted line the cumulative particle volume. It can be seen that the

particles between $10 \mu\text{m}$ and $500 \mu\text{m}$ contribute the most to the cumulative volume. The volume median diameter for this case is $85 \mu\text{m}$.

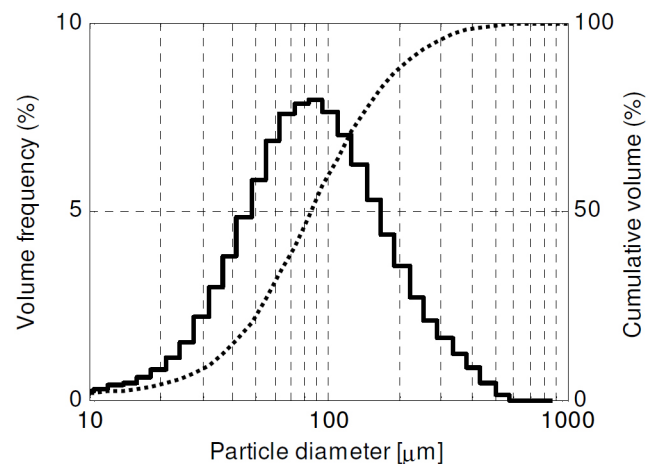


Figure 3. Snow size distribution in the Daimler climatic wind tunnel; measuring device Spraytec. Air temperature -30°C , wind speed 50 km/h and air pressure for atomization 7 bar .

Figure 4 shows snow particles which have been sampled on felt and photographed with a microscope. As expected the snow particles in the wind tunnel are more similar to a sphere than to a dendritic-shaped snow crystal or a needle crystal. By comparing the volume median diameter between the particles in the climatic wind tunnel ($85 \mu\text{m}$) and the rolled up particles on the road from the literature research ($300 \mu\text{m}$) one recognizes that the particles in the climatic wind tunnel are smaller.

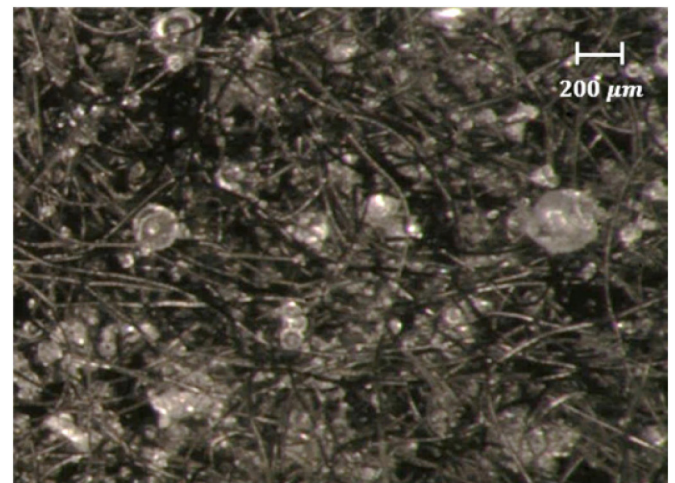


Figure 4. Photograph of snow particles in the Daimler climatic wind tunnel.

Measurement of the Snow Mass Flux

To decide which coupling regime (one-way coupling, two-way coupling or four-way coupling) is appropriate for the numerical simulation, the volume fraction of the dispersed phase α_p is an