A New Process to Evaluate the Risk of an Engine Power Drop Caused by Snow Particles

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Abstract. In cold and snowy regions roads are often covered with snow during the winter time. On these roads snow particles can be rolled up by vehicles and these particles can penetrate into the air intake system of the engine. As a result an engine power drop can occur. This paper discusses three different possibilities to evaluate the risk of such an engine power drop. One possibility is given by measurements on a natural testing area. The second possibility consists of measurements in a climatic wind tunnel and the third possibility is given by numerical simulations. As examples for the experimental testing a natural testing area in Arjeplog (Sweden) and two climatic wind tunnels in and near Stuttgart will be explained in more detail. Information for the snow particle generation, the snow particle size and the snow mass flux will be provided. Additionally to this experimental testing a method for the virtual testing will be presented. This method is based on an Eulerian/Lagrangian approach within a commercial CFD-software. The simulation method allows an approximate calculation of the snow amount, which penetrates into the air filter body.

In the past prototypes were built and measurements were carried out to evaluate the snow amount, which penetrates into the air filter body. These measurements were possible at a later stage of the vehicle development process. We suggest to introduce the simulation method in an earlier stage of the development process. Thereby the air intake system can reach a high level of maturity before first prototypes are built.

1 Introduction

In cold and snowy regions (e.g., Northern Europe) roads are often covered with snow during the wintertime. On such roads snow particles can be rolled up by vehicles (as shown in Fig. 1). When vehicles are driven in a row, snow particles can be rolled up by vehicles in front and penetrate into the air filter body of vehicles behind. Within the air filter body of the engine the snow particles are separated from the air flow by the air filter. Depending on the amount of snow within the air filter body an engine power drop can occur. Even an engine stop is possible.

Traditionally there are two possibilities to evaluate the risk of an engine power drop, which is caused by snow particles:

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Fig. 1. Snow particles rolled up by a vehicle.

1. Automobile manufacturers carry out measurements on natural testing areas. On such testing areas vehicles can be driven in a row (one behind the other). After a certain time, the snow amount inside the air filter body and the engine power drop can be evaluated.
2. Automobile manufacturers carry out measurements in climatic wind tunnels. Snow is artificially produced to create environmental conditions, which are similar to those on roads and natural testing areas. As on the natural testing area the snow amount inside the air filter body and the engine power drop can be evaluated after the measurement.

However, both possibilities have one large disadvantage: Prototypes of the vehicle have to be built to carry out such measurements. To develop new vehicles in a cost-effective manner, automobile manufacturers use numerical simulations to achieve a high level of maturity of the vehicle before first prototypes are built. Exemplarily a reduced sketch of the vehicle development process of the Daimler AG is shown in Fig. 2. This development process starts with the virtual testing of the vehicle. During this virtual testing the vehicle is improved until a certain level of maturity is achieved. Having achieved this level, prototypes are built and the testing is continued in wind tunnels, on natural testing areas and on roads. In the past the virtual testing didn't provide the possibility to evaluate the risk of an engine power drop, which is caused by snow particles. To evaluate this risk, measurements were carried out at a later stage of the vehicle development process. If adjustments to the vehicle were required in this late stage, high costs could emerge. To evaluate the risk of an engine power drop during the virtual testing phase, we suggest to use the simulation method as described in [1]. Using this simulation method the amount of snow, which penetrates into the air filter body, can be predicted and the air intake system can be improved at an early stage of the vehicle development process.

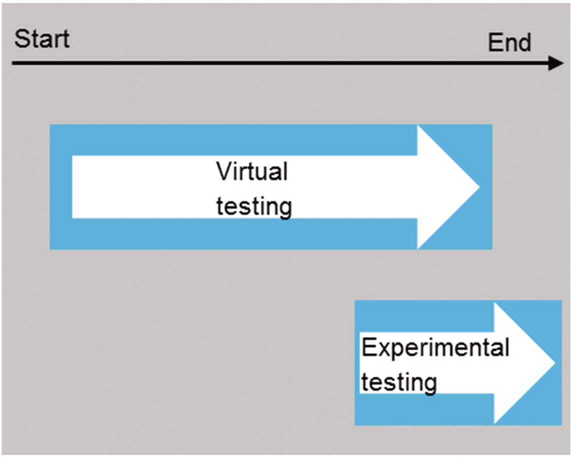

Fig. 2. Reduced sketch of the vehicle development process of the Daimler AG.

In the next section the traditional possibilities to evaluate the risk of an engine power drop are shown. After that the simulation method, which allows a virtual assessment of the risk, is explained. At the end results of the virtual testing will be compared to results of the experimental testing.

2 Traditional Possibilities to Evaluate the Risk of a Power Drop

To evaluate the risk of an engine power drop, which is caused by snow particles, Daimler AG has different testing areas in Northern Europe and two climatic wind tunnels in and near Stuttgart. In the following sections a testing Area in Arjeplog (Sweden) and the two climatic wind tunnels will be introduced.

2.1 Testing Area in Arjeplog

During the winter time Arjeplog offers cold temperatures, frozen lakes and a lot of snow. Due to these conditions Arjeplog is well suited for winter tests. The testing area of Daimler AG is on a frozen lake, which provides a circuit for the testing. To carry out the tests, two vehicles are required. Vehicle one drives in front to roll up snow (see Fig. 1). Vehicle two (the test vehicle) follows vehicle one in a certain distance. At the end of the measurement the snow amount inside the air filter body and a possible engine power drop can be evaluated.

In nature snow crystals can have many different particle shapes. For example there are needles, dendrites, plates or columns [2, 3]. These snow crystals grow from water vapor [3]. The size of these snow crystals in clouds are typically between a few micrometers and one centimeter [4]. Some of these snow crystals are hollow. Heymsfield [5] and Ono [6] carried out measurements to determine the snow crystal density.

In their measurements values between approximately 500 kg/m^3 and 917 kg/m^3 were observed. In this work rolled up snow particles are of interest. It is likely that these rolled up snow particles consist of fragments of snow crystals and snowflakes. In [1] the particle size of these rolled up snow particles was investigated. As can be seen in Fig. 3 the rolled up snow particles are typically between 30 μm and 500 μm. Figure 3 includes a distribution for the particle counts and for the volume of the particles. To measure the snow particle size a so called snow particle counter from Niigata Electric was used (see Fig. 4). The particle size distribution was measured in a distance of 0.7 m to the ground. In [1] the volume median diameter was used to characterize the particle size distribution. For the distribution shown in Fig. 3 the volume median diameter is approximately 260 μm. In [1] this volume median diameter was measured on different days on the testing area. Values between 180 μm and 380 μm were observed. This scattering represents a challenge for the natural testing area with respect to reproducibility: Fresh snow, different temperatures or different winds influence the measurement.

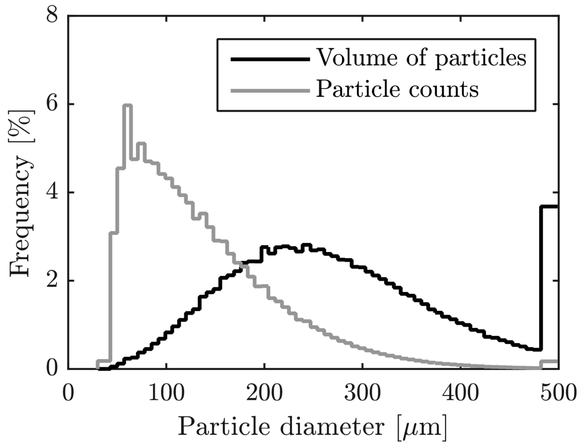

Fig. 3. Typical particle size distribution of rolled up snow on the test area in Arjeplog; data from [1].

Additionally to the snow particle size the snow mass flux in front of the test vehicle was measured in [1]. As for the particle size the snow particle counter was used to measure the mass flux. The results are shown in Fig. 5. On different days values between 20 and 240 $g/(m^2s)$ were observed. As mentioned before this scattering occurs due to different ambient conditions. Since the snow mass flux in front of the test vehicle has a direct influence on the snow amount inside the air filter body of the test vehicle, the normalized snow mass flux n was introduced in [1]:

$$n = \frac{snow\,mass\,flux\,at\,the\,inlet\,of\,the\,air\,filter\,body}{snow\,mass\,flux\,in\,front\,of\,the\,vehicle}. \quad (1)$$

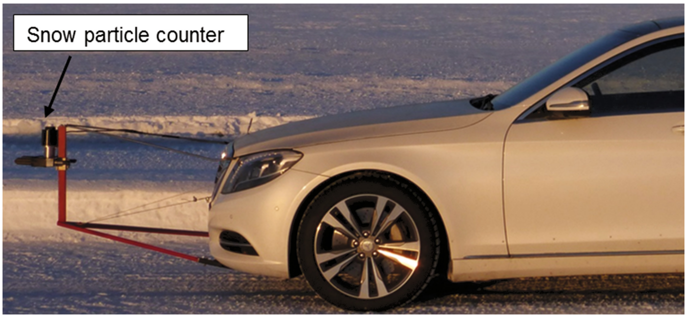

Fig. 4. Test vehicle with snow particle counter.

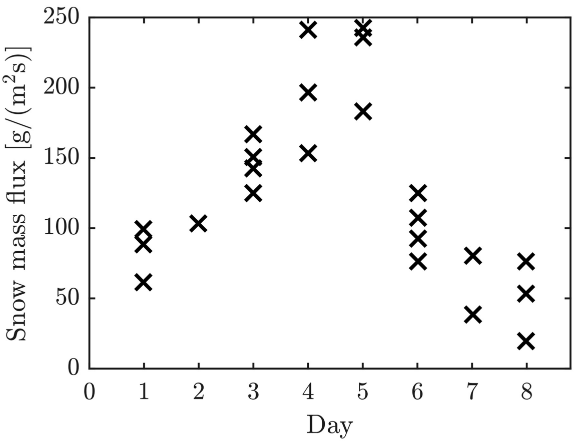

Fig. 5. Snow mass flux in front of the test vehicle on the testing area in Arjeplog at different days; data from [1].

This ratio compares the snow mass flux at the inlet of the air filter body to the snow mass flux in front of the test vehicle. The snow mass flux at the inlet of the air filter body was determined by weighing the snow amount inside the air filter body and dividing this amount by the measuring duration and the inlet area of the air filter body. The snow mass flux in front of the test vehicle mas measured with the help of the snow particle counter. The idea of introducing the ratio *n* is to increase the comparability between different measurements.

2.2 Climatic Wind Tunnels

The large advantage of a climatic wind tunnel is that measurements can be carried out all year long and that the conditions are reproducible. However, there is one difference (regarding the snow particles) compared to the testing on a natural testing area: the snow particles are artificially produced. Often small water droplets are generated in climatic wind tunnels. These water droplets will freeze in the wind tunnel and become solid. So these snow particles consist of frozen water droplets. Unlike to natural snow crystals these artificially produced snow particles don't grow from water vapor and this is the reason why the snow particle shape is different.

2.2.1 Climatic Wind Tunnel in Sindelfingen

One climatic wind tunnel of Daimler AG, which can generate snow particles, is located in Sindelfingen. In this wind tunnel temperatures between −40 °C and 40 °C can be realized. The maximum wind speed is 265 km/h. Figure 6 shows a schematic drawing of this wind tunnel. For snow tests two snow wings can be inserted into the nozzle of the climatic wind tunnel (see Fig. 6). Each wing has 8 two-fluid nozzles to atomize water and generate small droplets. As can be seen in the figure, the water is injected against the flow direction. Due to this procedure the particle flight time, until the particle impinges on the vehicle, can be increased. Especially for larger water droplets this increased flight time is necessary to obtain completely frozen particles.

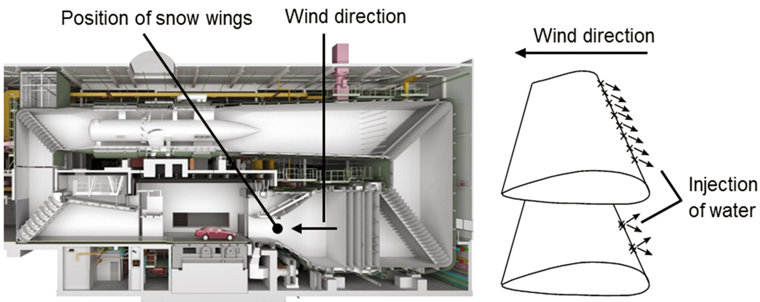

Fig. 6. Schematic drawing of the climatic wind tunnel in Sindelfingen; two snow wings can be inserted to generate snow particles.

In Fig. 7 the size distribution of these artificially produced snow particles is shown. As can be seen the particles are between 10 µm and 500 µm. The volume median diameter for this distribution is 85 µm. For this measurement the device Spraytec from Malvern Instruments Ltd. was used. Since the water droplets require a certain time to completely freeze the snow particle size in the climatic wind tunnel is limited. A typical value for the snow mass flux in this wind tunnel is approximately 70 g/(m^2s).

To evaluate the risk of an engine power drop in the climatic wind tunnel the two snow wings are inserted into the wind tunnel and after a certain time the snow amount inside the air filter body of the test vehicle and the engine power drop are evaluated.

2.2.2 Climatic Wind Tunnel in Stuttgart

Another climatic wind tunnel of Daimler AG, which can generate snow particles, is in Stuttgart. This wind tunnel is shown in Fig. 8. The maximum wind speed for this wind tunnel is 200 km/h. To generate snow particles a snow canon can be inserted into the wind tunnel. This snow canon produces small water droplets, which will freeze due to

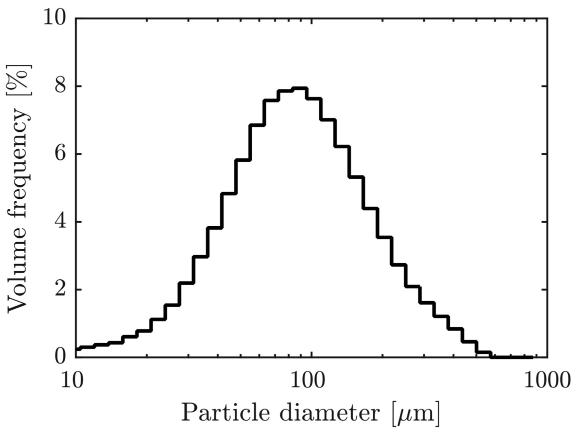

Fig. 7. Snow size distribution in the climatic wind tunnel in Sindelfingen; data from [7].

the low temperature in the climatic wind tunnel. As indicated in Fig. 8 the particles are sprayed into an opening. From this point the particles follow the air flow and eventually impinge on the vehicle. Using the snow particle counter a volume median diameter of approximately 160 μm was observed for this wind tunnel [1]. The snow particle size distribution is shown in Fig. 9. Regarding the snow mass flux a value of 105 g/(m^2s) was observed [1]. To evaluate the risk of an engine power drop in this wind tunnel the snow canon is activated and after a certain time the snow amount inside the air filter body of the test vehicle and the engine power drop are evaluated.

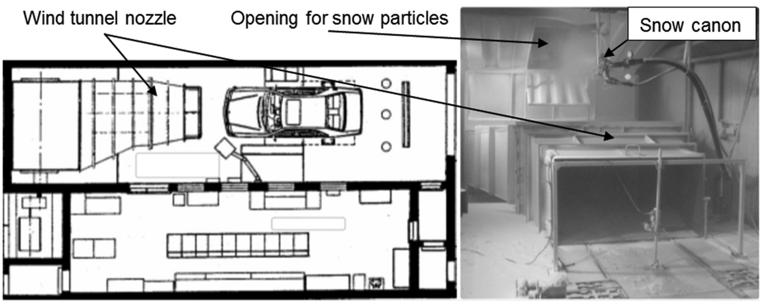

Fig. 8. Snow production in the climatic wind tunnel in Stuttgart.

3 Simulation Approach to Calculate the Snow Ingress

In [1, 7] a simulation approach to predict the amount of snow, which penetrates into the air filter body of the engine, is introduced. This simulation method allows a virtual testing of the vehicle during an early stage of the development process.

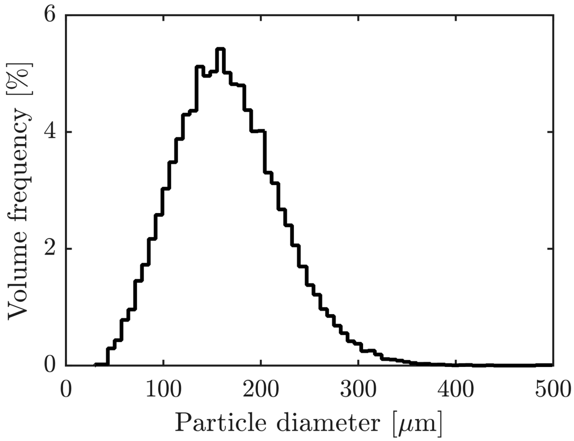

Fig. 9. Snow size distribution in the climatic wind tunnel in Stuttgart.

The simulation method for the particle-laden flow is based on an Eulerian/Lagrangian framework within a commercial CFD-software. For the continuous phase (air) an Eulerian framework is applied and for the dispersed phase (snow particles) a Lagrangian framework is utilized. By solving the Reynolds-averaged Navier-Stokes (RANS) equations the air flow can be calculated. For the particle-laden flow a one-way coupled flow is assumed. So the dispersed phase doesn't affect the continuous phase and particle-particle interactions are neglected. Furthermore the parcel concept is used. A parcel represents a group of particles, which have similar properties [8]. To calculate the snow particle trajectories Newton's second law has to be solved for each representative particle (or parcel):

$$m_p \frac{d\boldsymbol{v}_p}{dt} = \boldsymbol{F}. \tag{2}$$

Using this law the change of the particle velocity $\boldsymbol{v}_p$ can be determined by calculating the forces $\boldsymbol{F}$, which are acting on the particle. In Eq. (2) m_p is the mass of the particle. In the simulation approach described in [1] the drag force

$$\boldsymbol{F}_d = \frac{1}{2}\rho A_p c_d \left(\boldsymbol{v} - \boldsymbol{v}_p\right)\left|\boldsymbol{v} - \boldsymbol{v}_p\right|, \tag{3}$$

the gravitational force

$$\boldsymbol{F}_g = m_p \boldsymbol{g}, \tag{4}$$

and the pressure gradient force [8]

$$\boldsymbol{F}_p = -V_p \nabla p_{static} \tag{5}$$

are taken into account.

In Eq. (3) ρ denotes the fluid density, A_p the cross-sectional area of the particle, c_d the drag coefficient and $\boldsymbol{v}$ the velocity of the fluid. In Eq. (4) $\boldsymbol{g}$ is the gravitational acceleration and in Eq. (5) V_p denotes 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

$$m_p \frac{d\boldsymbol{v}_p}{dt} = \boldsymbol{F}_d + \boldsymbol{F}_g + \boldsymbol{F}_p. \tag{6}$$

3.1 Drag Force

To determine the drag force $\boldsymbol{F}_d$, the snow particles are treated as isolated particles in [1]. So the drag force of a particle is not influenced by its neighbors. To simulate spherical particles (for example frozen droplets or fragments of snow crystals, which are similar to a sphere) a correlation from Schiller and Naumann [9] is used to determine the drag coefficient c_d. To simulate non-spherical snow particles (e.g., plates, columns, needles) correlations from Loth [10] are used for c_d. Further information about the drag coefficient is given in [1].

3.2 Wall-Impact Behavior

Before snow particles enter the air filter body, they collide with vehicle parts such as the radiator grille or the license plate. As explained by Sommerfeld [11] particle-wall collisions can considerably influence the particle motion. Especially for larger particles this influence is significant. The collision process depends on many parameters. Some of them are: 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 [11].

When ice particles collide with a cold wall (<0 °C), there are two possible outcomes [12, 13]:

- they bounce off without fragmentation or
- they bounce off and disintegrate.

Hauk et al. [14] introduced a map for the ice particle breakup. Depending on the particle diameter and the particle velocity before the collision this map allows to estimate if fragmentation occurs. Therewith, we conclude that for typical driving speeds of 50 to 80 km/h on snowy roads and rolled up snow particles, with a size ranging from 10 μm to 500 μm, major fragmentation doesn't occur. For this reason fragmentation is not considered in the simulation approach described in [1].

To calculate the particle velocity after the wall collision an approach based on the momentum equations for the collision of a spherical particle with a wall [11, 15, 16] is used. Furthermore, it is assumed that the particles rebound on a smooth surface and that the particle rotation can be neglected. Using this approach the following equations are obtained:

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

$$v_{p,n}^{(2)} = -e_n v_{p,n}^{(1)} \tag{7}$$

$$v_{p,t}^{(2)} = \frac{5}{7} v_{p,t}^{(1)} \tag{8}$$

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

$$v_{p,n}^{(2)} = -e_n v_{p,n}^{(1)} \tag{9}$$

$$v_{p,t}^{(2)} = (1 - \mu_k(1+e_n)\tan(\theta))v_{p,t}^{(1)}. \tag{10}$$

In these equations $v_{p,n}$ denotes 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, which is defined as the angle between the particle velocity vector and the tangential vector of the wall. For the coefficient of kinetic friction μ_k a value of 0.05 is used [17]. To estimate the restitution coefficient e_n a model from Villedieu et al. is used [18]. Further information about the simulation approach can be found in [1, 7].

4 Comparison Between Simulation Results and Measurements

In this section the snow mass flux at the inlet of the air filter body, which was obtained by using the presented simulation approach, will be compared to measurements, which were carried out on the testing area in Arjeplog and in the climatic wind tunnel in Stuttgart. These results were first shown in [1].

4.1 Simulation Set-up

The simulations were realized in STAR-CCM+ [8]. As shown in Fig. 10 a full vehicle model was considered. The snow particles were injected in a distance of about 1 m in front of the vehicle. Regarding the snow particle size, the distribution from Fig. 3 was used. For the simulations and the measurements the normalized snow mass flux n, which compares the snow mass flux at the inlet of the air filter body to the snow mass flux in front of the test vehicle, was evaluated (see Eq. (1)).

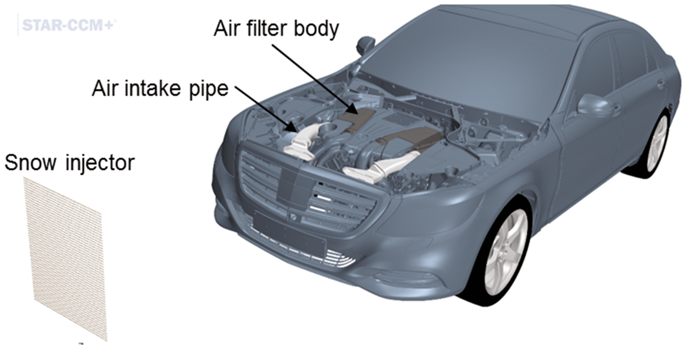

Fig. 10. Test vehicle with snow injector.

4.2 Results

Figure 11 compares the normalized snow mass flux *n* between two different engine speeds: 1000 rpm and 4500 rpm. Results are shown for the measurements carried out on the testing area in Arjeplog and for the simulations. In the simulations different values for the snow particle density were investigated since snow crystals can be hollow. In nature values between 500 kg/m^3 and 917 kg/m^3 can be observed [5, 6]. For this reason the values 917 kg/m^3, 750 kg/m^3 and 500 kg/m^3 were investigated. For the investigation of the snow particle density a spherical shape was assumed. As mentioned before natural snow crystals can have different particle shapes. Since the particle shape is not known for the testing area in Arjeplog, different basic shapes were considered: a sphere, a thin plate, a thick plate, a column and a needle. For the investigation of the particle shape a density of 917 kg/m^3 was assumed. As shown in Fig. 11, a lower engine speed results in a lower snow amount inside the air filter body. The comparison

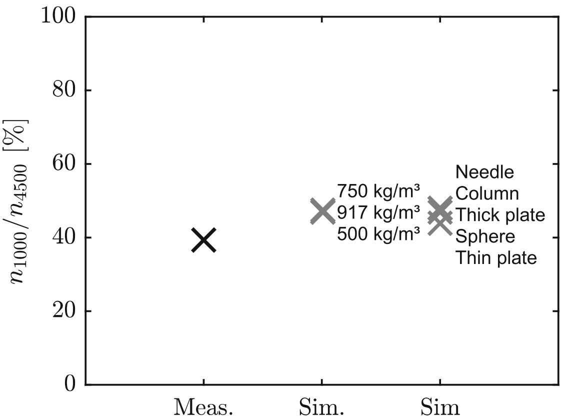

Fig. 11. Normalized snow mass flux *n* for the measurement (Meas.) and the simulations (Sim.): illustrated is the ratio of an engine speed of 1000 rpm and 4500 rpm; data from [1].

between the measurements and the simulation results shows a good agreement. It is likely that the difference between the simulation results and the measurements occur due to the modeling of the wall-impact behavior of snow particles. In the simulations it is assumed that all particles rebound on a smooth surface. However, the air intake pipe of the test vehicle is made of a felt-like material. During the tests in Arjeplog it was observed, that a small amount of snow can stick to this felt-like material. Furthermore, the restitution coefficient e_n can only be estimated by the model in [18].

Figure 12 shows the normalized snow mass flux n for two different vehicle configurations. As shown in this figure, configuration two has a radiator grille, which is partially closed. Illustrated are the simulation results and the measurements from Arjeplog. As mentioned before different snow particle shapes and different values for the snow particle density were investigated in the simulations. Especially the particle shape can be important for the simulation. Unfortunately this parameter is not known for the testing area in Arjeplog. Furthermore, it is possible that the particle shape varies on the natural testing area and on roads at different days. So during the virtual testing different particle shapes should be considered.

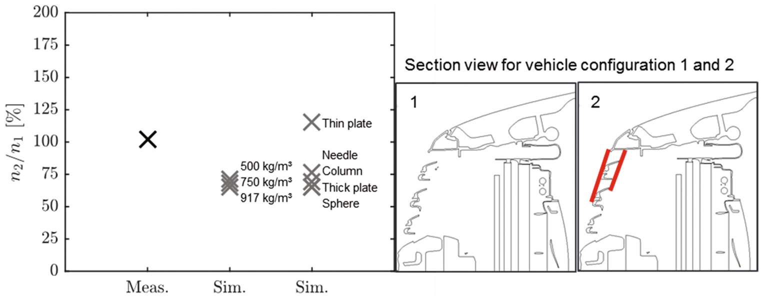

Fig. 12. Normalized snow mass flux n for the measurement (Meas.) and the simulations (Sim.): Comparison for two different vehicle configurations; data from [1].

In Fig. 13 the normalized snow mass flux n of a vehicle with an improved air intake system is compared to a reference vehicle. As shown in the figure the vehicle with the improved air intake system has a different air intake pipe. This new air intake pipe was designed to be advantageous for all considered snow particle shapes. In Fig. 13 the simulation results are compared to measurements, which were carried out in the climatic wind tunnel in Stuttgart. As shown in the figure the snow amount inside the air filter body could be reduced by 95% in the climatic wind tunnel. The simulation model predicted a similar benefit (99%). More information about the improved air intake system can be found in [1]. It should be noted that the new air intake system was designed with regard to snow. When designing the air intake system of a new vehicle there are two additional objectives: the total pressure drop and the risk of a hydro-lock should be low.

As these comparisons show, the simulation method can be used for an approximate calculation of the snow ingress. Furthermore, the simulation method can be used for

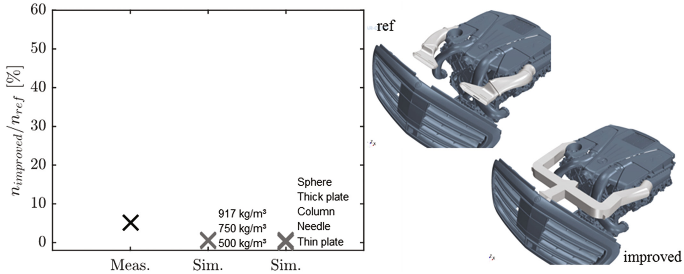

Fig. 13. Normalized snow mass flux *n* for the measurement (Meas.) and the simulations (Sim.): Comparison between an improved system and the reference system; data from [1].

improving the air intake system. To develop new vehicles in a cost-effective manner we suggest to introduce the simulation method within the virtual testing stage. During this stage the snow amount inside the air filter body of a successor model can be compared to its predecessor. If necessary the air intake system can be improved at an early stage of the vehicle development process and a high level of maturity can be achieved before first prototypes are built. Since there are simplifications applied in the simulation model (e.g., the wall-impact behavior), we suggest to approve the final air intake system in a climatic wind tunnel or on a natural testing area.

5 Conclusion

In cold and snowy regions snow particles, which are rolled up by vehicles, can cause an engine power drop. This paper shows possibilities to evaluate the risk of such an engine power drop. These possibilities include measurements on a natural test area, measurements in a climatic wind tunnel and numerical simulations. The measurements allow the evaluation of the snow amount, which penetrates into the air filter body, and the evaluation of the engine power drop. However, these tests are only possible in a later stage in the vehicle development process. If adjustments to the vehicle are required in this late stage, high costs could emerge. For this reason we suggest to introduce the described simulation method in the virtual testing stage. The simulation method allows an approximate calculation of the snow amount, which penetrates into the air filter body. If necessary, the air intake system can be improved at an early stage. Since there are simplifications applied in the simulation model (e.g., the wall-impact behavior), we suggest to approve the final air intake system in a climatic wind tunnel or on a natural testing area.

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