CHALMERS
UNIVERSITY OF TECHNOLOGY

CFD Modeling of Snow Contamination on Cars

Implementation of a Snow Adhesion Regime Map by User Defined Functions

Master's thesis in Chemical Engineering from the Program Innovative and Sustainable Chemical Engineering

Markus Enmark

Department of Chemistry and Chemical Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2017

CFD Modeling of Snow Contamination on Cars

Implementation of a Snow Adhesion Regime Map by User Defined Functions

Markus Enmark

Department of Chemistry and Chemical Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2017

CFD Modeling of Snow Contamination on Cars

Implementation of a Snow Adhesion Regime Map by User Defined Functions

MARKUS ENMARK

Department of Chemistry and Chemical Engineering
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

CFD Modeling of Snow Contamination on Cars
Implementation of a Snow Adhesion Regime Map by User Defined Functions
MARKUS ENMARK
Department of Chemistry and Chemical Engineering
Chalmers University of Technology, Gothenburg, Sweden 2017

Abstract

In the pursuit towards driverless cars and with more focus on innovations for active safety, technical equipment such as cameras, sensors and radars are becoming more developed and utilized in the vehicle industry. Contamination of various types can cause problems by covering and jamming this equipment. It is important to be able to predict where on the car contaminants will adhere without the need for field tests and wind tunnel experiments. By using Computational Fluid Dynamics to predict contamination patterns, decision support for design changes can be obtained in an early stage of a project.

A Computational Fluid Dynamics model for this purpose has been developed at Volvo Car Corporation. However the model lacks the ability to distinguish between if a particle sticks or not when colliding with the surface, making the model insufficient when it comes to predicting snow packing. To overcome this, Chalmers University of Technology have studied snow and its adhesion properties. The purpose of the thesis was to find a way to implement the snow sticking properties into the Computational Fluid Dynamics model to enable snow build-up modeling.

Several possible alternatives were investigated including, wall film models, the dense discrete phase model and implementation of user defined functions. User defined functions programming was seen as the most promising tool, so the work focused on developing a user defined function code to describe snow packing. Three different approaches were taken in the user defined function. One discrete particle model boundary condition was developed that could differentiate between stick or bounce when a particle hits the wall depending on normal and tangential impact velocities. One post processing tool was developed where snow particles on the exterior could be deleted in cells with high enough time averaged wall shear stress. Lastly a transient simulation user defined function was developed that was dependent on instantaneous wall shear stress in every time step.

Calculations were run with the user defined functions and the contour plots representing snow build-up was compared to climatic wind tunnel experiments and in field studies from northern Sweden. It was concluded that it is possible to describe snow packing by using user defined functions. A user defined function framework was developed that has the ability to use different sticking criteria for different types of snow. Contour plots that looks similar to test pictures could be obtained by the wall shear stress dependent post processing tool and the transient simulation tool. However the user defined boundary condition is the most promising approach to continue with since it is believed to better describe what happens in reality.

Keywords: Computational Fluid Dynamics, Snow modeling, User Defined Functions, Snow adhesion, Boundary condition, Regime map

Acknowledgements

First of all I would like to thank my two supervisors Ph.D. Per Abrahamsson and Ph.D. Matthias Eng for great advice and many interesting discussions during the thesis work. I would like to acknowledge Anders Lind, who has performed his master thesis within the same project, for great collaboration and input throughout the thesis work. I would also like to thank Professor Anders Rasmuson for being the examiner of the thesis as well as giving good advice throughout the project.

I would like to thank the people on the department Contamination and Core CFD at Volvo Car Corporation as well as the division of Chemical Engineering at Chalmers University of Technology for all the support. Particularly I would like to thank Jan Zbinden and Ph.D. Torbjörn Virdung at Contamination and Core CFD and Licentiate Soheil Soltani at the division of Chemical engineering for continuously giving great technical assistance.

Last of all I would like to thank my family and friends for all their support throughout the complete education.

List of Abbreviations

Meaning	*Abbreviation*
Volvo Car Corporation	VCC
Computational Fluid Dynamics	CFD
Exterior Water Management	EWM
Reynolds Averaged Navier-Stokes	RANS
Discrete Element Method	DEM
User Defined Function	UDF
Air Intake System	AIS
Computer Aided Design	CAD
Delayed Detached Eddy Simulation	DDES
Large Eddy Simulation	LES
Detached Eddy Simulation	DES
Discrete Particle Model	DPM
Custom Field Function	CFF
Graphical User Interface	GUI
Dense Discrete Phase Model	DDPM
Eulerian Wall Film	EWF
Lagrangian Wall Film	LWF

Table of Contents

1. Introduction

In modern cars, technology such as cameras, sensors and radars contributes to increasing traffic safety. To reduce the risk of accidents due to the human factor, such technology is playing a huge role. Examples of things that is being enabled by this technology is automatic braking, keeping distance in the traffic, keeping the car on the road if the driver falls asleep and parking assistance (Volvo Car Corporation, 2017).

Contamination on the exterior of a car can give rise to a lot of complications in the vehicle industry. Depending on the surrounding environment and driving conditions the source of contamination varies between for example dust, water and snow. The different types of contamination give rise to the same problem, particles or droplets can adhere to the car exterior and by doing so interfere with technology that is important for driver safety. It can also block the view of the driver as well as contribute to an unpleasant experience if dirt sticks to a customer’s hands or clothes (Gaylard, et al., 2014).

In the future the amount of contamination sensitive equipment on the car exterior is expected to increase as the pursuit towards driverless cars continues. To be able to release a driverless car model it has to be able to work under all conditions from harsh snowy winter conditions and heavy rain to dry dusty roads (Volvo Car Corporation, 2017).

When developing new car models Volvo Car Corporation (VCC) have to consider where to place sensitive equipment in order to minimize the exposure to all types of contamination, or alternatively make use of active cleaning if necessary. VCC has a large market in many northern countries, hence one important contamination type to study is snow.

Traditionally snow contamination has been tested in field studies by driving on snowy roads or in climatic wind tunnels. With increasing computational power and knowledge within Computational Fluid Dynamics (CFD) both time and money can be saved if a well working model can be developed that properly describes snow contamination under different conditions. A model, if proven trustworthy, can act as a decision support when determining where to put a radar or when working on new design adjustments.

At the Contamination and Core CFD department at VCC continuous work is carried out in order to accurately predict contamination issues. This is done in wind tunnel tests, field studies in different conditions and developing physical models such as CFD. This master’s thesis is a part of an ongoing research project in cooperation with Chalmers University of Technology and aims to develop a model that can simulate snow contamination.

1.1 Background

Problems of contamination can arise from three different sources which are described by Gaylard et al. There is contamination from the sky in the form of rain droplets or snow, there is contamination that is pulled off the ground by nearby vehicles and there is the contamination that is pulled off the ground by the vehicle itself, called “self-contamination” (Gaylard, et al., 2014).

To predict how the deposition of contamination on a vehicle’s exterior looks like after driving in different conditions several methods can be used, each of which have both pros and cons. Wind tunnel experiments are widely used and gives repeatable experiments. It is costly but it also gives the opportunity to test not yet released models. Testing on real roads or on test tracks gives results closest to reality but has poor repeatability since it can be hard to find the right conditions for the test. Today CFD calculations act as a tool to compliment these other test methods, the goal is to develop simulation models that can describe reality good enough to be able to replace the other methods (Gaylard, et al., 2014). In this research project both wind tunnel experiments and test track experiments have been used in order to be able to validate the simulation results from CFD.

Previous work on the problem to describe contamination with the help of CFD has mainly focused on water based road spray and vehicle soiling (Eng, et al., 2017). Already in 2001 Roettger et.al describes a method to track particles in the simulation domain to see where most particles hit the car exterior (Roettger, et al., 2001). In many later studies work has been focusing on impingement of water droplets and how the impingement creates a water film on the surface. Hagemeier et.al 2011 describes a procedure that is called Exterior Water Management (EWM) to examine water contamination in the vehicle industry. These accounts for:

1. The flow field around the geometry with the tracked particles.
2. Impingement on the surface.
3. Creation of a liquid film on the exterior.
4. How the liquid film behaves on the surface.
5. Film separation due to external forces or sharp edges.
6. Re-impingement of separated droplets. (Hagemeier, et al., 2011)

In 2012 Viner et.al created a model to describe water film build-up on the road during rain and how this affected self-contamination using a CFD model (Viner, et al., 2012). In 2014 Gaylard et.al developed a CFD model to predict self-contamination by water on the rear of a car (Gaylard, et al., 2014).

At the Contamination and Core CFD department at VCC work has been performed to develop a CFD model that describes the flow field around the car and that could trace the trajectories of injected discrete particles. It is based on a transient Delayed Detached Eddy Simulation (DDES) turbulence model which have been implemented and evaluated by Sterken et.al. (Sterken, et al., 2016). To make the model able to handle particles that hits the exterior of a car an Euler-Lagrangian multiphase model has been implemented by Eng et.al which make use of discrete particle injections from the tires (Eng, et al., 2017).

The model at this point is able to describe the flow field and the Discrete Particle Model (DPM) concentration and particle impacts around the car. One shortcoming of the model is that tracked particles can only be treated as either stick or bounce when colliding with the car surface. This makes the model insufficient for snow contamination prediction. Snow is a very complex matter to model within CFD and existing CFD models cannot predict adhesion or build-up of snow around the car. To enable this feature in the existing CFD model one must know the physical properties of different snow types and to know how a snow particle behaves when colliding with the car exterior. Hence experiments have been conducted on different snow types at Chalmers University of Technology to determine its structure and adhesion properties. With the help of the Discrete Element Method (DEM) the physical interaction of snow-wall and snow-snow can be modelled. From the DEM model a regime map can be created that describes if snow particles stick or bounce when colliding with the car surface. The work with the DEM modeling is done in a parallel thesis project (Lind, 2017).

To be able to convey the information from the DEM model into CFD there are several options that should be evaluated and tested.

1.2 Purpose

The purpose of this thesis is to find a way to make CFD calculations in ANSYS Fluent account for snow physics in order to predict snow build-up originating from road spray (self-contamination).

1.3 Research Questions

Several questions will be answered during the project. These are stated in this section.

What is the best way to account for snow-wall and snow-snow interactions in Fluent?
Can a regime map from the DEM model be implemented as boundary conditions in Fluent by using User Defined Functions (UDFs)?
Is it possible to accurately predict snow build-up on a car by implementing the regime maps into CFD?
Will the CFD model work for different snow properties?
What can be done to further improve the snow CFD model?
Will it be possible to get a three dimensional build-up model?

1.4 Limitations

The CFD model at this stage will be limited to snow contamination originating from the road and pulled up by the wheels. In the parallel thesis project the DEM model framework is developed to work for different input data corresponding to different snow types. However snow experiments and characterization of different snow types will be limited to snow from very cold conditions, wet snow from warmer conditions and climatic wind tunnel snow. Hence the CFD model shall not be limited to just one type of snow but the framework should work for different regime maps. The model will consider snow without any other contamination present. Depending on the snow type, different adhesive forces will have to be considered in the model. To save time and computational power the CFD simulation will initially be carried out with a simplified geometry in the form of a wedge. This is also done in order to have another test object to validate the calculations with by comparing to wind tunnel experiments. In the end simulations will be run on a full scale Volvo S90.

2. Theory and Literature Review

To be able to answer the stated research questions and work towards the aim of the thesis it is important to know some theory about snow and DEM modeling, this will be given first in the theory section. Then an introduction to CFD is given and a more thorough explanation of the CFD models that have been used. To wrap up the theory section, information about different particle impact models is given as well as possible ways to convey the findings from the DEM model to CFD.

2.1 Snow Characteristics

Snow is a very complex matter to model, this is due to its large variation in geometry and size for snowflakes and snow agglomerates. To be able to model snow, several simplifications has to be done. Properties of snow also varies a lot with temperature and humidity etc. and therefore it is also of importance to see how snow adhesion varies with these parameters.

Prior to this thesis snow from northern Sweden, snow from VCC climatic wind tunnel and snow created in a lab have been investigated by Per Abrahamsson (Abrahamsson, et al., 2017). From literature one can see that different nucleation procedures result in different snowflake structures at different temperature and humidity.

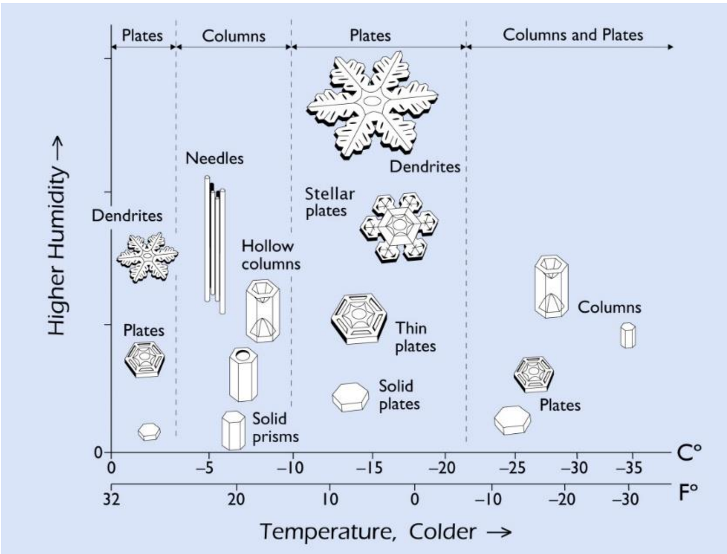


Figure 1: Shows how the nucleation procedure at different humidity and temperature result in different snow flake structures. (Libbrecht , 1999).

In this project it is not the snowflakes that are considered but instead small grains or clusters of snowflakes. This is due to that the structure of the snowflakes change over time when they have reached the ground by forming grains together with other snowflakes (Fierz, et al., 2009). There are two types of grain structures that can be formed, it is either hexagonal grains or spherical grains. The structure that the snow gets depends on the temperature gradient of the snow cover, moisture content of the air and how long time the snow has been lying on the ground (Colbeck, 1986) (Miller, et al., 2003). The shapes of the formed grains in a snow cover can be illustrated in a diagram as the one below.

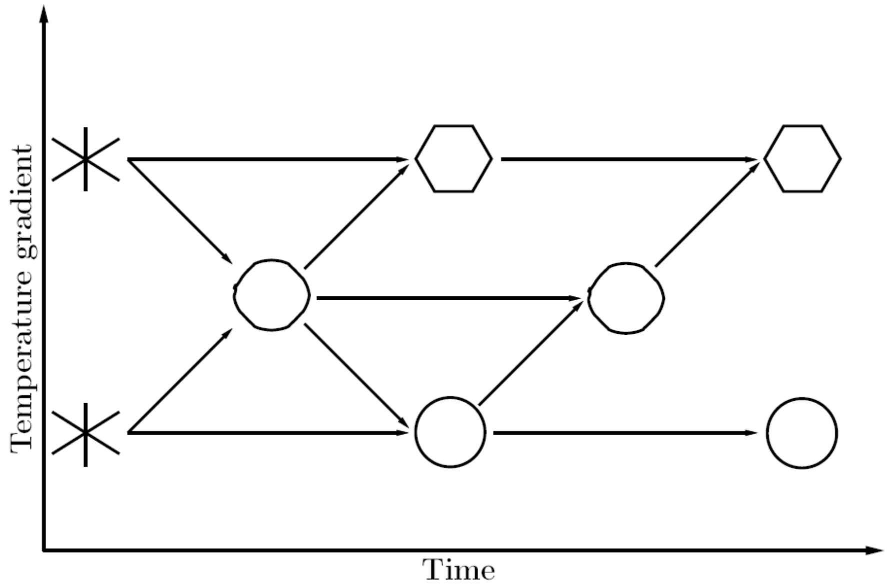


Figure 2: Shows how the shapes of snow-grains changes with temperature gradient and time in a snow cover (Lind, 2017).

From the diagram it can be seen that round grains are formed in a snow cover with a small temperature gradient. In order to simplify the snow modeling in the DEM and CFD calculations the snow is assumed to have a perfectly spherical particle shape in this project.

2.1.1 In-Field Studies of Snow Contamination and Snow Characteristics

To get a better understanding of snow contamination mechanisms, a number of experiments have been conducted in the project prior to this thesis. A field study has been performed on a test track in northern Sweden to see how snow builds up on a Volvo S90. The conditions during the tests were -20 °C, clear sky and snowy roads. These conditions mean that the snow particles are fine and dry. The car was driven a distance of 100 km at a speed of both 70 and 90 km/h (Eng, et al., 2017). The results shows that fine snow dust stick on the rear of the car according to a distinct pattern.

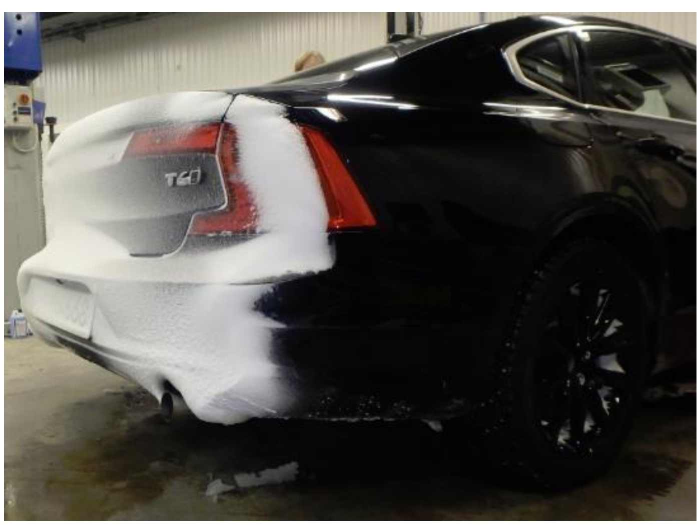


Figure 3: Snow contamination pattern on the rear of a Volvo S90 after a field test in northern Sweden.

To get more information about the snow at these conditions a microscope study was made on the snow dust. Snow was sampled from the wheel tracks (compressed snow), from the untouched part of the road, snow that had been pulled up by the wheels, snow falling from the sky as well as the snow stuck on the car exterior. In this way a qualitative observation could be done in a microscope to see the shape of the snow particles and also to quantitatively measure the size of the particles to create particle size distribution diagrams (Abrahamsson, et al., 2017) (Eng, et al., 2017).

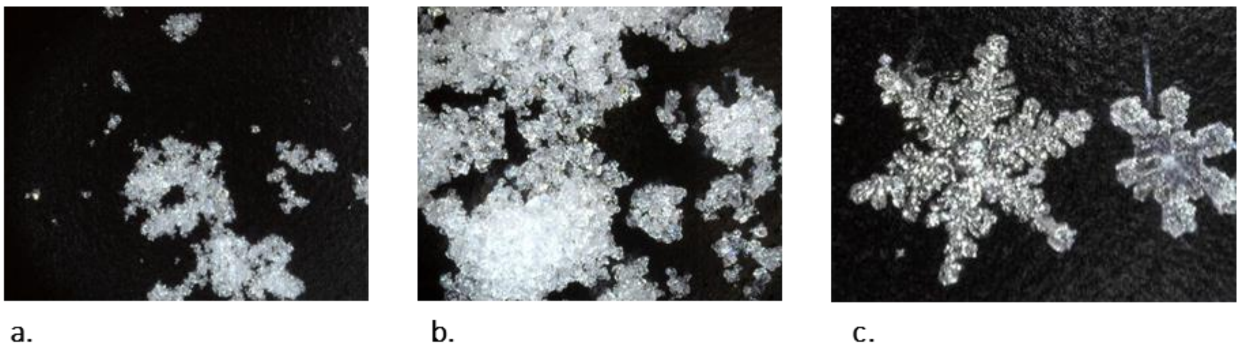


Figure 4: Picture a. shows snow sampled from the rear lamp of an S90 in northern Sweden. Picture b. shows snow sampled from the road in northern Sweden and picture c, shows a snow flake sampled in northern Sweden (Abrahamsson, et al., 2017).

In figure 4 a the sample was collected from the snow sticking on the rear lamp of the car. Figure 4 b shows snow sampled from the road and figure c shows snowflakes. The shape of the agglomerates in figure 4 a and b does not show a spherical shape. However these agglomerates are formed as smaller grains stick to each other, a more spherical shape was observed when snow was collected from the suspended snow dust in the flow field around the car and analyzed in a microscope. This indicates that the simplification of spherical particles is feasible. Looking closely at figure 4 a and b one can distinguish small spherical grains that make up the agglomerate, these grains were measured in order to create a particle distribution diagram seen in figure 5. The values are normalized against the highest measured value due to confidentiality reasons. (Abrahamsson, et al., 2017).

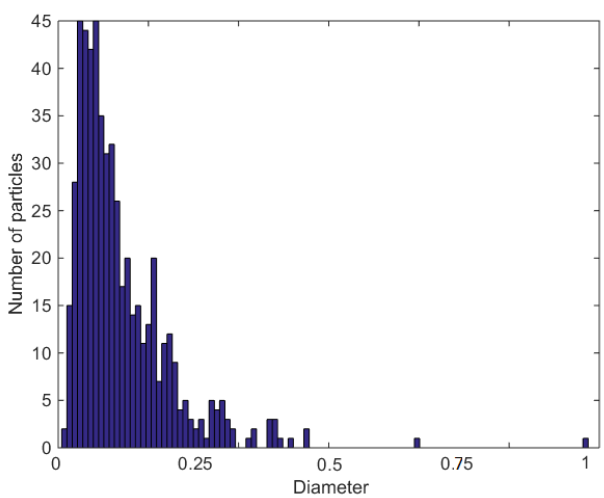


Figure 5: Particle size distribution diagram sampled from the particles that have been pulled up in the air by the wheels (Abrahamsson, et al., 2017). The diameter of the particles are normalized values.

Information obtained from this field study was valuable to determine the injection parameters in the CFD model, to know the size-range of particles to examine in the DEM study and to have reality test pictures to compare the CFD simulations with.

2.1.2 Important Particle Properties for Discrete Element Method Modeling

Since snow at different temperatures, size, humidity and age have different adhesion properties, it is not possible to have one universal model for snow. In the work of Per Abrahamsson and Anders Lind they both experimentally evaluated adhesion properties of snow at different temperatures and looked for snow particle data in already published literature. In this way it is possible to model snow at different temperatures with the help of the DEM by changing the input data for different snow types.

Particle properties that changes with temperature and particle size is for example coefficient of restitution, i.e. the outgoing normal velocity of a snow particle after collision divided with the incoming normal velocity before collision. Another particle property that is important to estimate values for is the work of adhesion between a grain cluster and a wall. The DEM model is also dependent on the Young's modulus as well as the Poisson ratio. More about these particle properties can be read about in the work of Anders Lind. It was found in his DEM study that these properties could vary depending on the source and therefore there are some uncertainties in the DEM modeling of snow. Generally it was found that smaller particles at a higher temperature have a higher tendency to stick to a surface (Abrahamsson, et al., 2017) (Lind, 2017).

2.1.3 Snow Modeling

There have been advances in snow modeling within several fields lately. In the automotive industry interesting work has been done on the Air Intake System (AIS) of a car. Huber et.al worked with a numerical model to predict the amount of snow particles that enters the AIS. Their numerical simulation was compared to wind tunnel experiments and field tests in Sweden. The numerical model made use of an Euler-Lagrange approach where the continuous phase is solved separately and then the discrete phase is tracked in the already solved flow field. Furthermore a k-ε turbulence model was used. From their literature study on snow and the numerical simulations it was concluded that the amount of snow coming in to the AIS is dependent on particle size, shape and wall impact behavior. In the numerical simulations it was assumed that all the particles hitting the boundary was reflected with a changed velocity. To further improve this model it was also concluded that more studies needs to be done on snow-wall impact behavior for small particles (Huber, et al., 2015).

Pure DEM studies have also been performed on snow, for example it is of interest to be able to predict how avalanches behave during different conditions. Hence a granulation study on snow during different temperatures was performed in a concrete tumbler and compared to pure DEM calculations. This study showed promising results and suggests that snow-snow interaction can be modelled quite accurately by DEM (Steinkogler, et al., 2015).

In this project DEM will be used to describe snow adhesion properties and the numerical findings will be implemented into CFD. In earlier studies similar modeling has been done by an integrated CFD-DEM parallel solver that different CFD software such as ANSYS Fluent already offers. However it has not been performed on snow particles but rather on other small and dense spherical particle systems such as fluidized beds and pilot scale batch crystallizers (Ren, et al., 2011) (Ali, et al., 2015). A parallel CFD-DEM solver is extremely computationally heavy and hence it cannot be used for the purpose of complete car CFD.

2.2 Particle Modeling

To investigate under which conditions snow particles stick or bounce, DEM was used in a parallel post doctorate and master thesis work by Per Abrahamsson and Anders Lind. Some brief theory about the subject is given in this section.

2.2.1 Discrete Element Method

Particle-wall and particle-particle interactions can be described by either the soft sphere model or the hard sphere model. The soft sphere model is the same as DEM when it comes to computer aided calculations. The particle-wall interaction is modeled in the same way as particle-particle collision, with the only difference that one particle is modeled with a large enough radius to be approximated as a flat wall. In this project the soft sphere model has been used to model the particle interactions. In the soft sphere model the Newton second law of motion is described in differential form, this is in contrary to the hard sphere model where it is given in integrated form. In both of the models the coefficient of restitution is retrieved which is the normal velocity after collision divided by the normal velocity before collision. An advantage with the soft sphere model is that one can track the instantaneous motion throughout the impact. According to the soft sphere model, when a particle collides, it starts to deform and an overlap arise between the two colliding particles. The forces arising between the particles during the collision can be modeled with a spring dashpot model, the spring represent the repulsive forces and the dashpot represent the dampening forces (Crowe, et al., 2012).

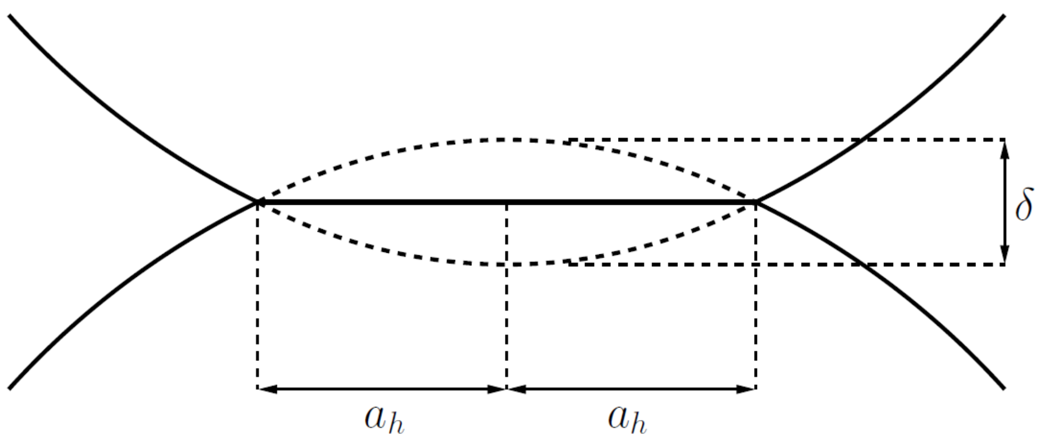


Figure 6: Shows the overlap (δ) between two colliding spheres according to the soft sphere model (Lind, 2017).

The soft sphere model itself cannot give any information about if particles stick or not when they collide, hence an extended version of the soft sphere model was used in the parallel thesis work. Johnson, Kendall and Roberts extended the soft sphere model by adding a surface energy term, this model has come to be called JKR model after the authors (Johnson, et al., 1971). When two particles collide the overlap and the energy dissipation at impact depends on the material, particle size and velocity. Depending on the overlap, the added surface energy term will vary, at one point this will mean larger adhesive forces than repulsive forces which will result in particle sticking (Krijt, et al., 2013). There are several approaches that can handle particle adhesion, these will not be described here, but it is important to know when to use which model. In the work of D. Tabor (Tabor, 1977) a parameter was created in order to evaluate if one model can handle collisions of a certain material type. The Tabor parameter is a dimensionless number which describes the ratio of the elastic deformation length scale and van der Waals adhesion length scale (Marshall & Li, 2014). It was estimated in the work of Anders Lind, that snow particles end up in the regime where the JKR model is most suitable (Lind, 2017).

2.2.2 Regime Map

By the use of the method described above it is possible to evaluate under which conditions a particle stick or bounce. Particles of varying size and normal velocity can be sent towards a wall and tracked with time steps as small as the nanoseconds scale. This was done in the work by Anders Lind and Per Abrahamsson. The idea was to find a cut-off limit in normal velocity for different particle sizes, the result of the calculations was presented in a regime map which can be seen below (Lind, 2017).

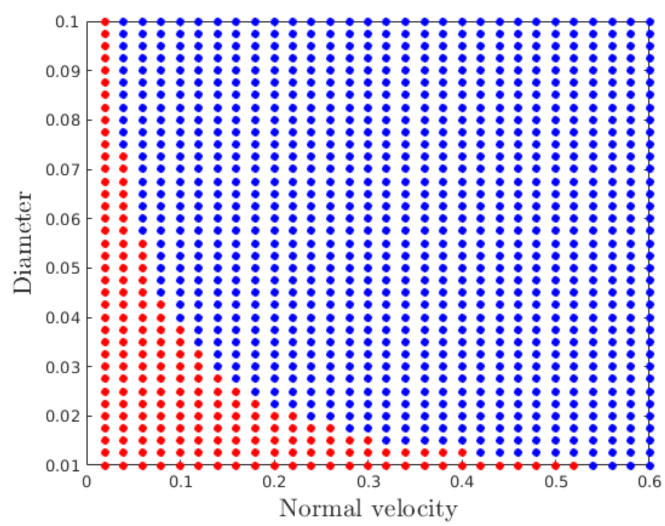


Figure 7: The result from DEM calculations on snow particle-wall interactions by Anders Lind resulted in a stick or bounce regime map depending on normal velocity and particle diameter. The red zone represent stick and the blue zone represent bounce. The values for diameter and normal velocities are normalized. The investigated particle diameters are the ones between 0.01 and 0.1 which is the most common range according to the particle distribution diagram shown in figure 5 (Lind, 2017).

The red color represent the "sticking zone" and the blue color represent the "bouncing zone". The calculations were made for a completely flat surface and all the particles were assumed to be spherical. Note also that both the particle diameters and the normal velocities are normalized.

2.2.3 Important Variables

From the DEM calculations that led to the regime map it was clear that the sticking or bouncing depends on the two parameters normal velocity and particle size. It is discussed in the paper by Anders Lind why sticking is dependent on only these two parameters. It was initially believed that the impact angle would be an important parameter to consider, but after including it in a 3 dimensional regime map it was clear that it did not matter if the particle collided with different impact angles. This is considered as a limitation of the DEM model at this stage. To understand why impact angle is not a factor one has to know more about the underlying theory of DEM and how the behavior of a collision depends on the particle properties that needs to be defined in a calculation. This will not be given here but can be read about in the master's thesis of Anders Lind (Lind, 2017).

2.3 Computational Fluid Dynamics

CFD is a powerful tool within many areas of engineering and in the department Contamination and Core CFD at VCC it is used to predict various types of contamination. Before going in to the models used for this purpose at VCC some general information about CFD will be given.

2.3.1 General CFD Methodology

CFD means to solve a set of differential conservation equations, such as continuity and momentum to describe how a system behaves, this is done in every cell in a created mesh. The method of dividing the domain into many cells is called finite-volume method. In this method the differential conservation equations are solved as linear algebraic equations in every cell. The reformulation of the conservation equations introduce an error to the solution called discretization error. A good quality mesh involving many cells means a better quality of the solution by reducing the discretization error to the cost of computational effort (Andersson, et al., 2016).

An important choice in a solver is if the flow should be solved as steady or unsteady depending on the turbulent fluctuations in time. For turbulent flows there is always a variation with time, the question is if it varies to such an extent that it should be solved as unsteady. If the flow consists of different phases for example gas-liquid or liquid-solid, an appropriate multiphase model should be chosen. There are numerous different turbulence models and multiphase models, they will not be mentioned here but brief information about the models used in this project is given in section 2.4 (Andersson, et al., 2016).

Before a simulation can be run in the solver many physical properties of the system need to be defined, some examples are the properties of the continuous phase, the dispersed phase and injection of the dispersed phase. All the boundary conditions for the system needs to be defined and initial conditions to start a simulation need to be set. The calculation can then be started and be run until the convergence criteria is met for a steady state calculation or until it is stopped for a transient simulation. After a calculation has been run, the system can be analyzed in a post processing step to see if the solved solution gives a good representation of reality. This is done by comparing contour plots of a solved calculation to experiments, in this way it is possible to evaluate if the applied models are appropriate to use and if the mesh and settings in the solver are correctly specified (Andersson, et al., 2016). More about post processing can be read in section 2.6.4.

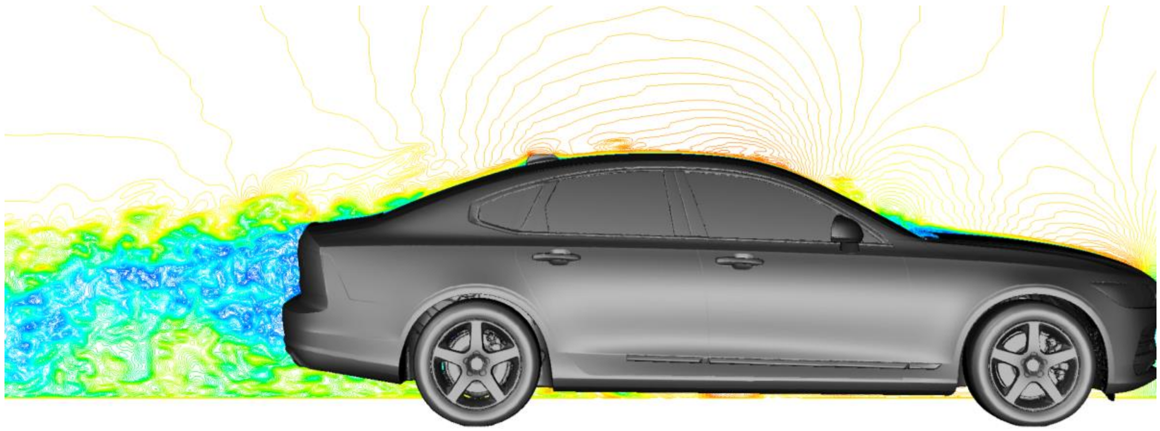


Figure 8: Shows a transient simulation of the flow around an S90. The color scale represent the instantaneous velocity magnitude. Large fluctuations can be seen behind the car.

2.4 Existing Computational Models

Before the start of this thesis CFD models have been developed to predict the aerodynamics and particle trajectories of injected discrete particles. Hence it has been a very useful tool to predict contamination of wet and dry dust around the car. When it comes to this type of contamination, the physics behind the sticking of particles are a little different, small wet particles always tend to stick and stay on the car exterior more or less independently of shear stresses. Field tests have been performed to compare self-contamination of dry and wet dust to the predicted self-contamination in CFD and the results looks promising (Eng, et al., 2017). With alterations to an existing CFD contamination model it should be useful for predicting snow contamination as well. In this chapter the underlying theory of the existing CFD models are described for both a steady state case and a transient case.

Generally for both steady state and transient simulations an Euler-Lagrange approach is used for multiphase modeling. This means that the continuous phase, the air flow around the car, is solved separately. Then the dispersed phase, the discrete particles, are tracked in the flow field throughout the calculation. The continuous phase is solved by the Navier-Stokes momentum differential equation and the discrete phase is solved by a force balance on each tracked parcel (ANSYS® Fluent Theory Guide, 2016). The discrete particles have a defined size and density and are injected into the computational domain from the tires. From there they enter the flow field and some of them hit the car exterior. The discrete particles are tracked as parcels, which means that many discrete particles are tracked together, but the force balance is calculated on the basis of an individual particle (Eng, et al., 2017).

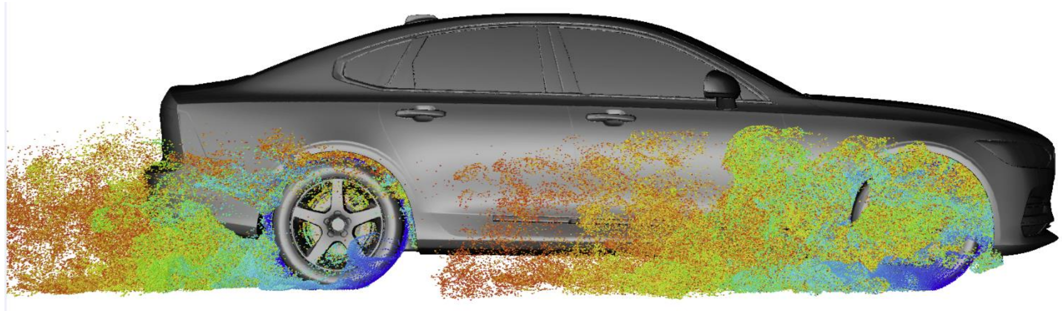


Figure 9: Shows the injected parcels that are tracked through the domain. The parcels are injected from the wheels and are colored by their residence time.

2.4.1 Steady State Model

In the steady state CFD model a realizable k-ε turbulence model is used, the continuous phase is solved until convergence is reached, i.e. when the error of the solution is as small as the user has specified. After a converged solution for the continuous phase is obtained it is decided how many parcels one want to track through the solved flow field. Since the solved continuous phase is a time averaged result of the calculation, no fluctuations can occur, the discrete particles follow this time averaged flow field. In order to introduce dispersion to the particles the discrete random walk model is used, this enables fluctuations depending on the turbulent kinetic energy (Eng, et al., 2017). The theory behind the k-ε turbulence model and the discrete random walk model will not be given here but can be read about in ANSYS Fluent Theory guide (ANSYS® Fluent Theory Guide, 2016). Comparing the steady state model to the transient model, the transient one has proven to give more accurate results but the steady state model is far less computationally heavy.

2.4.2 Transient Model

The reason to why the transient model predicts particle contamination more accurately lies within the turbulence model's ability to resolve the large scale turbulence fluctuations. In the aerodynamic flow field of a car, the largest turbulence fluctuations occur in the wakes. Since the Stokes number of the tracked parcels is low, they follow the flow field, it is necessary to have a model that can predict these fluctuations in turbulence in each time step since it will heavily influence where the particles end up (Eng, et al., 2017).

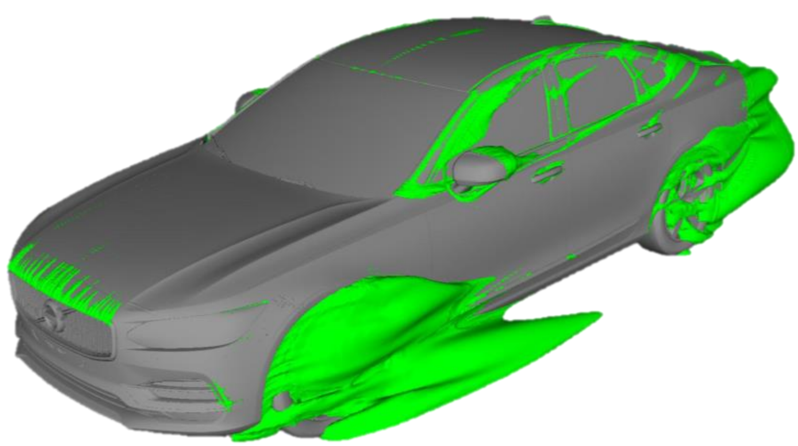


Figure 10: Shows the iso-surface of pressure. The colored zones is where most fluctuations in turbulence occurs.

The transient turbulence model used is the Delayed Detached Eddy Simulation model (DDES). Detached Eddy Simulation (DES) is a hybrid model which resolves the flow areas separated from the wall with the help of Large Eddy Simulation (LES) and applies a RANS solver close to the wall. A DDES solver is good for high Reynolds numbers i.e. highly turbulent flows. For the problem with unresolved fluctuations in the large turbulence scales that was present in the steady state solver, this model performs much better (ANSYS® Fluent Theory Guide, 2016). This turbulence model has been evaluated and tested in the work of Sterken et.al and it is shown that the aerodynamic calculations performs well in accordance to wind tunnel experiments and that the computational time it takes in order to get a converged flow field is reasonable for industrial applications (Sterken, et al., 2016).

The addition of a discrete particle injection in every time step of the simulation adds some computational time but this has been minimized by putting a wall 4.5 m behind the car in the domain which is supposed to abort the particles from the domain. This only has the purpose of aborting the parcels and does not affect the flow field at all. Computational time increase for every time step if more parcels are being tracked in the domain. Hence it is good practice to delete the parcels when they have travelled away from the car and is unable to hit the exterior. Everywhere else on the geometry of the car the particles are reflected upon hit, leaves a mark, and continues to being tracked by the solver (Eng, et al., 2017).

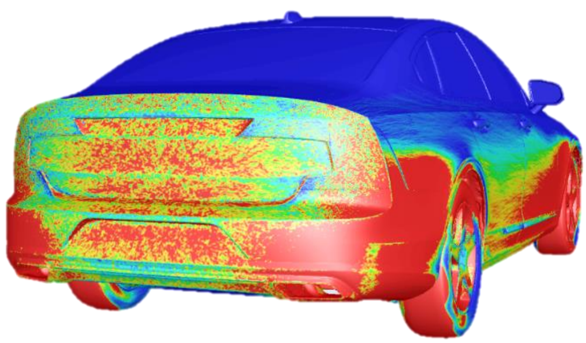


Figure 11: Shows a contour plot of DPM concentration around the S90 after a transient simulation.

How a particle is treated when it collides with a wall boundary is defined by choosing a boundary condition (Eng, et al., 2017). This is the main problem addressed in this thesis, it is of great interest to be able to decide when the particle reflects or not. Comparing figure 11 to figure 3, one can see that the time averaged Discrete Particle Model (DPM) concentration on the rear of the car matches the snow contamination pattern quite well. However the contour plot shows DPM concentration on the sides as well, here there is no snow contamination at all.

2.5 Particle Impact Models

To model build-up of matter around an object several approaches can be taken. The literature study on which available approach that should be used in this case was done and the theory behind different approaches will be given in this chapter.

2.5.1 Dense Discrete Phase Model

Within the Lagrangian DPM described in section 2.4, the particles are seen as small and disperse enough to never interact nor affect the continuous phase. Within the Eulerian multiphase model in ANSYS Fluent there is the possibility to use the Dense Discrete Phase Model (DDPM). This model introduce an extension to the conservation equations for mass and momentum which makes it possible to model build-up of the discrete phase. The build-up becomes dependent on the volume fraction of the discrete particles, enabling the possibility to define a critical packing limit and simulate how the discrete particles build up around a geometry (ANSYS® Fluent Theory Guide, 2016). One limitation with the DDPM that is very relevant for this thesis is that no integrated DEM model is available for the simulations. It would be possible to use a user defined boundary condition to distinguish between stick and bounce of a particle at the wall. But the three dimensional build-up on the exterior will only be dependent on volume fraction when a particle hits the built up particle layer instead of the surface where the boundary condition is applied. Another very relevant limitation is that the DDPM does not work with a DDES turbulence model (ANSYS® Fluent Theory Guide, 2016), which makes it completely inapplicable for the transient case.

2.5.2 Discrete Particle Boundary Conditions

A wall boundary condition for the discrete phase model determines how to treat a particle when it hits the face of the boundary. In ANSYS Fluent there are several preprogrammed boundary conditions to choose from to determine how the particles will be treated upon impact. Those existing are reflect, escape, trap, wall jet, interior and wall film (ANSYS® Fluent User Guide, 2016). The existing wall film models are interesting since they model particle impingement on the wall and simulates a layer build-up in the form of a liquid film. If this boundary condition could be modified to work for more solid particles it would be a valid option in this thesis. More information about the wall film boundary conditions is given in section 2.5.2.1.

2.5.2.1 Wall Film Models

ANSYS Fluent has two available wall film models in their software, the Eulerian Wall Film (EWF) model and the Lagrangian Wall Film (LWF) model. A wall film model's purpose is to describe creation of a liquid film on a wall and also the behavior of the film. The liquid film models are compatible with the DPM model, when a discrete particle hits the wall boundary several impingement phenomena can happen. The liquid droplet can either stick, rebound, spread or splash and the outcome of the impingement is governed by the impact energy (ANSYS® Fluent Theory Guide, 2016).

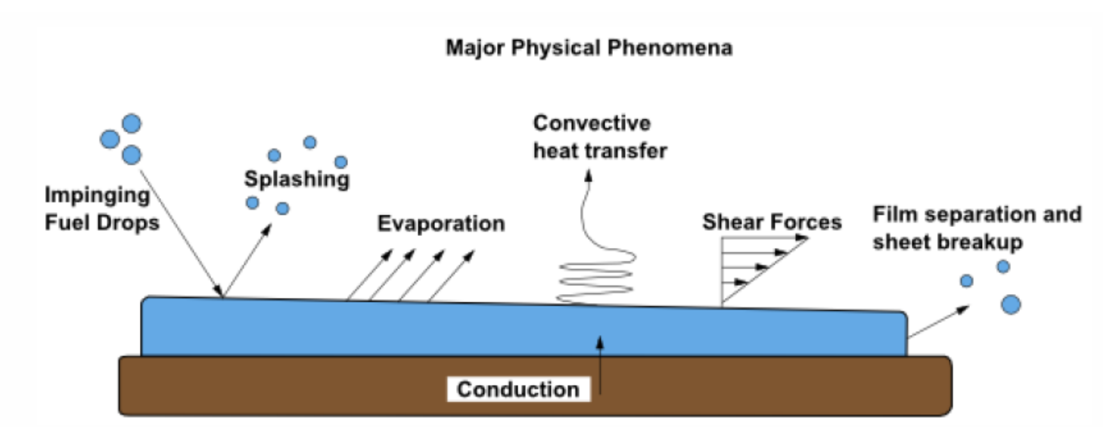


Figure 12: Shows the different physical phenomena that is handled within a wall film model (ANSYS® Fluent Theory Guide, 2016).

The liquid film seen in the picture is limited to a thickness of about 0.5 mm for both EWF and LWF models, this is called the thin film approach. The reason behind this is that the liquid flow in the film can be seen as parallel to the wall and that there are no property gradients over the film thickness (ANSYS® Fluent Theory Guide, 2016).

2.6 User Defined Functions and Post Processing

Standard features and models in ANSYS Fluent can be modified and extended by using UDFs. A UDF is a code written in the C programming language which often includes predefined macros provided by ANSYS and described in their UDF manual. A UDF can have many applications and different macros serves different purposes (ANSYS® Fluent UDF Manual, 2016). Some examples on features relevant for this project is; to modify the discrete particle boundary conditions, improve the post processing and execute a UDF in every time step for the transient simulation. Additional information about the used macros in this thesis is explained further in the coming sections.

2.6.1 DEFINE_DPM_BC

DEFINE_DPM_BC is a macro provided by ANSYS Fluent that makes it possible to modify the standard discrete particle boundary condition. The macro is hooked to every boundary where you want it to be executed. Every time a discrete particle hits the boundary the macro will be executed and determine how to treat the colliding particle and set its reflected velocity and angle (ANSYS® Fluent UDF Manual, 2016).

This macro can be used in order to determine if a particle will stick or bounce when it hits the boundary. To distinguish between the two, a criterion can be programmed depending on several parameters, for example inbound normal velocity and tangential velocity of the particle. If the particle has fast inbound velocity it is decided to be reflected by the macro PATH_ACTIVE. If the particle is slow enough to stick to the surface it can leave a mark on the surface that can be seen in a contour plot and then be deleted from the domain with the macro PATH_ABORT.

2.6.2 DEFINE_ON_DEMAND

DEFINE_ON_DEMAND is another macro provided by ANSYS Fluent. As the name suggests this macro is executed on demand which means that the user decides when to execute the function (ANSYS® Fluent UDF Manual, 2016). One of many applications of this macro is that it can be used in for example post-processing of different variables after a calculation has been run. It is then possible to write a condition for where snow would stick on the geometry depending on mean values of a chosen variable. Another relevant application for this thesis is that it can be used to erase already stored values in a User Defined Memory (UDM).

2.6.3 DEFINE_EXECUTE_AT_END

DEFINE_EXECUTE_AT_END is a very similar macro to the DEFINE_ON_DEMAND but the difference is that it executes at the end of every time step in a transient simulation or at the end of a steady state simulation (ANSYS® Fluent UDF Manual, 2016). This makes it possible to write a condition for snow sticking that is dependent on instantaneous values in a transient simulation instead of mean values from the full simulation.

2.6.4 Post Processing

An important tool for this thesis is post processing in ANSYS Fluent. Here one can look at contour plots for desired variables to evaluate the calculations and compare to experiments. Many different variables exist by default to post process after a simulation. However it is sometimes necessary to create new variables or modify the already existing ones to analyze in a contour plot. In this section some theory about important post processing variables and tools for this thesis will be given.

2.6.4.1 Discrete Particle Model Concentration

Contour plots of DPM concentration have been used to analyze the self-contamination of dust and gravel particles by Eng et.al (Eng, et al., 2017) an example of such a contour plot can be seen in figure 11. The contour plot of DPM concentration for the exterior shows the concentration distribution of discrete particles in the cells closest to the wall. This means that the presence of the parcel in the cell is enough to be accounted for in the DPM concentration plot.

2.6.4.2 Discrete Particle Model Accretion

Contour plots of the variable DPM accretion shows where during the simulation parcels actually hit the wall. So if a parcel hits a wall it leaves a mark that can be seen in the end of the simulation. The mathematical formula for accretion is:

$$R_{accretion} = \sum_{p=1}^{N_{particles}} \frac{\dot{m}}{A_{face}} \tag{1}$$

where $\dot{m}$ is the mass flow rate of the discrete particles colliding with the cell and A_{face} is the area of the face of the cell (ANSYS® Fluent Theory Guide, 2016).

2.6.4.3 Custom Field Functions

ANSYS Fluent gives the option to create new contour plots by using already existing contour plots and mathematical operations. This can be done in the Graphical User Interface (GUI) and the newly defined Custom Field Function (CFF) will be visible in the contour plots drop down list after it is defined.

2.6.4.4 User Defined Memory

When a UDF is modifying the solver it is often desirable to create new contour plots that shows a variable that is calculated through the UDF. This can be done by allocating a UDM slot for the desired variable that is calculated through the UDF. By enabling as many memory slots in the GUI as have been allocated inside the UDF it is possible to see the desired variables as contour plots.

2.6.4.5 Wall Shear Stress

The wall shear stress is the tangential force exerted on the wall boundary by the fluid in the layer next to the wall (ANSYS® Fluent User Guide, 2016). It is calculated by:

$$\tau_w = \mu \frac{\partial v}{\partial n} \tag{2}$$

where μ represent dynamic viscosity, *v* is the fluid's velocity and *n* is the distance to the wall.

2.6.4.6 Tangential Impact Velocity

The tangential impact velocity is the velocity component of a parcel that points parallel to the wall. If the velocity magnitude and the impact angle is known for a parcel the tangential velocity is calculated by:

$$v_t = v_{mag} * \cos(\alpha) \tag{3}$$

where v_{mag} is the velocity magnitude of the parcel and α is the impact angle.

2.6.4.7 Normal Impact Velocity

The normal impact velocity is the velocity component of a parcel that points perpendicular towards the wall. If the velocity magnitude and the impact angle is known for a parcel the normal velocity is calculated by:

$$v_n = v_{mag} * \sin(\alpha) \tag{4}$$

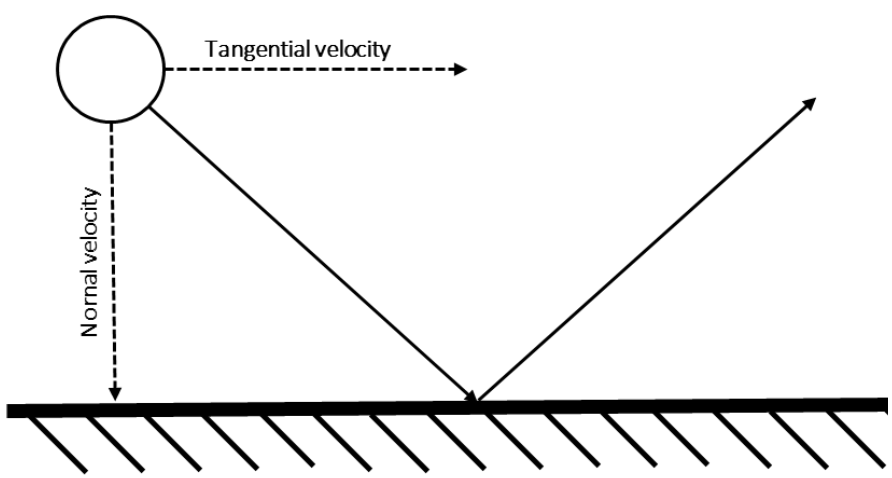


Figure 13: Shows a particle approaching a surface with its tangential and normal velocity vectors. The particle is here seen to be reflected with the same angle to the wall as the collision angle. This means that both the normal and tangential coefficient of restitution is equal to 1 and that no energy is lost in the collision. This is not the case in reality.

3. Methodology

When this thesis started much work had already been done in the overall project. The idea behind this thesis work was to link together the work done at Chalmers University of Technology with the work done at VCC. At Chalmers snow has been studied and a DEM model of snow particles is used to create a regime map to describe particle behavior at collision with a flat wall. At VCC the CFD simulation model was developed without consideration of snow adhesion properties.

3.1 Methodology for Particle Adhesion

The link between the work done at Chalmers to the CFD model at VCC meant to make the CFD model dependent on the information from the regime map i.e. how a snow particle will behave when colliding with a wall. It was thought that UDF programming of a boundary condition that could differ between stick and bounce of a particle was the method to work with. However, when starting to work with the problem, several different approaches to the problem were investigated.

The EWF model was one option, although this model was created to handle liquids, it was believed that parameters in the model could be changed in order to handle a solid material like snow. However since EWF cannot interact with a user defined boundary condition and has restrictions when it comes to film thickness (maximum 0.5 mm) this approach was discarded in an early stage of the thesis.

Another alternative that seemed quite interesting was the DDPM. With this model it would be possible to model both build-up in the order of magnitude that we want and implement a boundary condition for particle interaction with the wall. However the turbulence model used in this project is DDES and the DDPM cannot interact with this turbulence model.

The last alternative considered was the LWF model. The LWF model is the only alternative of the three that could have worked in this case. It is possible to implement user defined boundary conditions in order to describe the impingement of droplets on the wall. But since we handle solid particles in this project it was decided to go for a user defined boundary condition without any wall film model active.

Since the main problem of the existing CFD model lies within how the parcels are treated by the existing boundary conditions, a framework for a user defined boundary condition was developed that could differ between stick or bounce of a parcel depending on different criteria that is defined by the user.

In the parallel thesis work a DEM framework for creation of regime maps was developed. These regime maps should in the end work as a tool to define the criteria set for stick or bounce in the UDF. When all the characteristics of different snow types are known, regime maps can be created and the UDF criteria could be used for simulation of the different snow types in CFD.

3.2 Virtual and Experimental Setup

The work to better describe snow adhesion in CFD was mainly carried out on a simple test geometry in the form of a wedge. In a later stage an even simpler geometry was created in order to use it for debugging of newly programmed UDFs. In the end of the thesis the developed UDF framework could be run on a full scale S90 CFD case.

3.2.1 Test Object Model

To evaluate how one could address the issue of describing snow build-up in the best possible way it is necessary to have a CFD case that is easy to work with. Since the S90 mesh consist of approximately 200 million cells it takes a lot of time to just load the case (Eng, et al., 2017). Hence a test object model in the form of a wedge, from here on referred to as “the wedge”, has been created by Matthias Eng. The mesh of the model contains about 16.6 million cells and is easier to work with. One significant difference between the S90 case and the wedge is that the injection of the discrete particles is in front of the wedge instead of at the tires. The flow field and the injected parcels goes from the left to the right of the wedge from the perspective seen in figure 14 and figure 15 and the velocity of the continuous phase simulated in CFD was set to 70 km/h.

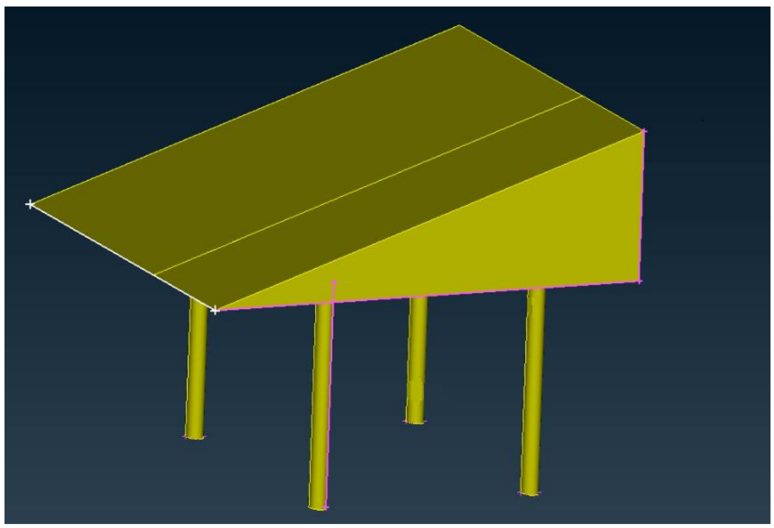


Figure 14: Shows the CAD geometry of the wedge that was used for CFD simulations.

The wedge was not only created for CFD calculations but was also built in order to run snow adhesion tests in the VCC climatic wind tunnel. The conditions regarding where particles are injected and wind speed that were set in the CFD model were similar in the climatic wind tunnel experiments. This made it possible to compare test results from the wind tunnel experiments to the CFD simulations for validation of the computational model.

Figure 15: Shows the wedge in the wind tunnel where the snow adhesion experiments were performed.

The mesh of the CFD case for the wedge still had to be fine enough to get accurate results from the calculations and therefore it is not perfectly convenient to use it for UDF debugging.

3.2.2 Simple Model

An even simpler geometry was meshed and set up in Fluent by Matthias Eng. This CFD model's purpose is to fast and easily be able to debug UDFs in order to see if they compile and run as they should. The mesh for this case consisted of 125 996 cells.

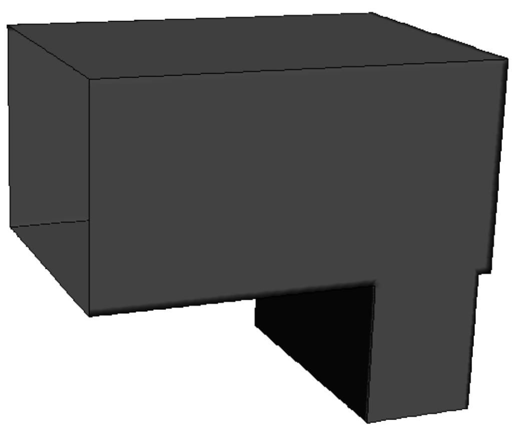


Figure 16: Shows the geometry of the simple case used for debugging of UDFs.

The particles are injected in the opening to the top left seen in figure 16, with a defined velocity and are hitting the wall to the top right before they exit at the bottom end.

3.2.3 Full Scale Car Model – Volvo S90

The S90 case was only used towards the end of the project when the written code had been debugged and run on the wedge to evaluate its performance. A picture of the S90 case can be seen in figure 11 where a contour plot of DPM concentration without any implemented UDF is shown. An advantage with simulation on the S90 was that the results could be compared to both in-field test pictures from northern Sweden and pictures from the climatic wind tunnel. This was favorable for analysis of the CFD simulations since the purpose of the project was to predict self-contamination coming from the tires of the car. The car has a simulated driving speed of 100 km/h in CFD and the parcels are injected into the domain from the rotating wheels. The wind speed used in the wind tunnel experiments was 70 km/h hence more emphasis was put on the comparison between the in-field study in northern Sweden and the CFD simulation.

3.3 Parameter Study with Custom Field Functions

From the existing CFD model, contour plots of relevant post processing variables such as accretion/erosion and DPM concentration could be obtained. At this point the boundary condition included in the model could be set to either stick or reflect at the wall. The chosen setting then applies to all the discrete particles hitting the wall. It is known from experiments that this is not what happens in reality for snow particles, a snow particle hitting a wall either sticks or reflects. The first stage in the work with the CFD model was to post process the existing contour plots with the help of CFFs. The idea was to set a cut-off limit for stick and erase the zones where this cut-off limit is exceeded.

At this point it was not known which parameters that affected the stick or bounce phenomena the most. However, it could be observed by just looking at contour plots of time averaged wall shear stress from the transient simulations that this contour plot resembles the pictures of snow build-up from field experiments very well. In regions with low wall shear stress more snow build-up occurred. It is believed that regions with high wall shear stress experience snow “rip-off” to larger extent than regions with low wall shear stress.

This reasoning lead to the idea to start post-process the wall shear stress contour plot. From in field studies of snow adhesion a critical wall shear stress value for rip-off could be estimated. A CFF was created by taking the theoretical snow adhesion value minus the wall shear stress contour plot. The idea was that the areas with positive numbers should show where snow build-up is allowed to happen due to low wall shear stress. This method of predicting snow build-up areas was proven to be poor due to the difficulty of estimating the adhesion force of a single snow particle.

The creation of CFFs demands that the variables to be used exists as a contour plot. Due to this fact this approach of describing snow build-up was rather limited. Instead the work continued with UDF programming.

3.4 UDF Programming

With the help of a UDFs it is possible to modify and extend the standard features in ANSYS Fluent. Initially a user defined boundary condition was programmed that determines if a particle would stick or bounce upon impact. Later on additional macros were used in order to extend the post processing tool by usage of UDMs and also to modify the solver at every time step during the calculation by setting wall shear stress criteria. Several macros are included in the final UDF, the features of the different macros are explained in theory section 2.6.

3.4.1 User Defined Discrete Particle Boundary Condition

The UDF programming started with the macro DEFINE_DPM_BC which is used to modify the discrete particle boundary condition. This macro executes every time a discrete parcel hits a wall and made it possible to program a criterion for if a particle stick or bounce when it hits the wall.

By programming and implementing UDFs to describe the behavior at collision it was possible to create contour plots by storing parameters in UDMs. Several parameters were saved to be able to compare contour plots of different parameters to pictures from climatic wind-tunnel experiments. This was done in order to investigate which parameters that are dominant in the stick or bounce criterion. The parameter values stored in UDMs can be divided into two categories, there are parameters that were evaluated for significance on snow build-up and parameters that should represent snow build-up. Several of these parameters were calculated and stored in the boundary condition macro. These can be seen in the table below.

Table 1: Shows the parameters that were stored in UDMs for the DEFINE_DPM_BC macro divided into two categories.

Parameters used to evaluate significance on snow build-up	**Parameter representing snow build-up**
Impact angle	Accumulated discrete particle mass
Normal velocity	
Tangential velocity	
Wall shear stress at particle impact	

The DEM model, created in the parallel thesis work, indicates that stick or bounce is only depending on particle normal velocity and particle size. In reality it is believed that impact angle also plays a significant role. This could also been seen after running a calculation with the boundary condition when it was only dependent on normal velocity. The contour plot of accumulated particle mass still had significant build-up on the sides since the normal velocity is rather low here. Hence tangential velocity was included in the final boundary condition to capture the dependency on impact angle. This means that if a parcel impacts the surface with either too high normal velocity or tangential velocity it will be reflected.

A reflected parcel will not lose any energy at impact with the boundary. This means that a parcel is reflected perfectly when colliding with the surface, see figure 13. The reflected angle can be altered in the code but at this point it is not known what the coefficient of restitution in normal and tangential direction should be set to. This can have an effect on the result since reflected parcels could hit the boundary again after a collision. If a parcel has low enough velocity to stick to the surface its mass is stored at the wall in a UDM and then the parcel is deleted from the computational domain by the macro PATH_ABORT in order to save computational memory. Since the faces of the cells in the mesh can be of different sizes the stored mass is divided by the area of the face it hits. A picture of a particle approaching a wall can be seen in figure 13.

Since the particle-“clean wall” and particle-“contaminated wall” interaction is different, the code that describes impact was programmed to handle both types. If a particle hits the wall it is possible to give that impact one criterion and if the particle hits a cell with an already stored mass value it is possible to give this impact another criterion. In the results for this thesis it was assumed that the interaction between snow-snow makes the particles stick easier, hence a looser criterion was set for the snow-snow interaction. This means that if a particle manage to stick on the surface, chances are that the stored mass value will continue to increase at a faster pace.

3.4.2 User Defined Post Processing Macro

It was seen that the snow build-up in wind tunnel tests clearly follows the pattern of wall shear stress on the exterior for both the S90 and the wedge. Therefore the DEFINE_ON_DEMAND macro was used in order to write a condition for snow build-up that is only dependent on mean wall shear stress. The parameters that were stored in UDMs can be seen in the table below.

Table 2: Shows the parameters that were stored in UDMs for the DEFINE_ON_DEMAND macro divided into two categories.

Parameter used to evaluate significance on snow build-up	**Parameters representing snow build-up**
Mean wall shear stress	Time averaged discrete particle concentration
	Accretion

Unlike the DEFINE_DPM_BC, the DEFINE_ON_DEMAND macro is not preprogrammed to know when or where to execute. Hence it has to be specified where in the domain the calculation shall be performed. In this macro a loop was created that ran over all the wall IDs in the domain that made up the geometry and executed the criterion for wall shear stress in every cell on those walls.

If the mean wall shear stress in a cell exceeds that of the specified criterion the cell value is deleted. The post processing macro has the limitation that it is only dependent on mean values throughout the simulation. For a steady state simulation this does not matter, but for a transient simulation this means that the fluctuations in wall shear stress is not taken into account.

3.4.3 User Defined Macro Executed at Each Time Step

To overcome the limitation with mean wall shear stress dependency, the macro DEFINE_EXECUTE_AT_END was used. This macro executes at the end of every time step for a transient simulation. Therefore it was possible to have the snow sticking criterion dependent on instantaneous wall shear stress. The parameters that were stored in UDMs can be seen in the table below.

Table 3: Shows the parameters that were stored in UDMs for the DEFINE_EXECUTE_AT_END macro divided into two categories.

Parameter used to evaluate significance on snow build-up	**Parameter representing snow build-up**
Instantaneous wall shear stress	Accumulated discrete particle concentration

Like with the DEFINE_ON_DEMAND macro, a loop has to be run over all the wall IDs of the geometry for this macro as well. Since this loop executes in every time step it adds a significant amount of computational time to the solver.

The DPM concentration in every time step is fetched from Fluent and added up in the cells where the instantaneous wall shear stress is low enough. If the instantaneous wall shear stress exceeds the criterion in a cell in any time step, the cell value is deleted.

3.4.4 Parallelization

A problem that arose during the programming of the UDFs was that some code pieces cannot run on parallel cores. This problem was addressed by executing certain pieces of the code on either just the host or at the nodes by excluding the host. ANSYS Fluent has preprogrammed macros that can be implemented in the code to convey where to execute the code pieces in the solver. This does not mean that the solver lose any vital information.

3.5 Implementation of Regime Map

In the parallel thesis project a regime map was created which is based on DEM calculations. A thorough investigation was done to evaluate several particle-wall interaction parameters. Normal velocity, particle size and impact angle were all included in the study and it was concluded that the DEM particle-wall interaction was just dependent on normal velocity and particle size. The fact that the DEM model is not dependent on particle impact angle was not expected and is not believed to reflect reality, but is instead seen as a limitation with the DEM model at this stage.

The idea was to implement the values of normal velocity and particle size into the UDF and CFD model to see if the simulation results reflect reality. However since the thesis work with the DEM model ran parallel to this thesis this could not be done until the end of the project.

So instead of using normal velocity and particle size parameter values from DEM calculations another approach was used to find reasonable stick or bounce criteria. By comparing contour plots of normal velocity to pictures from wind tunnel experiments it was possible to find approximately in what range the stick or bounce limit for normal velocity should be in CFD. The same procedure was done for wall shear stress and tangential velocity in order to include the effect of the continuous phase on the particles and the angle dependency of the particle impact behavior.

In the end of the project the parameter value for normal velocity from the DEM calculations matched the CFD calculations fairly well and could be used in the UDF. See results sections for contour plots for simulations with different stick or bounce criteria. Snow build-up dependency on wall shear stress and angle i.e. tangential velocity, could not be described with the DEM model, hence these criteria are solely set by comparing contour plots to wind tunnel experiments as described in section 3.3.

3.6 Wind Tunnel Experiments

In order to have experiments to compare the numerical model with, wind tunnel experiments were performed in VCC climatic wind tunnel. Experiments were carried out on both the wedge and a Volvo S90.

The first test was carried out in order to test the stability of the wedge. The wedge was placed in the middle of the tunnel and the wind speed was starting at 30 km/h and step wise increased to 90 km/h with an interval of 20 km/h. The wedge was proven to be stable all the way up to 90 km/h, although some vibrations were observed at 90 km/h. To avoid these vibrations the tests were run in a wind speed of 70 km/h. Five tests were run in total on the wedge, all with different set ups in order to test different scenarios. The snow cannon was run with a constant volumetric flow rate throughout every test. All the tests were run for 30 minutes and the temperature was kept constant at -15 °C. The experimental setup for every test will be given below:

Test 1 wedge:
Heating patches placed in bottom left corner on the backside of the wedge. The heating patches where placed inside the wedge. Temperature measurement placed in the same position as the heating patches but on the outside of the wedge.

Test 2 wedge:
No heating patches were running and no temperature measurement device was place on the outside of the wedge.

Test 3 wedge:
Heating patches were running with same effect as in test one but this time there was no temperature measurement on the outside.

Test 4 wedge:
No heating patches or temperature measurement. Test was running with a steam injection hose placed just below the wedge. Test was only run for 2 x 5 min due to that the steam injector had a limited water storage tank.

Test 5 wedge:
Test with heating patches attached to the area where least snow build-up occurred in the first 3 experiments.

Test 6 S90:
A Volvo S90 was placed in the wind tunnel and run with the same conditions regarding temperature, wind speed and water injection as the wedge. Pictures were taken to see snow build-up after 5, 15 and 30 minutes. When the test was performed the engine was running and the front wheels were rotating while the rear wheels were kept stationary. The exhaust gases produced were led away by a suction pipe mounted on the exhaust pipe. This means that the exhaust gases did not affect the snow contamination results from this test.

The test results with the heating and steam injection were inconsistent and no direct conclusions could be drawn from these tests, therefore they will not be given any further comments. Test number 2, with no heating showed good pictures for snow build-up and these pictures came to use in the validation and discussion about the results of the calculations.

3.7 Evaluation of Final Model

Many simulations were carried out during the project both on the wedge and the S90 in order to evaluate different parameter criteria in the UDF. In the end of the project, four different cases were run for the wedge and one for the S90. Two different particle sizes were tried for the wedge as well as different criteria regarding normal velocity and wall shear stress. Only one case could be run for the S90 due to the long computational time it takes to get representative results. All the different setups for the calculations are presented in table 4 and table 5. In the end the contour plots of stored mass on the exterior, DPM concentration and accretion was compared to the pictures from the wind tunnel experiments for all the different macros.

4. Results and Discussion

From the method section it is clear that the chosen technique to implement a snow adhesion model into Fluent was by writing UDFs. Three types of macros were used with different conditions to describe snow build-up. This section will first give an overview of the test pictures from field tests in northern Sweden and VCC climatic wind tunnel for both the wedge and the S90. Then contour plots of the parameters that were investigated for significance on snow build-up is shown. In the end contour plots of snow build-up is given for four different wedge simulation cases and one S90 simulation.

4.1 Field Tests in Northern Sweden

Before the start of the thesis, pictures were taken after field tests in northern Sweden. The conditions of the tests can be read about in section 2.1.1. The pictures of the tests are given here to be able to compare to the CFD simulation results.

a. b.

Figure 17: Pictures taken after driving in snowy conditions on a test track in northern Sweden.

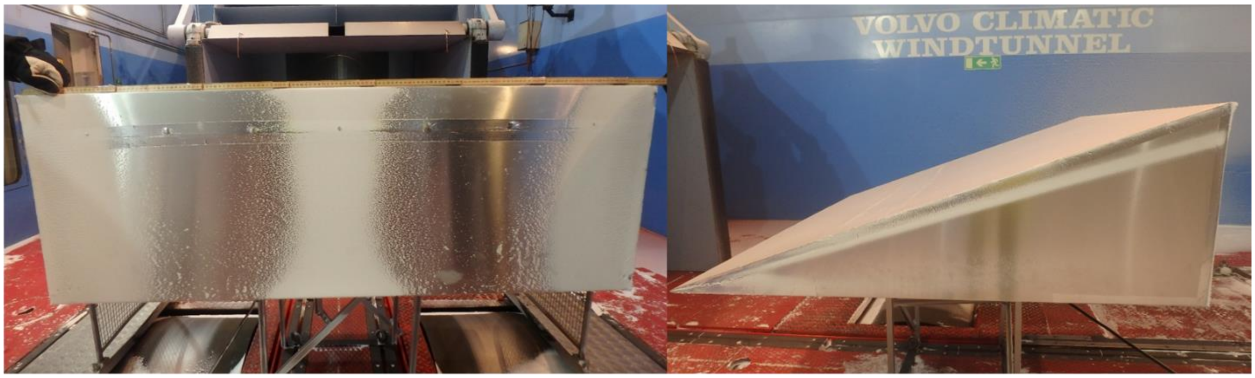
Since the field tests represent self-contamination of snow these test pictures will be most interesting to compare to the contour plots from CFD calculations of the S90. Notice that figure 17 a. is a mirrored figure in order to eliminate any asymmetry arising from for example exhaust gases since that is not considered in the CFD model. A distinct snow pattern can be seen and several areas experience more snow build-up than others. Generally snow accumulates more in the middle of the rear and on the sides. A clear pattern can be seen where the snow stops to build up on the side. This could be due to that the wall shear stress that is acting on the exterior exceeds the adhesion forces of snow in this area and thereby rips off the snow. It could also be due to that the normal or tangential velocity of particles hitting the area here is too large for them to stick.

4.2 Climatic Wind Tunnel Experiments

To have reference pictures to compare the wedge calculations to, experiments were conducted in VCC climatic wind tunnel. The S90 was also run in the wind tunnel and pictures were taken after 30 minutes run time both for the wedge and the S90. How and under which conditions the tests were performed are described in section 3.6.

4.2.1 The Wedge

The pictures of the wedge is from test 2 described in section 3.6 where no heating or external measurement was performed.



a. b.

Figure 18: Pictures taken after 30 minutes in VCC climatic wind tunnel.

Even though the wedge has a rather simple geometry, a clear snow pattern is seen in figure 18 a and b. Like the S90, contamination on the wedge is most severe in the middle and on the sides of the rear while two zones between the middle and the sides are left clean from snow, as seen in figure 18 a. In the wake behind the wedge an irregular and turbulent zone exist with a distinct vortex flow pattern. That is why snow can build up on some of the zones here. It is either that the wall shear stress is low enough to allow sticking or that some of the particles hits with low enough normal and tangential velocities to stick. In figure 18 b, one can see a string of snow on the side, this is due to the flow separation that occurs when the airflow hits the front tip of the wedge. This separation also creates a turbulent zone with lower wall shear stress and different impact velocities for the snow particles. The wedge is completely clean from snow on the top.

4.2.2 S90

To complement the field study pictures from northern Sweden shown in figure 17 a and b, the S90 was run in the Climatic Wind Tunnel as well. The difference with this test is that the snow is coming from the front of the car instead of from the tires. This must be kept in mind when comparing to the CFD contour plots since the CFD model injects the discrete parcels from the tires. Another condition that is different in the wind tunnel is the snow type. Artificially created snow is different from natural snow crystals but the size, shape and density used in the CFD simulations are valid to represent this type of snow as well.

a. b.

Figure 19: Picture of the S90 taken after 30 minutes in VCC Climatic Wind Tunnel.

Even though conditions were different between the climatic wind tunnel experiments and in field studies, clear similarities between figure 19 and figure 17 can be observed. The pattern on the rear follows the same general trend with some differences. The rear lamps are more evenly covered, there is less snow around the exhaust pipe and there is snow sticking on top of the tailgate for the climatic wind tunnel test.

4.3 CFD Parameter Study

To evaluate which parameters that affect snow build up the most, a parameter study was done which is described in section 3.4. CFD calculations were done on both the wedge and the S90. The wedge simulations were run for 6.5 s with a time step of 0.001 s and the S90 was run for 3.5 s with a time step of 0.0005 s.

Contour plots of accretion, DPM concentration, mean wall shear stress, instantaneous wall shear stress, normal velocity and tangential velocity are shown. All the contour plots are for simulations that were run with a mean particle size that was found in the size distribution study.

4.3.1 The Wedge

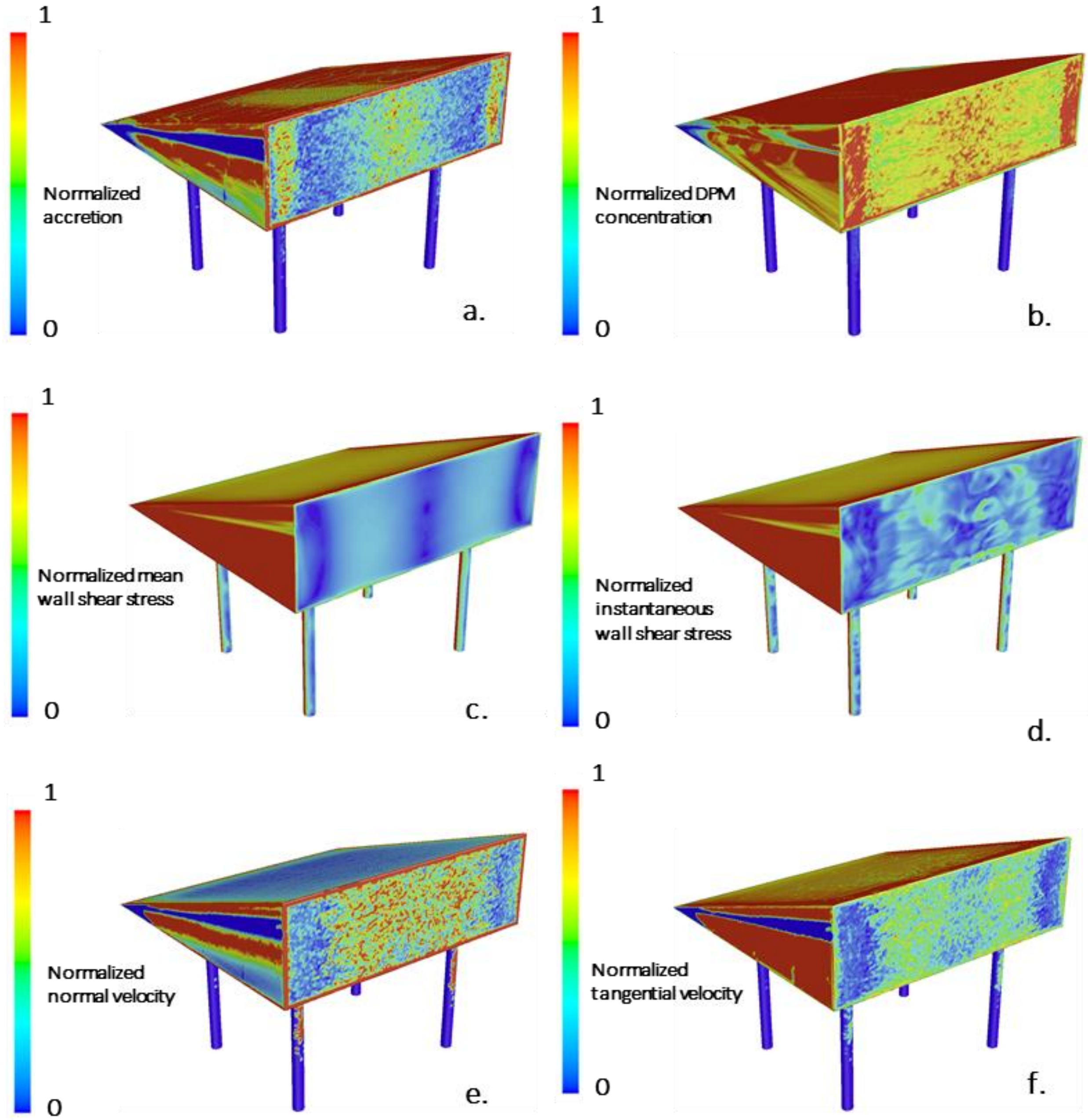


Figure 20: Contour plots of the wedge showing the parameters studied for snow build-up. The case was run for 6.5 s with a mean particle size. The color scale in the pictures is normalized for every parameter.

Both the accretion plot in figure 20 a, and the DPM concentration plot in figure 20 b, resembles the wind tunnel test pictures fairly well on the rear of the wedge. One can see trends that most particles are located in the zones where we have most snow build-up. For all the plots where particles leave a mark on the wall boundary i.e figure 20 a, e and f, there are no particles hitting the wall in the string on the side. Looking at the test picture in figure 18 b, it can be seen that this is a zone with snow build-up. This means that there is a limitation with the CFD model here, it is not possible to capture this impingement with the current model. For the DPM concentration plot however there are particles present even in the string. This is due to that

DPM concentration shows the value for the entire cell volume closest to the boundary and not the actual collision with the wall. Thus it can be said that there are particles in that region that might have collided in reality but in the simulation they never touch the surface.

The mean wall shear stress plot in figure 20 c, which is a time averaged version of the instantaneous wall shear plot shown in figure 20 d, shows a pattern that is strikingly similar to snow build-up pictures. In zones where the mean wall shear stress is low, there is snow build-up. However it can be seen that the mean wall shear stress on the string on the side is in the same order of magnitude as on the top of the wedge where we have no snow build-up and it is also significantly higher than on the rear. If snow build-up only would have been dependent on wall shear stress, there should be no snow build-up in this area on the sides, which is not the case. It can also be that the CFD model overestimates the wall shear stress in this area on the side. However it is believed that snow build-up is dependent on a combination of normal and tangential impact velocity as criteria for stick or bounce and wall shear stress as a criterion for rip-off.

The normal- and tangential velocity plots in figure 20 e and f. shows the velocity at parcel impact. There are tendencies that the normal velocities of the parcels are higher in the center of the rear of the wedge, this is logical because the turbulent zone behind the wedge shows a streamline pattern where the air circulates towards the middle of the rear side. Looking at the tangential velocity plot it can be seen that the color scale follows the wall shear stress plot quite well seen in figure 20 c. This is expected since the parcels have small inertia and follows the flow field, meaning that the parcels have large tangential velocities in areas with high wall shear stress.

4.3.2 S90

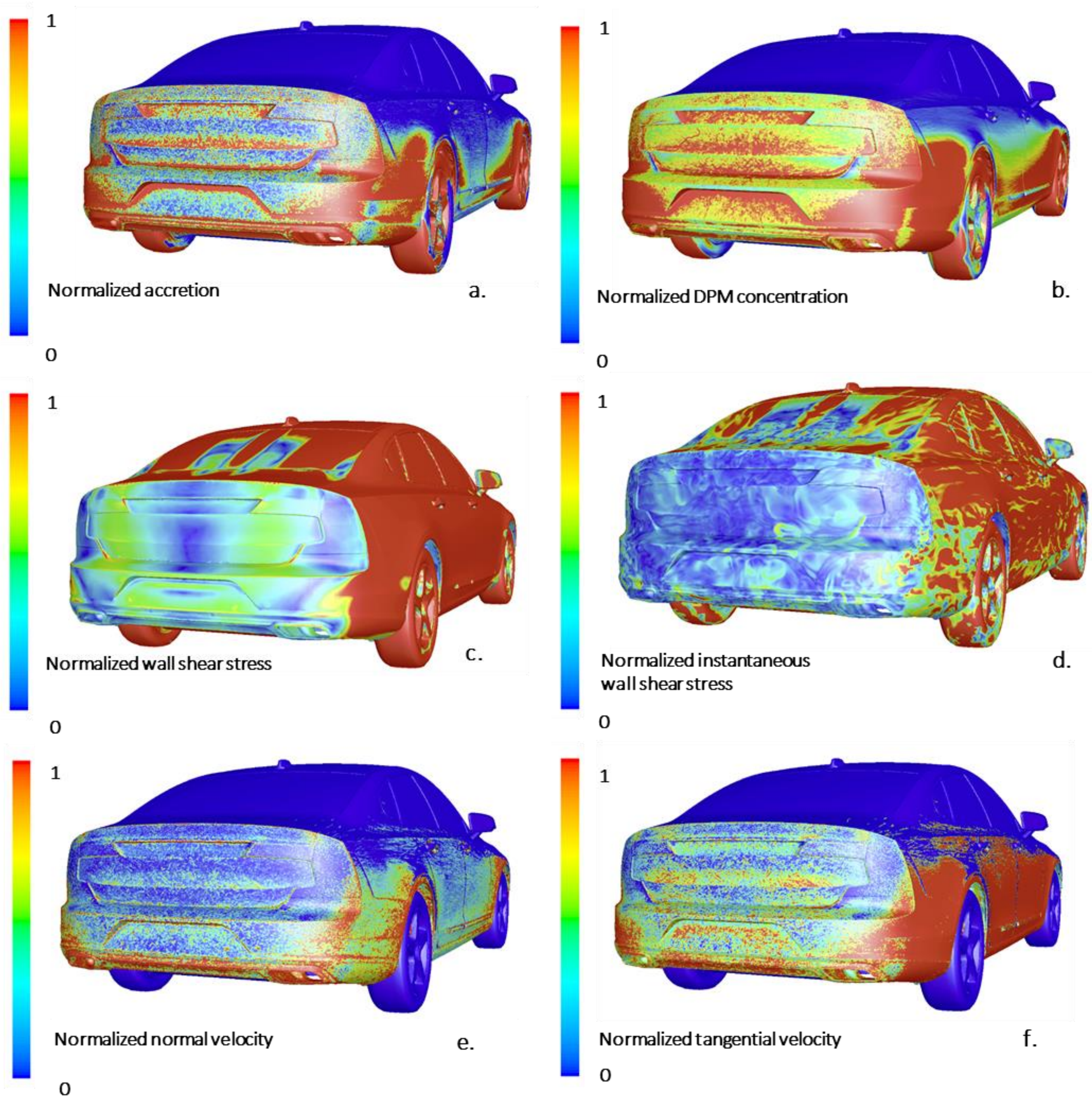


Figure 21: Contour plots of the S90 showing the parameters studied for snow build-up. The case was run for 3.5 s with a mean particle size. The color scale in the pictures is normalized for every parameter.

The same discussion goes for the S90 as for the wedge in section 4.3.1, same trends can be seen which indicates that the wedge was a good simplified test geometry to use. The accretion and the DPM concentration plots in figure 21 a and b, shows similarities to both field study and climatic wind tunnel pictures, with the DPM concentration plot showing somewhat better resemblance. Since accretion only leaves a mark on every particle impact on the wall this plot is less continuous and it is harder to see any clear gradients at a simulation time of only 3.5 s. This together with the fact that parcels are present in the cell closest to the wall but never actually hits the surface contributes to a more representative DPM concentration plot.

Looking at the normalized wall shear stress plot in figure 21 c, and comparing to figure 17 b, it is seen that the zone where the snow build-up starts on the side of the rear bumper is very clearly represented in the mean wall shear stress plot. Once again a clear correlation is seen between wall shear stress and snow build-up.

4.4 CFD Study of Snow Build-up

Four different simulation cases were run for the wedge and one for the S90, the parameters that were varied includes injected particle size and the snow-sticking condition depending on either normal velocity or wall shear stress. The different simulation cases are presented in table 4 and 5. The injection size and specific cut-off values for the criteria in the UDFs are not given by absolute numbers, this is due to confidentiality reasons, instead they are referred to as baseline or something else if the cut-off value was changed for that simulation. The different macros that have been used to describe snow build-up are color coded where the boundary condition macro is colored green, the post processing macro is colored red and the macro executed every time step is colored blue.

The boundary condition macro was chosen to be dependent on normal velocity and tangential velocity of the discrete particles, see figure 20 e and f. The cut-off values were different depending on if a particle hits a clean wall or if it hits a contaminated wall. The post processing macro was chosen to be dependent on mean wall shear stress, see figure 20 c. For the macro that is executed in every time step, instantaneous wall shear stress was chosen as the condition for snow build-up, see figure 20 d.

Table 4: Shows the injection sizes and the conditions for normal velocity, tangential velocity and wall shear stress for the different wedge calculations.

	Injection size	**Boundary condition cut-off limits**				**Post processing cut-off limit**	**Execute every time step cut-off limit**
The Wedge	Particle diameter	Normal velocity condition for particle-clean wall	Normal velocity condition for particle-contaminated wall	Tangential velocity condition for particle-clean wall	Tangential velocity condition for particle-contaminated wall	Mean wall shear stress	Instantaneous wall shear stress
Case 1	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline
Case 2	Baseline	DEM value	Higher than DEM value	Baseline	Baseline	Baseline	Baseline
Case 3	Larger	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline
Case 4	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Lower

Table 5: Shows the injection sizes and the conditions for normal velocity, tangential velocity and wall shear stress for the S90 calculation.

	Injection size	**Boundary condition cut-off limits**				**Post processing cut-off limit**	**Execute every time step cut-off limit**
S90	Particle diameter	Normal velocity condition for particle-clean wall	Normal velocity condition for particle-contaminated wall	Tangential velocity condition for particle-clean wall	Tangential velocity condition for particle-contaminated wall	Mean wall shear stress	Instantaneous wall shear stress
Case 1	Baseline	Baseline	Baseline	Baseline	Baseline	Higher	Baseline

4.4.1 The Wedge

Case 1

The cut-off limits for particle stick or bounce was chosen by looking at the contour plots in figure 20. They were chosen in order to give results that looks similar to the climatic wind tunnel test pictures. All the cut-off values chosen for this case are referred to as baseline values. The comparison of the plots should be done between the different cases rather than comparing two contour plots of different parameters.

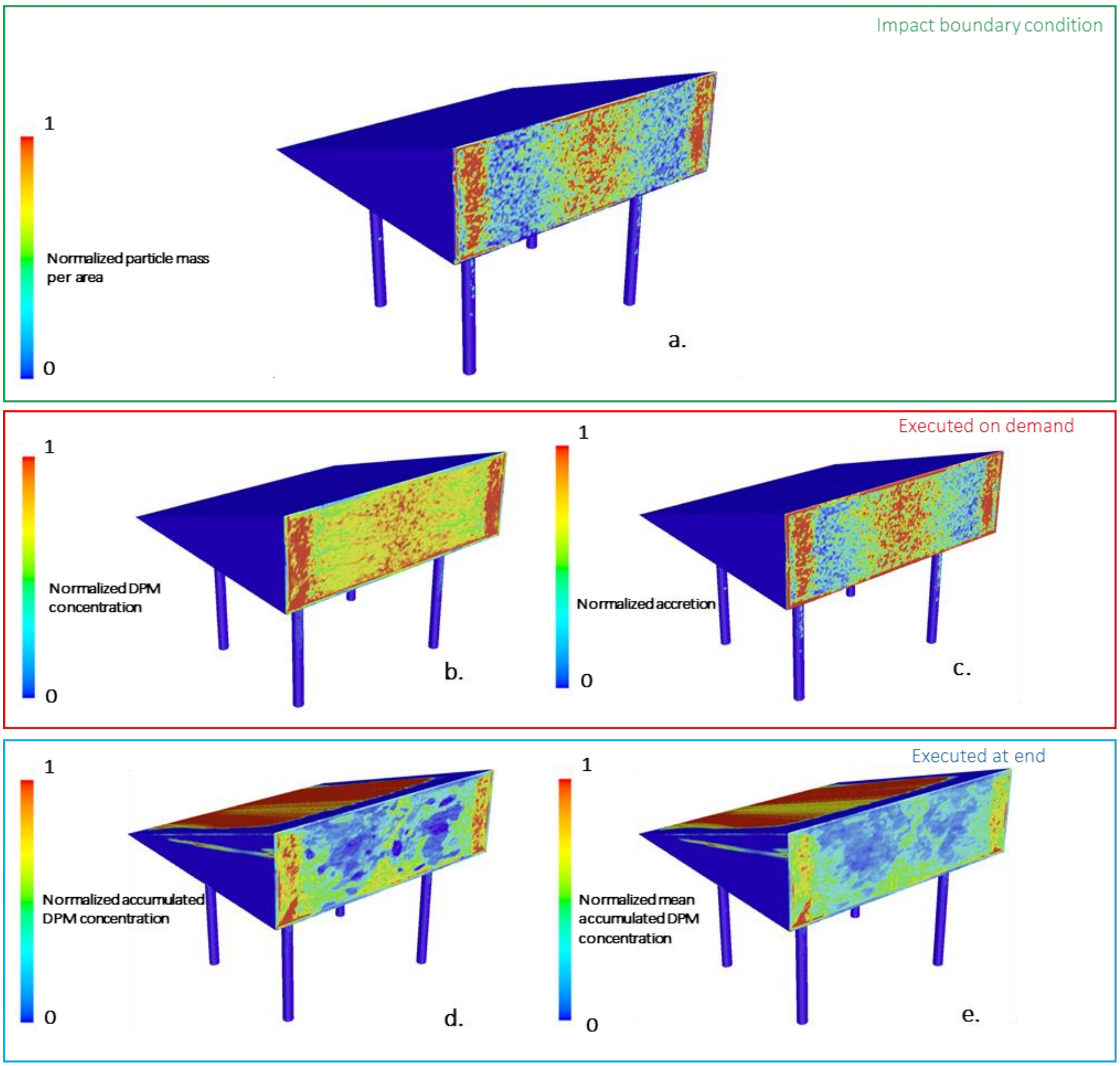


Figure 22: Contour plots of snow build-up for case 1 of the wedge. The pictures are showing different parameters to represent snow build-up which have been calculated by the different macros. The color scale in the pictures is normalized for every parameter. The color of the frame around the pictures represent the macro.

The boundary condition macro, colored green in figure 22, registers the hit of every particle on the boundary and leaves mass on the face of the cell depending on the normal and tangential velocities of the particles at impact. With the set conditions there is no snow accumulating on the sides or on the top of the wedge. As discussed in section 4.3.1 the snow build-up on the string on the side is not captured with this boundary condition, however this was not expected to be captured since the registration of particles works in the same way as the accretion plot.

The execute on demand macro, colored red in figure 22, deletes both the DPM concentration and the accretion values in the zones that exceeds the specified cut-off value for mean wall shear stress. It was believed that the DPM concentration could have captured this build-up on the sides, but as discussed in section 4.3.1, the mean wall shear stress on the strings on the sides are in the same order of magnitude as on the top. So lowering the cut-off limit would result in DPM concentration on the top as can be seen in figure 22 d and e, in the execute at end macro.

The execute at end macro, colored blue in figure 22, makes use of the instantaneous wall shear stress shown in figure 20 d, in every time step and deletes all the accumulated DPM concentration that has been built up in a cell if the cut-off value is exceeded. The idea was that snow might build up on the geometry but fluctuations in wall shear stress could rip-off snow from areas at different points in time due to fluctuations. This created a contour plot with an unsatisfactory result due to the many areas where DPM concentration was removed at a late simulation stage and thereby created steep gradients as seen in figure 22 d. This was solved by time averaging the contour plot over the entire simulation time and the result is represented in figure 22 e. This result looks much better on the rear but there is still DPM concentration on the top which is unsatisfactory. The method of time averaging the contour plot created a good looking pattern but lacks physical reasoning and connection to what actually happens in reality.

Case 2

This case was run in order to compare the results of the cut-off condition for normal velocity set in case 1 to that of the DEM model. The cut-off value for normal velocity was fetched from the regime map created in the parallel thesis work and shown in figure 7.

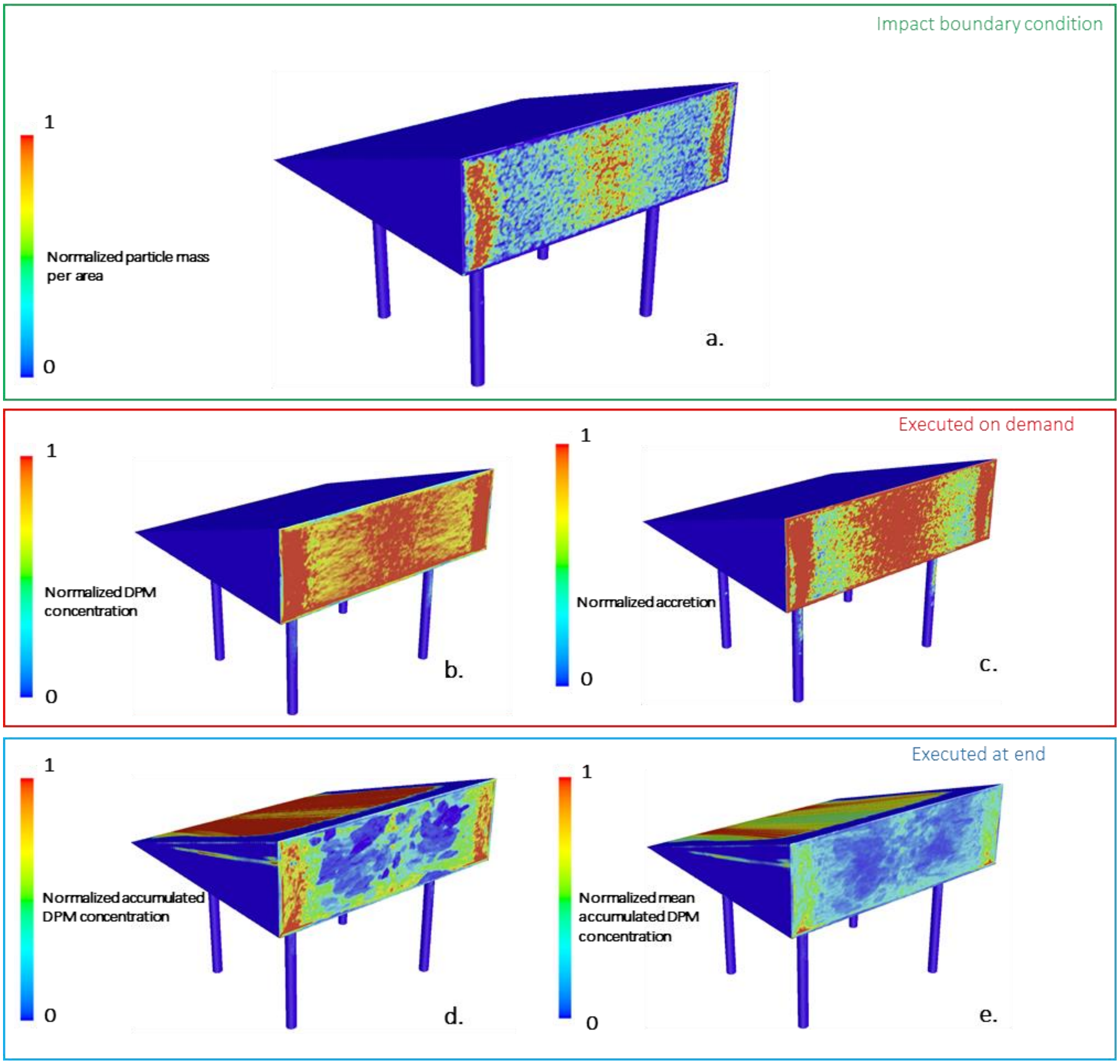


Figure 23: Contour plots of snow build-up for case 2 of the wedge. The pictures are showing different parameters to represent snow build-up which have been calculated by the different macros. The color scale in the pictures is normalized for every parameter. The color of the frame around the pictures represent the macro.

The normal velocity criterion for the boundary condition macro was lower than baseline for this simulation. This means that more particles hitting the rear of the wedge was reflected due to the normal velocity condition. Comparing figure 23 a, to figure 22 a, for case 1, it can be seen that the main difference is that the particle mass stored on the edges of the rear does not stick for case 2. Looking at what happens in the climatic wind tunnel in figure 18 b, one can see that more snow builds-up on the edges, this indicates that the normal velocity criterion might be a little too low.

In figure 23 b and c, it can be seen that the DPM concentration and accretion has larger values for this case. This should not be the happening since the normal velocity condition change only affects the boundary condition macro. This has to do with how the code in the macro fetches the data stored in Fluent. This case had been run for 17 s in total, while case 1 had been run for 11 seconds in total. Even though the time was reset and the UDMs nullified, the value fetched in the execute on demand macro is not. Hence the plots in figure 23 b and c corresponds to 17 s of simulation time. To overcome this problem one has to initialize the simulation and run it from scratch, however this was not done due to that a converged flow field was considered more valuable.

Case 3

This case was run in order to test the effect of the size of the injected particles, hence the case was run with the baseline conditions but with a particle diameter that was set to 10 times larger than the baseline case.

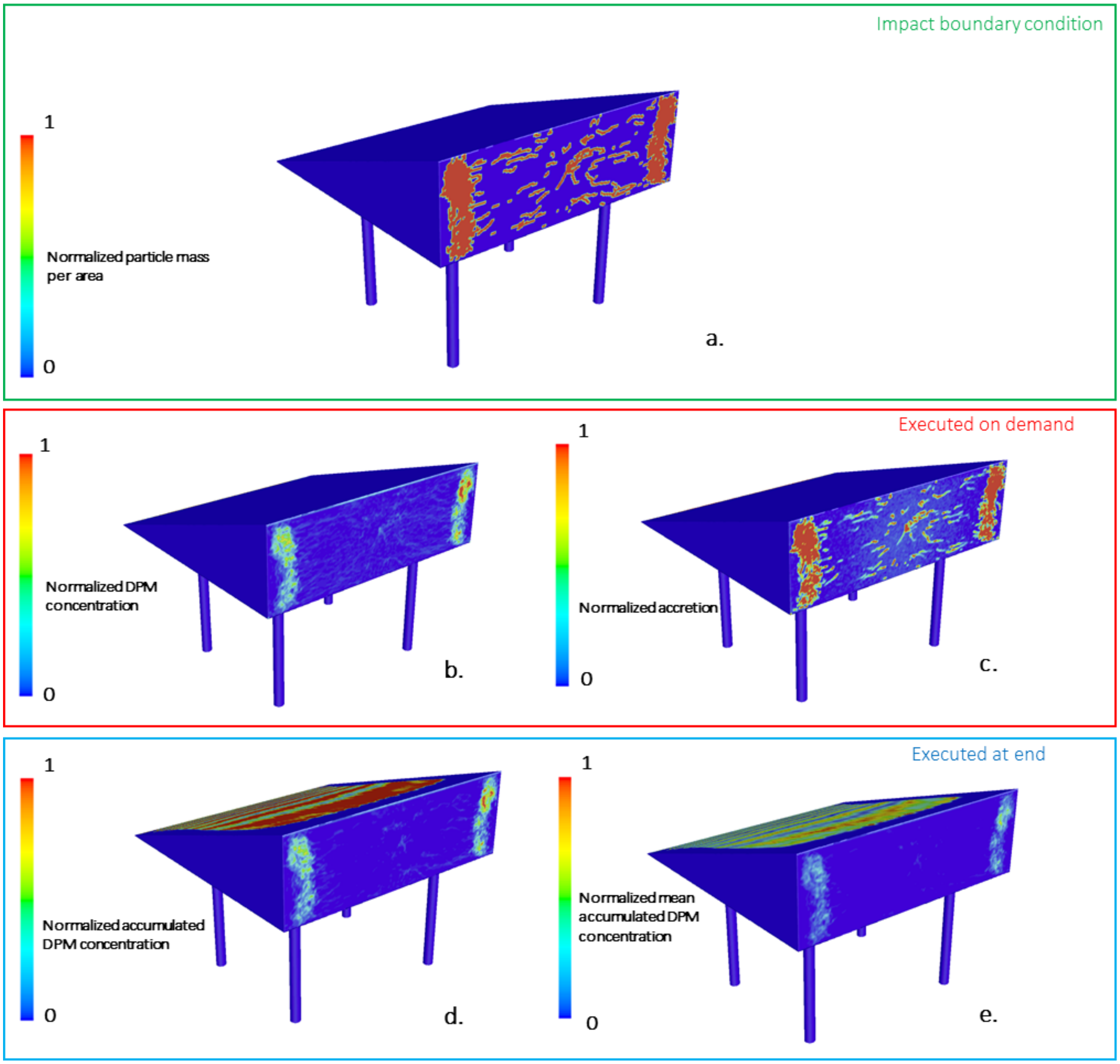


Figure 24: Contour plots of snow build-up for case 3 of the wedge. The pictures are showing different parameters to represent snow build-up which have been calculated by the different macros. The color scale in the pictures is normalized for every parameter. The color of the frame around the pictures represent the macro.

The particle size change caused a large difference for every macro. Looking at the boundary condition macro in 24 a, there are fewer particles hitting and they do not have as large dispersion when hitting the exterior but rather hits in the same areas all the time. When it comes to figure 24 b, d and e, The DPM concentration goes down compared to the baseline case. However the instantaneous and mean wall shear stress is still about the same, so this means that larger particles have a significantly lower particle concentration at the wall. This is most likely due to that fewer parcels follow the flow field into the wake and is instead just passing by the wedge due to higher inertia.

In figure 24 c, a vague pattern of accretion can be seen behind the clear red pattern. This is due to the same problem discussed for case 2. The size of the injected particles was changed without initializing the solver. Hence the written UDF code remembers the accretion values stored throughout the simulation.

Case 4

In the previous cases it could be seen that the snow build-up predicted with the execute at end macro had a substantial amount of DPM concentration on the top of the wedge. The idea with case 4 was to set a tougher criterion for the instantaneous wall shear stress to see if a result could be reached that matches reality better.

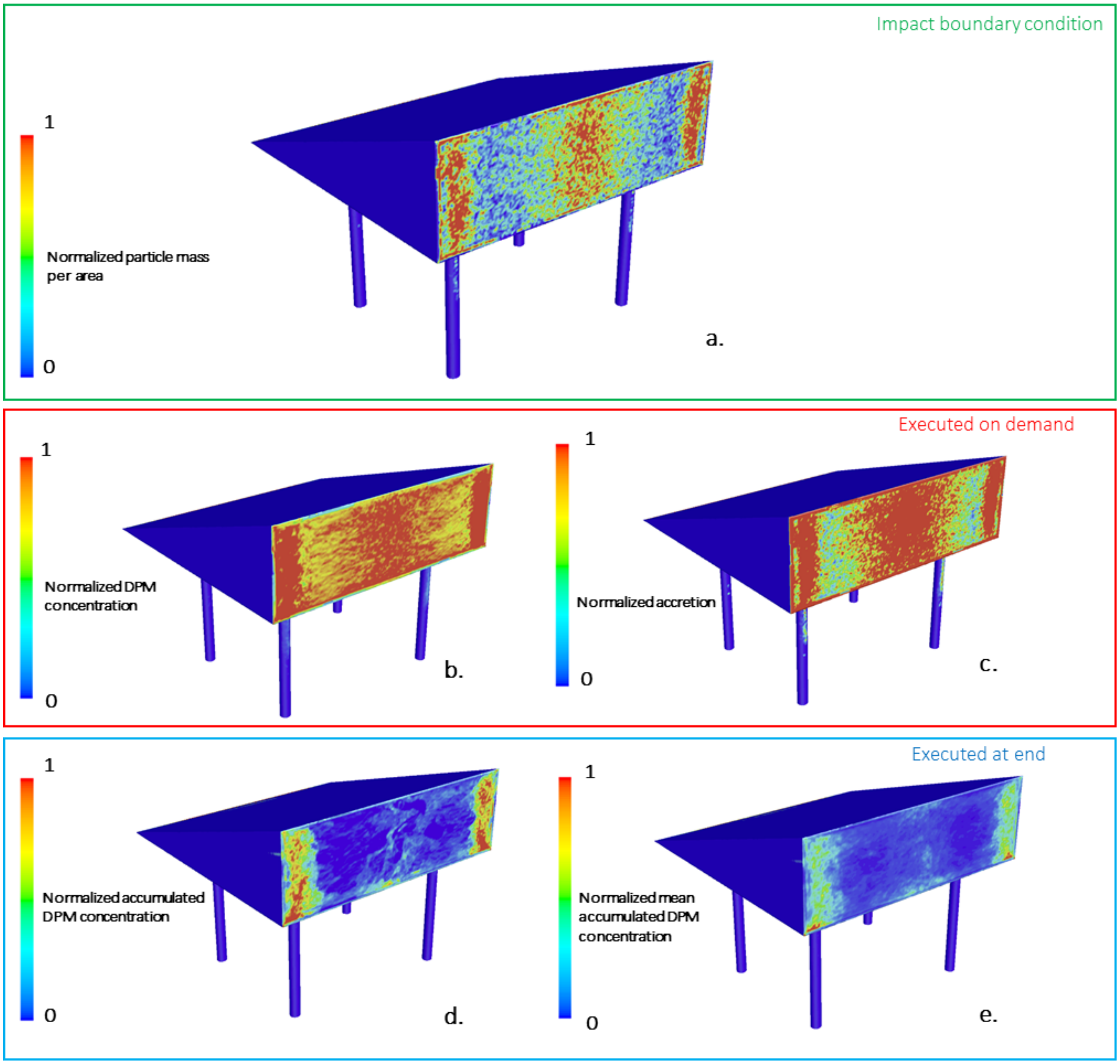


Figure 25: Contour plots of snow build-up for case 4 of the wedge. The pictures are showing different parameters to represent snow build-up which have been calculated by the different macros. The color scale in the pictures is normalized for every parameter. The color of the frame around the pictures represent the macro.

Looking at figure 25 d and e, there is no longer any DPM concentration on the top of the wedge. This unfortunately entails that the string on the side that was hoped to be captured is almost completely removed as well. However the pattern on the rear looks really promising especially for the mean values displayed in figure 25 e.

4.4.2 S90

The S90 was run with the baseline settings for normal velocity, tangential velocity and instantaneous wall shear stress. The mean wall shear stress cut-off limit had to be increased due to higher wall shear stresses around the car that arise due to the faster simulated driving speed of 100 km/h. The particle size used was the mean size found from the particle size distribution study.

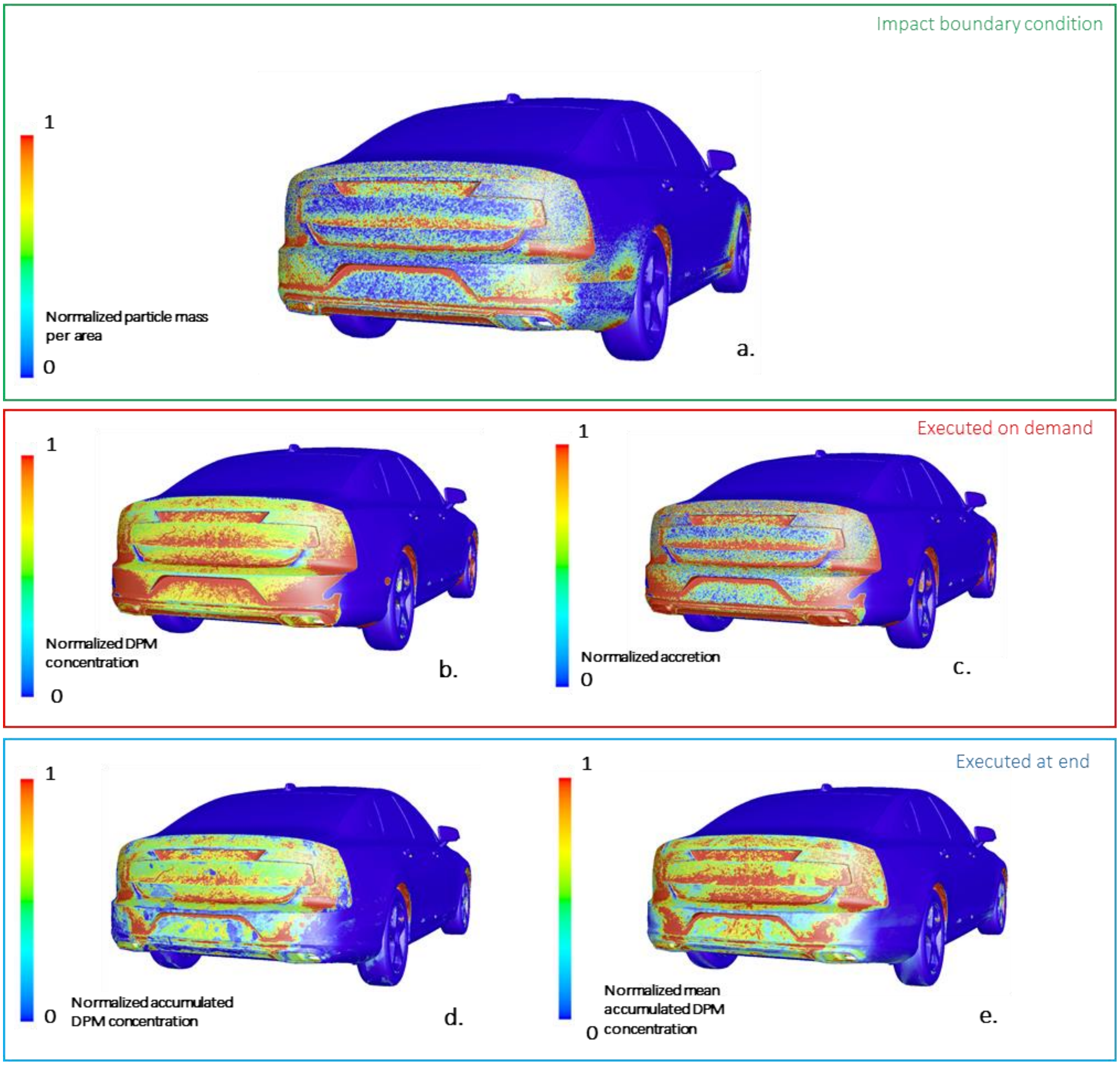


Figure 26: Contour plots of snow build-up for the S90. The pictures are showing different parameters to represent snow build-up which have been calculated by the different macros. The color scale in the pictures is normalized for every parameter. The color of the frame around the pictures represent the macro.

Figure 26 a, shows a promising start of a pattern on the rear, there is a trend that more particles are hitting in the zones where most snow build-up is observed in figure 17 a and b. However the DPM concentration plots in figure 26 b, d and e, gives a more correct trend if comparing to the field experiment pictures in figure 17. If the simulation could be run for a longer time it is believed that a more representative trend could be observed for the particle mass in figure 26 a. For now the DPM concentration plot is the most accurate, but since it cannot be said that these parcels actually hit the surface, there is an uncertainty in trusting the DPM concentration plot.

A limitation with the particle mass plot at this stage is that it does not capture the very clear line where the snow build-up stops on the rear bumper. This is due to that a flow separation behind the rear tires creates a zone with turbulent fluctuations where particles are allowed to stick in some time steps. This could be solved by decreasing the allowed sticking limit for normal velocity and tangential velocity, but that would also result in less particles sticking on the rear and further increase the computational time needed to get a representative pattern. It is good to have in mind that the simulation is run for 3.5 seconds, the test pictures from the in field studies were run for 100 km and the climatic wind tunnel test pictures were taken after 30 minutes in heavy snow conditions. There is a possibility that the sticking condition for snow particles regarding normal velocity and tangential velocity allows too many particles to stick. It could be that the sticking pattern would look even better if the criteria were lowered and the simulation time increased. But due to an already high computational time, this was not feasible to try at this point.

In figure 26 b and c, the very clear line can be observed between where the snow stick and where it does not. This is of course expected since the accretion and DPM concentration is simply deleted in areas with high wall shear stress. The wall shear stress is generally a little higher on the S90 since this case was run with a driving speed of 100 km/h instead of 70 km/h which was used for the wedge. Even though the wall shear stress is higher at a driving speed of 100 km/h, snow is observed to stick on the rear of the car, this may be an indication on that snow build-up is more dependent on normal and tangential velocity of particles at impact rather than wall shear stress.

Concluding thoughts about the wedge and S90 simulations is that the boundary condition macro is the most promising, with chosen cut-off conditions like in the baseline case a good representation of where most particles are expected to stick is reached. It is believed that snow build-up is dependent on normal velocity and tangential particle velocity at impact. It is also believed that snow build-up is dependent on wall shear stress. The boundary condition is now a tool to predict if a particle will stick at collision. The post processing macro and the execute at end macro acts as a tool to see where snow is being ripped off due to external forces being greater than adhesion forces. It is believed that the particle that sticks behind the rear tires in figure 26 a, would be ripped off by high instantaneous wall shear stresses like in figure 26 d and e. In the end when the wall shear stress and tangential velocity dependency have been investigated more, the boundary condition should take all parameters into account with scientifically investigated cut-off limits.

5. Conclusions

The best way to account for snow particle collision interactions in Fluent without using an integrated CFD-DEM model is by using UDFs. It was possible to create a condition for particle stick or bounce originating from a regime map. However since the DEM study resulted in a regime map that is dependent on particle size and normal velocity at impact, a tangential velocity criterion had to be introduced without consideration to the DEM model. The tangential velocity criterion was chosen empirically by looking at contour plots and comparing to wind tunnel experiments. Since all the injected particles have the same size in a CFD case, the criteria set for stick or bounce for normal velocity and tangential velocity becomes single values that can be read from the regime map instead of a function.

Three different approaches were taken to describe snow build-up with UDFs. The resulting contour plots that represent snow build-up for the different approaches resembles the wind tunnel test pictures and pictures from field studies in northern Sweden with different degree of accuracy. The user defined boundary condition is seen as the most promising tool since it is believed that it represent what happens in reality. However it takes a lot of computational resources and time to get a representative result. The post processing UDF can act as a tool to fast describe where most snow is expected to stick by only considering wall shear stress as a rip-off criterion. The transient simulation macro gives contour plots which have steep gradients in accumulated DPM concentration, this could be solved by taking a mean value of the DPM concentration over the whole simulation time. This gives a good representation of snow build-up but lacks physical reasoning to what is expected to happen in reality. The general conclusion is that the framework for the UDF makes it possible to describe snow build-up but further studies needs to be performed in order to scientifically prove the cut-off limits for either impact angle or tangential velocity of a particle as well as the rip-off effect of wall shear stress.

At this point a regime map exists for dry cold snow and that has been implemented in the UDF. However the UDF framework will work for different regime maps as well, one simply has to change the stick or bounce criteria in the code.

6. Future Studies

To further improve the snow build-up model it will be important to study angle dependency of particle impact as well as the effect of wall shear stress. The UDF should base its sticking criteria on scientifically proven parameter values like the normal velocity criterion. In the future it will also be interesting to see if it is possible to create an injection with different particle sizes and if it will be feasible to run such a calculation with existing computational resources.

In the user defined boundary condition it is possible to define the reflection angle and velocity. At this point outgoing angle and velocity is the same as the incoming. This can have an effect on the results. Hence it is of interest to make the reflection angle and speed dependent on DEM calculations as well, instead of assuming that no energy is lost in the collision.

For the UDF further studies should focus on three dimensional build-up of snow around the car. Interesting work has already been performed in the field, where the aim has been to model three dimensional snow build-up in the AIS of a car by the usage of UDFs. A study should be performed on how this can be implemented in complete car CFD and if the three dimensional build-up looks similar to the color scale contour plots and wind tunnel experiments.

References

Abrahamsson, P., Eng, M. & Rasmuson, A., 2017. An infield study of road snow properties related to snow-car adhesion and snow smoke. *Unpublished.*

Ali, B. et al., 2015. Coupled Computational Fluid Dynamics-Discrete Element Method Simulations of a Pilot-Scale Batch Crystallizer. *Crystal Growth & Design,* 15(1), pp. 145-155.

Andersson, B. et al., 2016. *Computational Fluid Dynamics for Engineers.* 12th ed. Gothenburg: Cambridge University Press.

ANSYS® Fluent Theory Guide, 2016. In: *ANSYS Fluent Theory Guide 17.0.* s.l.:ANSYS, Inc.

ANSYS® Fluent UDF Manual, 2016. In: *ANSYS Fluent UDF Manual 17.2.* s.l.:ANSYS, Inc.

ANSYS® Fluent User Guide, 2016. In: *ANSYS Fluent User Guide 17.0.* s.l.:ANSYS, Inc.

Colbeck, S., 1986. Classification of Seasonal Snow Cover Crystals. *Water resources research,* 22(9S), pp. 59S-70S.

Crowe, C., Sommerfeld, M., Tsuji, Y. & Schwarzkopf, J., 2012. *Multiphase flows with droplets and particles.* 2nd ed. s.l.:CRC Press.

Eng, M., Sterken, L. & Abrahamsson, P., 2017. Unsteady CFD Particle Methodology for Snow Self-Contamination of a Passanger Vehicle. *Unpublished.*

Fierz, C. et al., 2009. The International Classification for Seasonal Snow on the Ground. *UNESCO-IHP,* IHP-VII Technical Documents in Hydrology N°83(IACS Contribution N°1).

Gaylard, A. P. et al., 2014. Insights into Rear Surface Contamination Using Simulation of Road Spray and Aerodynamics. *SAE International Journal of Passenger Cars - Mechanical Systems,* 7(2), pp. 673 - 681.

Hagemeier, T., Hartmann, M. & Thévenin, D., 2011. Practice of vehicle soiling investigations: A review. *International Journal of Multiphase Flow,* Volume 37, pp. 860-875.

Huber, C., Weigand, B., Reister, H. & Binner, T., 2015. Modeling and Numerical Calculation of Snow Particles Entering the Air Intake of an Automobile. *SAE International Journal of Passanger Cars - Mechanical Systems,* 8(2), pp. 538-545.

Johnson, K., Kendall, K. & Roberts, A., 1971. Surface energy and the contact of elastic solids. *Proceeding of the Royal Society of London. Series A, Mathematical and Physical Sciences,* 324(1558), pp. 301-313.

Krijt, S. et al., 2013. Energy dissipation in head-on collisions of spheres. *Journal of Physics D: Applied Physics,* 46(43).

Libbrecht , K. G., 1999. *snowcrystals.com.* [Online]
Available at: http://www.snowcrystals.com/morphology/morphology.html
[Accessed 23 January 2017].

Lind, A., 2017. *DEM Modeling of Snow-Wall Adhesion,* Gothenburg: Chalmers Publication Library.

Marshall, J. S. & Li, S., 2014. Contact Mechanics with Adhesion Forces. In: *Adhesive Particle Flow, A Discrete-Element Approach* . s.l.:Cambridge University Press, pp. 86-88.

Miller, D., Adams, E. & Brown, R., 2003. A microstructural approach to predict dry snow metamorphism in generalized thermal conditions. *Cold Regions Science and Technology,* 37(3), pp. 213-226.

Ren, B. et al., 2011. Modeling of Gas-Particle Turbulent Flow in Spout-Fluid Bed by Computational Fluid Dynamics with Discrete Element Method. *Chemical Engineering & Technology,* 34(12), pp. 2059-2068.

Roettger, S., Schulz, M., Bartelheimer, W. & Ertl, T., 2001. Automotive Soiling Simulation Based On Massive Particle Tracing. In: Eurographics, ed. *Data Visualization.* Vienna: Springer, pp. 309-317.

Steinkogler, W. et al., 2015. Granulation of snow; From tumbler experiments to discrete element simulations. *Journal of Geophysical Research,* 120(6), pp. 1107-1126.

Sterken, L., Sebben, S. & Löfdahl, L., 2016. Numerical implementation of Detached Eddy Simulation on a passanger vehicle and some experimental correlation. *Journal of Fluids Engineering,* 138(9).

Tabor, D., 1977. Surface forces and surface interactions. *Journal of Colloid And Interface Science,* 58(1), pp. 2-13.

Viner, H., Dunford, F., Coyle, F. & Nesnas, K., 2012. Development of a Prediction Model For Splash and Spray. *7th Symposium on Pavement Surface Characteristics: SURF 2012.*

Volvo Car Corporation, 2017. *Autonomous Driving.* [Online]
Available at: http://www.volvocars.com/intl/about/our-innovation-brands/intellisafe/autonomous-driving
[Accessed 1 February 2017].

Volvo Car Corporation, 2017. *Intellisafe.* [Online]
Available at: http://www.volvocars.com/intl/about/our-innovation-brands/intellisafe
[Accessed 1 February 2017].

Zhou, X. et al., 2016. Numerical simulation and wind tunnel test for redistribution of snow on a flat roof. *Journal of Wind Engineering and Industrial Aerodynamics,* Volume 153, pp. 92-105.