

WINDSHIELD DEFROST SIMPLIFIED CFD MODEL

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Summary: The windshield defrost system, in general, is a vehicle safety feature. Thus, its restricted by variety of directives. However, the OMEs' benchmark targets could be even more demanding as the deicing process is in addition also part of passengers comfort. From vehicle design point of view the windshield defrost system is typically connected to HVAC unit (Heating, Ventilation and Air Conditioning). In the technical solution the windshield is heated via hot air convection. Nevertheless, other methods are becoming more and more popular, like directly heated glass by hot wire ohmic heating (heated glasses). The defrost CFD model should predict the ice layer thickness in time and space and in environmental conditions defined according to appropriate directives and technical solution. The accurate and fast modelling technique is essential part of a vehicle development, especially nowadays, where the optimization techniques area widely used and requires hundreds of simulations runs. Modelling requests are even increasing with modern pure electric vehicles (EVs), were the thermal and energy management is more demanding compared to the classical internal combustion engine (ICE) vehicles. The aim of the work is to verify possibility to model the ice layer thickness with simplified approach, which could be beneficial from computational time burden.

Key words: Windshield defrost, CFD, ice layer thickness, VOF, Thin Film

INTRODUCTION

The work is focused on the ice layer thickness prediction in time by using CFD simulations. Hence, the prediction of hot air convection or vehicle ambient heat transfer conditions etc. is out of the scope of work. As the view out of a vehicle is part of safety, the directives specify a computational model (physical test) initial and boundary conditions as well as required targets (1). However, the targets are irrelevant from modeling point of view and OEM requirements could be even more demanding.

Nowadays, the stat-of-the-art CFD techniques used for defrosting simulations are based on direct modeling of the melting domain. These models are capable to predict whole melting process including mushy zone, solidification, etc. and they are under continuing development (2, 3).

The simplified model like so-called Thin Film implemented in Siemens STAR-CCM+ is not defined accurately in the required conditions as well as needs empirical correlation. The model is based on additional scalar value of ice layer thickness on the boundary elements without direct modeling of the melting zone, thus its much less time step sensitive, thus cheaper.

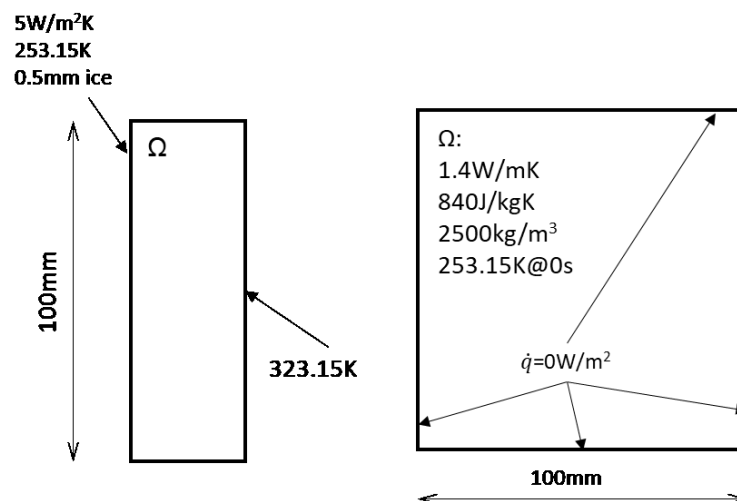
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Within the study Siemens Star-CCM+ commercial CFD tool were used to compare simplified model to the more detailed and suggest improvements of the simplified model to satisfy ambient conditions and predict accurately the melting process.

Nevertheless, multiple assumptions were done in aim to use simplified model. The ice layer thickness is negligible compared to the cell size. The ice layer is not geometrically or dynamically significant like it is in case of so-called airfoils icing. Hence, the momentum of the ice, mushy zone and melted ice is neglected. It should be also pointed that it is assumed all the properties and behavior is based on atmospheric pressure of 101325Pa.

1. TEST CASE DEFINITION

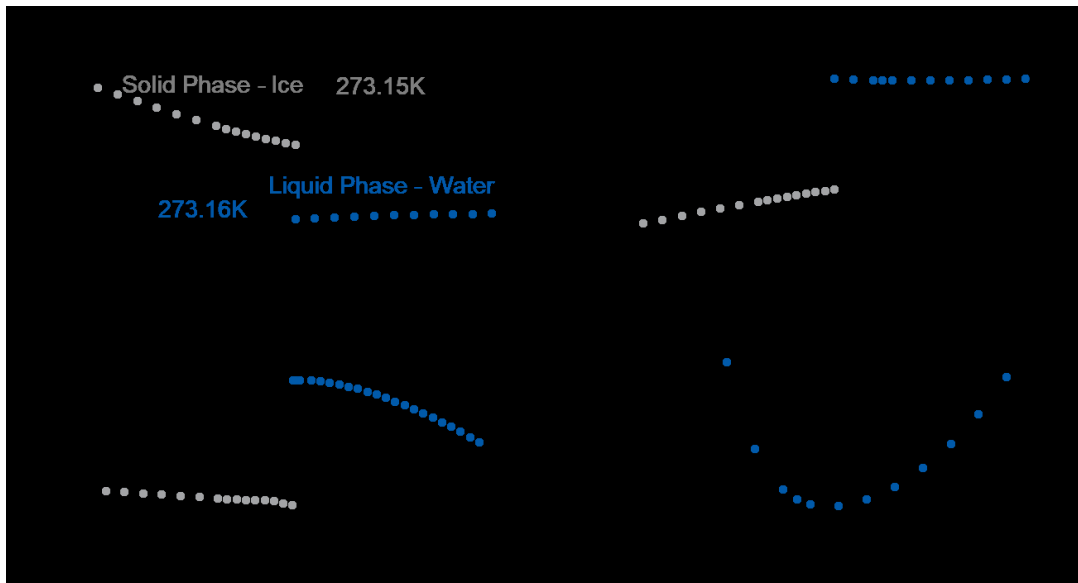
As aforementioned the convection or other heat transfer method is not in the scope of the work. Henceforth, the test case is simple glass box with one hot wall with temperature boundary conditions (b.c.) opposite of the wall with the ice layer. The ice layer wall is defined as convection b.c. defined by prescribed heat transfer coefficient (HTC) and air temperature. Rest of the walls are adiabatic. The ambient temperature and initial conditions (glass solid temperature and initial ice layer thickness) were prescribed according to the appropriate legislation (4, 5). The test case definition is highlighted in the Picture 1 below:



Source: Author

Fig. 1 – Test Case

However, the *Picture 1* shows material properties of the used glass, the water properties in ice and liquid phase should be prescribed as well. The water material properties were used as temperature depended curves, as could be seen in the *Graph 1* (6). The melting and solidification temperature were defined as 273.15K, respectively 273.16K.



Source: (6)

Graph 1 – Solid/Liquid Water Phase

2. GOVERNING EQUATIONS

Within the work there were tested the Thin Film model and Volume of Fluids (VOF) approach. The first one mentioned is the simplified one where only scalar field of the ice thickness is evaluated, the second one could model whole melting including more phenomena like mushy zone, bulk forces, solidification etc. Thus, the Thin Film model requires only the glass solid domain and the VOF needs to model a fluid domain.

In the case of both model's convection and conduction heat transfer should be captured and its defined according to familiar formulas 1 and 2 (7). The thermal diffusion in a solid domain could be expressed in differential form 3 (7). As the momentum of the melting/fluid domain is neglected, the fluid regain reacts in heat transfer as a solid region.

$$\dot{q} = -k\nabla T \tag{1}$$

$$\dot{q} = h(T_w - T_{ref}) \tag{2}$$

\dot{q} ... local heat flux (W/m^2)

k ... thermal conductivity (W/mK)

∇T ... temperature gradient (K/m)

h ... HTC (W/m^2K)

T_w and T_{ref} ... local wall and air reference temperature (K)

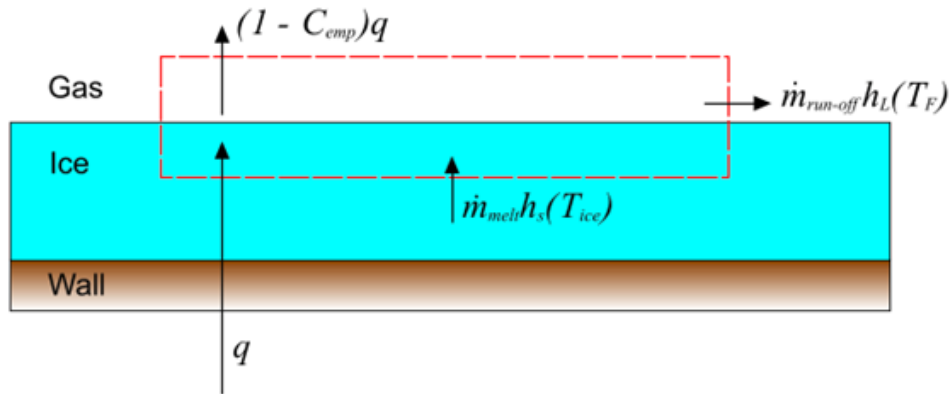
$$\dot{T} = \alpha \nabla^2 T \tag{3}$$

α ... thermal diffusion (m^2/s)

∇^2 ... Laplac operator

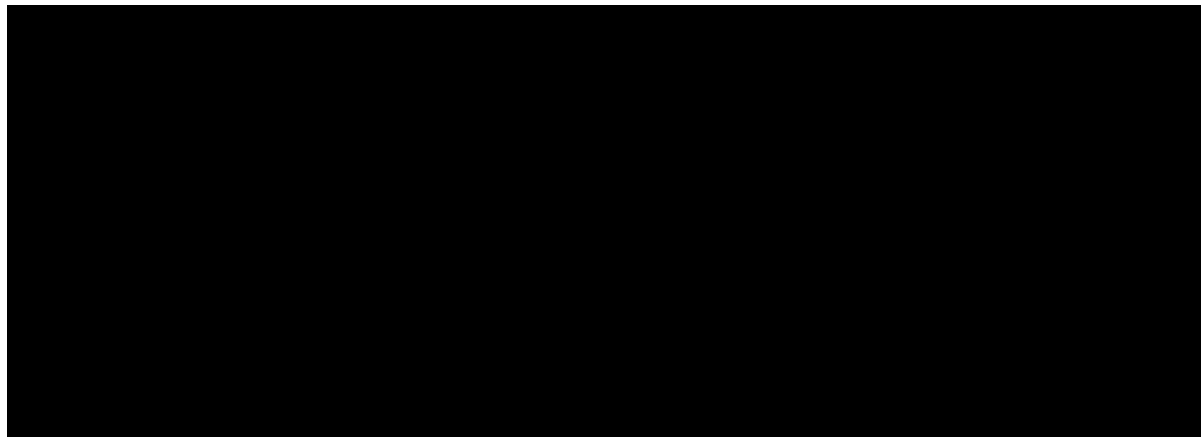
2.1 Thin Film Melting

The melting definition for the Thin Film model is based on quast-static approach and heat balance as could be seen in the *Picture 2 (8)*. The melting is than expressed with equation 4.



Source: (8)

Fig. 2 – Thin Film Model



As stated also in the used software theory guide (8): “*The model formulation implicitly assumes that the temperature surrounding the ice is above the freezing temperature. If this assumption is not correct, the model could produce some non-physical values (for example, the ice could start melting at temperatures which are below the freezing temperature).*” This assumption is not valid for the ambient temperature below freezing point required by directives (4)(5).

2.2 VOF Model Melting

The VOF model melting and solidification is in the software implemented by the equations 5 (8).

$$h_{ls}^* = h_{ls} + (1 - \alpha_s^*)h_{fusion} \tag{5}$$

$$\alpha_s^* = \begin{cases} 1 & \text{if } T^* < 0 \\ f(T^*) & \text{if } 0 < T^* < 1 \\ 0 & \text{if } 1 < T^* \end{cases} \quad f(T^*) = 1 - T^* \quad T^* = \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}}$$

h_{ls}^* , h_{ls} a h_{fusion} ... liquid – solid phase, fusion and sensible enthalpy (α_s^* ... relative solid volume fraction (1)

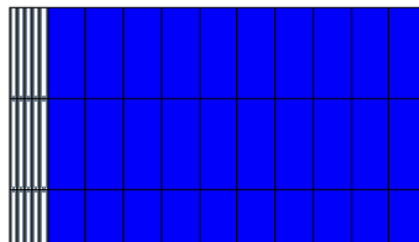
T^* , T , $T_{liquidus,solidus}$... normalized, cell, melting and freezing temp. (K)

$f(T^*)$... fraction solid curve(K)

The fraction solid curve definition is used linear as shown in one of the equations 5. It should me mentioned that more complicated models exist.

2.3 Computational Mesh

Finite volume representation (139k of hex structured elements) is shown I the *Picture 3*. The blue region represents the glass and the white is created for the VOF/liquid region. Thus, the white region is not presented in the Thin Film model.



Source: Author

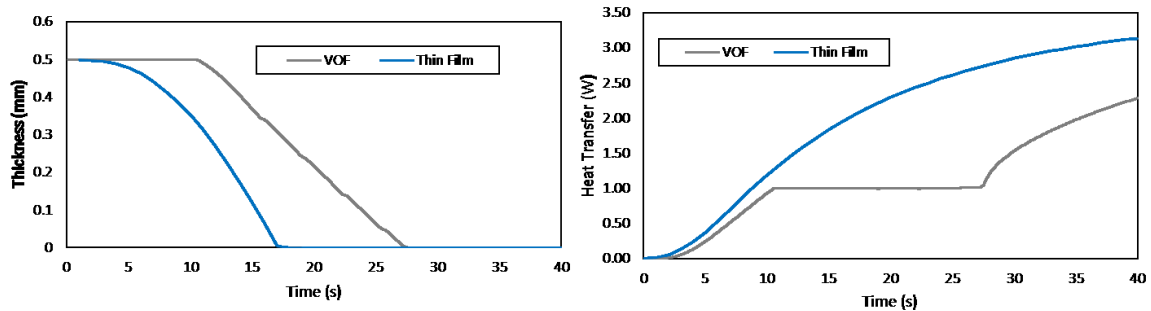
Fig. 3 – Finite Volume Mesh Detail

3. MODEL COMPARISON

Important contrast between the model could be observed in the stability, the Thin film model converged with time step of 1s, whereas the VOF model requires time step of 0.001s to be fully converged. This conclusion is very case sensitive and the ration between the time steps cannot be generalized (could be lower as well as higher), however Thin Film model is cheaper in general.

As mentioned above and by (8) the Thin Film model is not valid in the required ambient conditions and leads to melting of the ice even the temperature is below freezing point as shown in the *Graph 2*. Within the *Graph 2* it could be also observed that the Thin Film model does not capture the latent heat in the overall heat transfer through the wall. Likewise, the heat transfer in the initial stage, where the ice layer is heated to melting temperature (fist ~10s), differs between the Thin Film and VOF model. This is caused by missing thermal resistivity of the solid/liquid water and thermal capacity of the layer, even its only 0.5mm

thick. The Thin Film model capture the latent heat and the ice mass only within the additional scalar field and not into the computational domain.



Source: Author

Graph 2 – Model Comparison Results

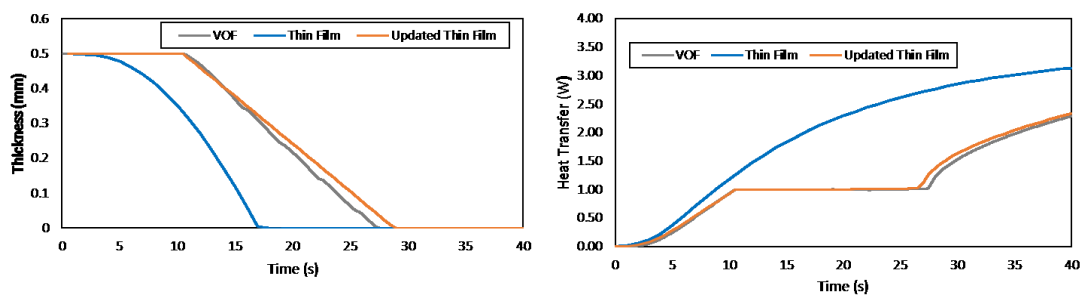
4. UPDATED THIN FILM MODEL

According to the previous chapter there were suggested improvements of the Thin Film model in aim to capture thermal mass of the melting region as well as the latent heat into the whole computational domain. The idea of the Updated Thin Film model is to use Thin Film approach with artificial solid region (the VOF white region in the *Picture 3*) with material properties from *Graph 1*. This should increase accuracy of the results in terms of thermal resistivity and ice/water heat capacity.

In aim to include latent heat into the overall heat transfer the specific heat capacity of this artificial solid regain is increased at the melting temperature to absorb the latent heat. This artificial specific heat capacity value was calculated based the known initial ice mass and small temperature difference of 0.01K. The issue with melting below the freezing point were mitigated by suppressing Thin Film equations until the melting point were reached.

However, we could still observe some difference between the Updated Thin Film and VOF model in the *Graph 3*, significant improvement of results was achieved.

The effect of ice layer thickness change in time and space is not implemented into the artificial specific heat capacity. Similarly, the issue with freezing temperature should be fixed in a way to capture space distribution of the surface temperature. These topics should be implemented to improve the accuracy. as the temperature field is heavily nonuniform on a windshield, nevertheless, the work proves the Updated Thin Film model philosophy.



Source: Author

Graph 3 – Updated Simplified Model Results

CONCLUSIONS

Within the work simplified Thin Film model were compared to the more complex VOF approach. The results confirm suggestion that the simplified model is not valid for the defrosting defined according to legislation boundary conditions (ambient temperature below freezing temperature).

The simplified model was modified in purpose of capturing melting layer heat transfer behavior. The Updated simplified model results are comparable to the VOF approach, with keeping the benefit of large time steps. The Updated simplified model could be performed with time step of 1s, thus ~100x higher than the complicated VOF model.

There were created assumptions related to the melting region, for example neglecting fluid and mushy zone motion is not valid in general. However, in case of design optimizations where huge amount simulations runs (higher hundreds), the Updated simplified model could be still beneficial compared to the detailed models.

Nevertheless, future work hast to verify model accuracy according to a test dada as detailed model were simplified as well. The VOF model review should be done as well, as only linear fraction solid curve was used and the results with momentum equation should be included as well. Other step would be implementation of the model inside the commercial tool directly via user code to avoid increasing the mesh size by the artificial solid region and include nonuniform scalar fields distribution.

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