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Windshield Defrost Simplified CFD Model

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Abstract

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.

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1. 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 (Tesař, 2012). 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 (Al-abidi et al., 2013; Kheirabadi, 2015; Sadananda, 2016, Danalia et al., 2014).

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.

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.

2. 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 (SAE J381, 2019; SAE J902 2011). The test case definition is highlighted in the Figure 1.

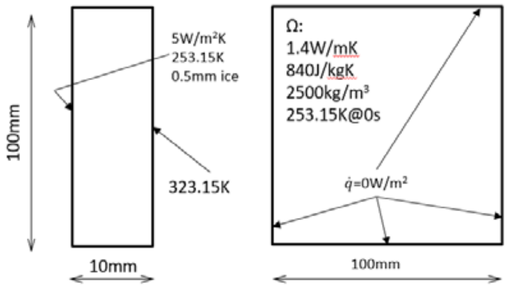

Fig. 1. Test Case

However, the Fig. 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 Fig. 2. The melting and solidification temperature were defined as 273.15K, respectively 273.16.

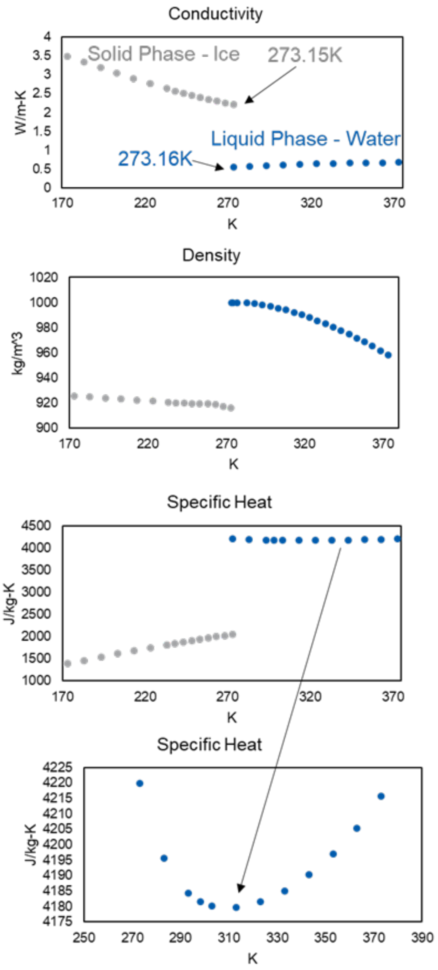

Fig. 2. Solid/Liquidus Water Phase

3. 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 (Bergman, 2011). The thermal diffusion in a solid domain could be expressed in differential form 3 (Bergman, 2011). As the momentum of the melting/fluid domain is neglected, the fluid regain reacts in heat transfer as a solid region.

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

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

where:

$\dot{q}$ – local heat flux (*W/m*^{2}),
k – thermal conductivity (*W/mK*),
∇ – temperature gradient (*K/m*),
h – HTC (*W/m*^{2}*K*),
T_s and T_{ref} – local wall and air reference temperature (*K*)

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

$\dot{T}$ – temperature (*K*),
α – thermal diffusion (*m*^{2}*/s*),
∇ – Laplace operator.

3.1. Thin Film Melting

The melting definition for the Thin Film model is based on quasi-static approach and heat balance as could be seen in the Fig. 3 (Siemens STAR-CCM+ Theory Guide, 2018). The melting is than expressed with equation 4.

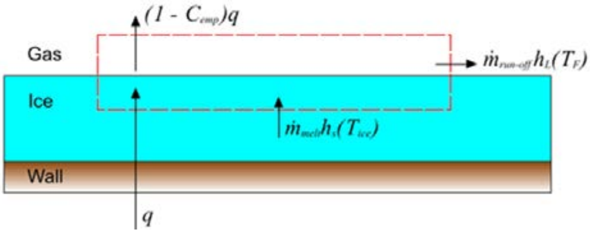

Fig. 3. Thin Film Model

$$m_{m\dot{e}lt} = \frac{c_{emp}q}{c_{p,s}(T_F - T_{ice}) + L} \tag{4}$$

where:

$m_{m\dot{e}lt}$– melted ice mass flow (*kg/s*),
q – heat flux (*W*),
C_{emp} – empirical constant, amount of heat absorbed by ice,
$C_{p,s}$ –ice specific heat capacity (*j/kgK*),
T_F and T_{ice} – melting temperature (*K*),
L – latent heat (*J*).

As stated also in the used software theory guide (Siemens STAR-CCM+ Theory Guide, 2018): "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 (SAE J381, 2019; SAE J902 2011).

3.2. VOF Model Melting

The VOF model melting and solidification is in the software implemented by the equations 5 (Siemens STAR-CCM+ Theory Guide, 2018).

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

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

where:

h_{ls}^{*}, h_{ls} and h_{fusion} – liquid – solid phase, fusion and sensible enthalpy (*J*),

α_s^{*} – relative solid volume fraction (1),

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

$F(T^{*})$ – solid fraction 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.

3.3. Computational Mesh

Finite volume representation (139k of hex structured elements) is shown in the Fig. 4. 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.

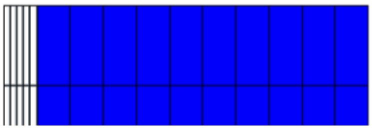

Fig. 4. Finite Volume Mesh Detail

4. 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 (Siemens STAR-CCM+ Theory Guide, 2018) 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 Fig. 5. Within the Fig. 5 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 0.5 mm 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.

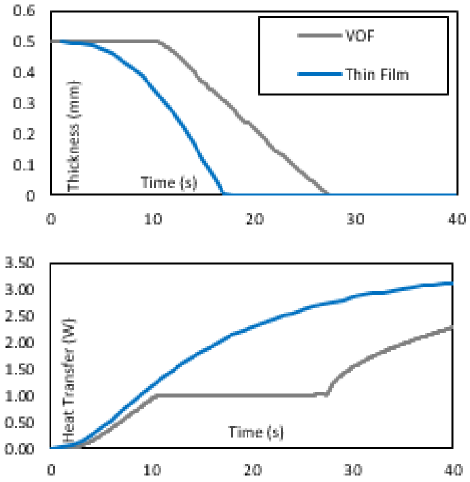

Fig. 5. Model Comparison Results

5. 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 Fig.4. Finite Volume Mesh Detail) with material properties from Fig. 2. 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 Fig. 6 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.

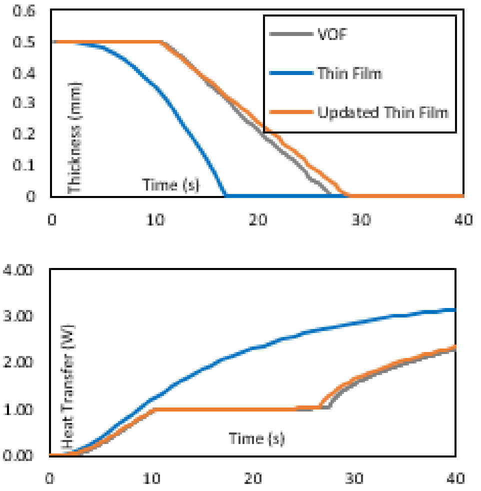

Fig. 6. Updated Simplified Model Results

6. 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 behaviour. 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 run (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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挡风玻璃除霜简化CFD模型

關鍵詞
挡风玻璃除霜
差价合约
冰层厚度
VOF
薄膜

摘要

挡风玻璃除霜系统通常是车辆的安全功能。因此，它受到各种指令的限制。然而，由于除冰过程也是乘客舒适度的一部分，因此OMEs的基准目标可能会更加苛刻。从车辆设计的角度来看，挡风玻璃除霜系统通常连接到HVAC单元（供暖，通风和空调）。在技术解决方案中，通过热空气对流加热挡风玻璃。然而，其他方法也越来越流行，例如通过热丝欧姆加热直接加热玻璃（加热玻璃）。除霜CFD模型应根据适当的指令和技术解决方案，在定义的时间和空间以及环境条件下预测冰层厚度。准确，快速的建模技术是车辆开发的重要组成部分，尤其是在当今，优化技术被广泛使用并且需要进行数百次仿真的今天。与传统的内燃机（ICE）车辆相比，热和能源管理的要求更高，因此现代纯电动汽车（EV）对建模的要求甚至不断增加。这项工作的目的是通过简化的方法来验证对冰层厚度进行建模的可能性，这可以从计算时间负担中受益。