Accelerated Headlight Defrost using Modelling and Simulation

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Abstract

Although just one component associated with a vehicle that has thousands of parts, headlights play a crucial role in driver and passenger safety. Specifically, both rear and front headlights illuminate a vehicle whether it be day or night, thereby allowing other road vehicles to perceive the vehicle in question. In summertime, the main source of headlight ray obstruction is bugs or insects that accumulate on the headlight surface, particularly when travelling at high speeds. However, during the wintertime, the main cause of light ray obstruction occurs prior to travelling, when the vehicle is still warming-up. In this phase, often ice that has accrued on the headlight's cover while the vehicle is at rest needs to be melted away via heat emitted from a wire filament embedded in the Makrolon polycarbonate cover of the headlight. When the driver and/or passengers are in a hurry, it is imperative that the defrost of the headlight ice layers occurs as rapidly as possible. With the increasingly more powerful hardware and software capabilities on the market, it is now possible to optimize the headlight defrost scenario, where the hot wire filament melts away the ice layer on the headlight's front, for reduced time entirely virtually. The present work uses modelling and simulation (MODSIM) on Dassault Systèmes' unifying computer-aided engineering (CAE) software platform, where both computer-aided design (CAD) and Navier-Stokes based computational fluid dynamics (CFD) tools are combined, to optimize this defrost time. A key aspect of the current workflow is the H2O phase change that is modelled by implementing a temperature dependent specific heat capacity with a spike at 0°C to account for H2O's heat of fusion. Furthermore, the MODSIM process allows the simulation scenario set-up of a parameterized CAD model to be automatically updated when the geometry in question is changed. For the headlight geometry in question, which is provided by a Tier I automotive component supplier called Weldex, the headlight filament wiring is parametrized and optimized in shape for minimized defrost time using a parametric design study approach. The constraint is that the headlight geometry itself cannot be changed, as this is dictated by the automotive original equipment manufacturer (OEM) that has purchased the headlight.

1. Introduction

Digital twins are computer models of their real-life counterparts. They are developed using a combination of continuum-based physics-driven simulation technology and artificial intelligence / machine learning algorithms. At first, used mainly in industries like transportation & mobility, aerospace & defense, and cities & infrastructure, they are now increasingly being applied in less conventional market segments such as life sciences & healthcare as well. According to Fortune Business Insights, the digital twin market in Europe is the third largest worldwide, while the global digital twin market is projected to grow to USD 137.67 billion by 2030 from a value of just USD 8.60 billion in 2022 [1]. While several CFD studies have explored automotive defrosting systems—such as windshield defrosters [2] or defogging approaches in automotive headlamps [3]—simulation-based research specifically targeting headlight defrosting remains limited. Previous collaborative simulation work between Weldex, a Tier I automotive component supplier, and 3DS on thermal headlight defrost has been reported in a prior paper [4]. This paper extends that work by optimizing the headlight defrost time using a parametric design study (PDS) performed on **3D**Experience Platform with its native Navier-Stokes based computational fluid dynamics (CFD) solver called FMK encapsulated in the Fluid Dynamics Engineer role. The remainder of the paper is structured as follows: section 2 outlines the precise methodology / workflow, section 3 discusses the results, section 4 provides a conclusion, while section 5 offers an outlook on potential future work to try out.

2. Methodology

To begin, as part of the PDS methodology, a MODelling and SIMulation (a.k.a MODSIM) workflow is employed. This workflow integrates computer-aided design (CAD) and simulation tools within a unified environment. In this context, CAD and computational fluid dynamics (CFD) tools are used in combination, enabling a direct link between the parameterized CAD model and its corresponding simulation setup. This means that any alterations made to the CAD model by changing the geometry's parametric parameters automatically lead to an updated mesh in the CFD simulation scenario. Through MODSIM, the entire simulation workflow is left-shifted, enabling an earlier use of CFD simulation in the design process, thereby reducing late-stage failure and cutting product development time drastically. The entire PDS workflow for the thermal headlight defrost CFD simulation set-up, with the embedded MODSIM process, is depicted in figure 1. The individual steps are subsequently described in more detail:

- First, in step 1, define the geometry parameters that the PDS is meant to explore the influence of on the optimization target.

- Next, in steps 2 to 3, run a single CFD simulation of the baseline set-up. This is a sanity check to make sure that the simulation has been configured correctly.
- After that, in step 4, define the camera positions and sensors that are meant to be used in the PDS to assess / compare the results of each simulation.
- Following that, in step 5, specify the design improvement study by selecting the optimization target.
- Subsequently, in step 6, set the number of simulations that are to be run in the PDS optimization study and run checks to make sure that the automatically generated (through MODSIM) simulation set-ups are actually feasible from a geometry perspective.
- In step 7, use the PDS graphical-user-interface to review the produced results per simulation run.
- And finally, in step 8, select the optimal case and/or generate design alternatives based on the optimized geometry.

Figure 1: Schematic of the PDS optimization workflow for the headlight defrost simulation scenario

Having described the general MODSIM and PDS workflow, the parameterization of the headlight geometry from Weldex must now be detailed. The overall shape of the headlight casing cannot be changed, as this is dictated by the original equipment manufacturer (OEM) purchasing the headlight from Weldex; the headlight must fit into the general assembly of the vehicle. Therefore, the only avenue of influencing the defrost time of the headlight is by changing the shape of the heating wire filament that spans the headlight front. It is the wire that is parameterized. The parameters are summarized in figure 2. It is important to differentiate between those parameters that constrain the parameterization and the actual variable parameters. Figure 3 shows that the first constraint is the *total* height of the wiring; it cannot surpass 85mm. Figure

4 illustrates the remaining constraints. The *radius* of the wire turns is fixed at 0.995mm, the *bendwidth* (i.e. spacing) is computed from the *total* height and *n*, which represents the number of horizontal wire segments; and finally, the *short* end length of the wiring is computed from the *bendwidth*. The two variable parameters that are actively altered in the PDS are *n* (the number of horizontal wire segments) and *wirewidth* (the wire diameter), since all other presented parameters are derived from these two.

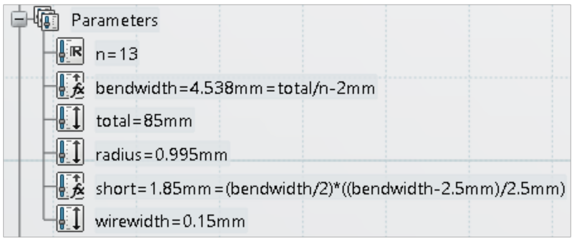

Figure 2: Summary of parameters used to vary the heating wire's shape

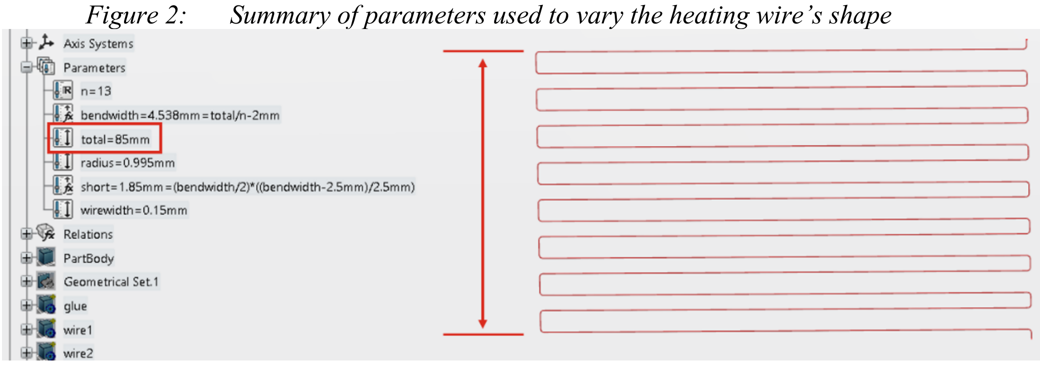

Figure 3: The vertical "total" height constraint of the wire filament

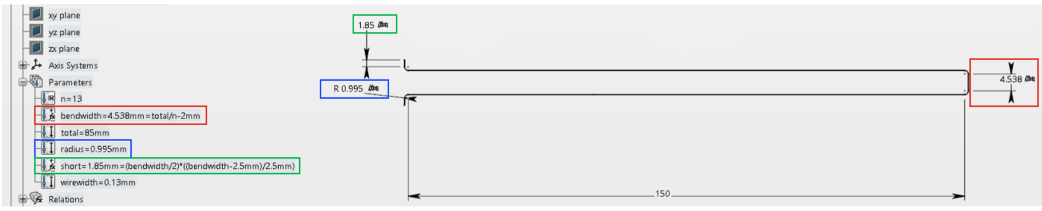

Figure 4: The remaining wire geometry constraints: "radius, "bendwidth", and "short"

With the MODSIM based geometry parameters dictated, the simulation scenario set-up is briefly described here. It includes the discretization of the air domain using hexahedral elements and the solid components, such as the ice layer, using tetrahedral elements (thickness of 1mm). Mesh refinement is applied near the fluid domain's stagnation inlet, pressure outlet, and around the headlight boundaries, with prism layers added adjacent to solid walls to better resolve the boundary layer. The Reynolds-Averaged Navier-Stokes (RANS) realizable k-ε model is selected. For further details, please refer to the previous SIMULIA paper from the 3DS–Weldex collaboration [4]. Most importantly, the phase change is enabled by adding a spike in the temperature dependent specific heat capacity at 0°C. The spike should be such that its integral ("the area under the curve") is equal to the heat of fusion for water. Furthermore, a critical simulation parameter that needs to be specified is the Joule heating (a.k.a Ohmic heating) value of the wire filament. As equation 1 illustrates, Joule heating (P) depends on the voltage (V) applied, the cross-sectional area (A) of the wire, the resistivity (ρ) of the wire material, and the wire's total length (L):

$$P = \frac{V^2 A}{\rho L} \qquad \text{Eq. 1}$$

For the PDS exploration step, the voltage is set to 12.8V and the resistivity to 1.68e-8Ωm (for copper). The cross-sectional area A is bounded by a wire diameter range of 0.1-0.2mm, which is provided by Weldex. Meanwhile, the length of the wire L is bounded physically by n ranging from 9 to 19; anything beyond these bounds is geometrically not possible. Joule heating range is calculated with varying A and L: [29.17W -35.7W]. The average value 32W is selected for the PDS study.

Once the combined MODSIM and PDS workflow as depicted in figure 1 is complete, the five best cases are selected. The criteria for selecting these five best cases are as follows:

1. They have to deliver high average "ice layer" temperatures by the end of the transient simulation.
2. Their true power output has to be close to the customer requirements of 30W. This means that wire configurations that perform well/better in the PDS are discarded in the event that their true power output is very low due to long wire length (see equation 1), meaning their true defrost time is much longer.

These five cases are then simulated with their correct Joule heating value, which is evaluated using equation 1. From the five simulations with correct Joule heating value, the simulation that has the highest average "ice layer" temperature by the end of the transient simulation is chosen to possess the best wire geometry for optimized headlight defrost time. It is important to note that, throughout this analysis, it is assumed that highest average "ice layer" temperature at the end of the simulation time correlates with an earlier total defrost time, where the ice layer has been completely melted away.

Finally, with the best heating wire filament configuration found, material temperature bounds need to be checked. Specifically, the headlight casing is made of Makrolon, a polycarbonate, which melts when exposed to a temperature greater than or equal to 408.15K. To make sure the optimized wire configuration does not cause the plastic casing of the headlight to melt, a steady-state room temperature simulation of 293.15K is run with an applied heat load generated by 16V. These 16V are chosen, as the voltage applied could switch to this value should the micro-controller that dictates the voltage fail and switch to this default value. If the final steady-state temperature, that the headlight casing is exposed to, is lower than 408.15K, the optimized wire configuration is deemed acceptable.

3. Results

To begin, the design space explored in the PDS is illustrated as well as its results. As figure 5 shows, a total of 44 simulations are performed with the *wirewidth* varying from 0.12mm to 0.15mm, and *n* varying from 9 until 19. It is also at this stage that the generated simulation set-ups are checked for geometric feasibility. Upon completion of the PDS, the window shown in figure 6 is produced. It shows a plot where average "ice layer" temperature is compared to *n* and the *wirewidth.* The simulations at the lower-end of the temperature range are discarded, as their average "ice layer" temperatures are low. Meanwhile, the simulations at the upper-end of the temperature range are not considered further either, since their actual Ohmic heating value would be very low due to their long wire length (see equation 1). The five best simulation scenarios for further simulation are chosen from the *n* range of 13 to 16, as indicated by the red box in figure 6. This is because these set-ups have high average "ice layer" temperatures and their true Ohmic heating value is close to the requirement of 30W.

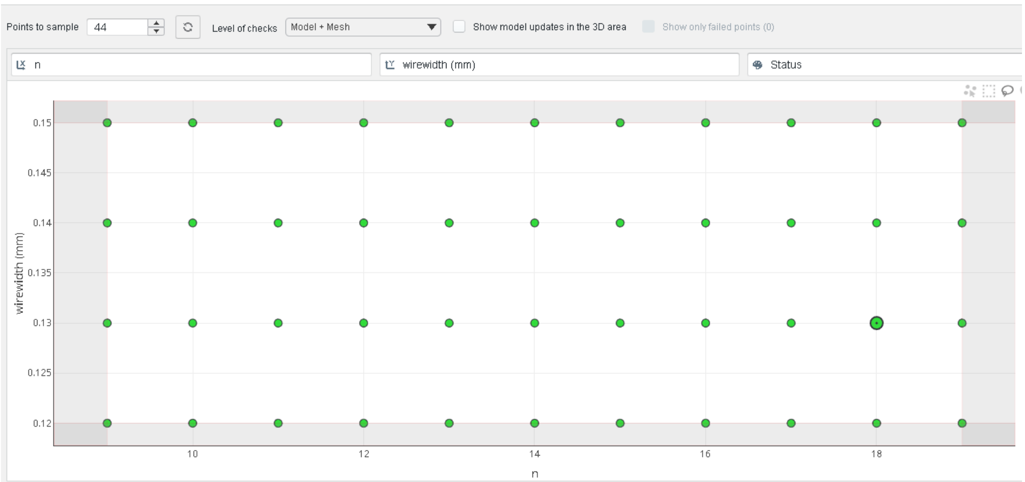

Figure 5: The design space explored in the PDS

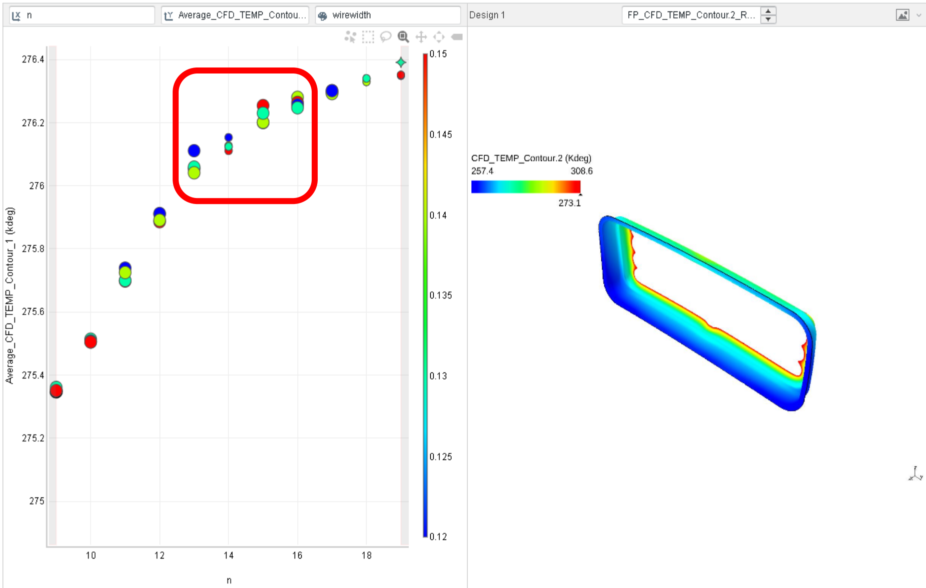

Figure 6: Results from the PDS with the range of simulations for further consideration marked as well

Table 1 contains the results of the five simulation set-ups run at their true Ohmic heating value. The baseline set-up is also shown for comparison to see the benefits of the improved configuration(s). In the end, the scenarios with *n* of 13 and *wirewidth* of 0.14mm, and *n* of 14 and *wirewidth* of 0.15mm are selected for the material test simulations (the rows are marked in **green** in table 1). This is because these simulation set-ups:

1. Provide Ohmic heating values that are almost equal to 30W.
2. Have close to the shortest inflection point times, i.e. times where the phase change begins to end.
3. And have almost the highest average "ice layer" temperature by the end of the transient simulation.

Although the set-up with *n* of 13 and *wirewidth* of 0.15mm does appear to be the best design, it is deemed to have a power rating that is too far from the 30W target value provided by Weldex.

Table 1: Best case simulations run at their true Ohmic heating value

Design (“n”, “wirewidth [mm]”)	Ohmic Heating [W]	Max Temp. [K]	Inflection Point [s]	Avg. Temp [K]
Baseline	30	298.4	550	273
13, 0.14	30.49	302.6	535	273.8
13, 0.15	35.01	309.8	460	276.9
14, 0.15	30.82	303.9	518	274.1
15, 0.15	27.85	299.3	570	272.1
16, 0.15	25.4	295.3	614	270.5

The simulations to test material bounds are run at steady-state with a room temperature value of 293.15K and a heat load generated by 16V. Overall, these simulations are run for a total of 2000 iterations. Evidently, as figure 7 depicts for both chosen designs, the final steady-state headlamp lens temperatures are well below the 408.15K threshold set by the Makrolon polycarbonate material. As such, it can be asserted that the two wire geometries / designs for optimized (i.e. shortened) headlight defrost time do not cause the plastic material of the headlight to fail by melting.

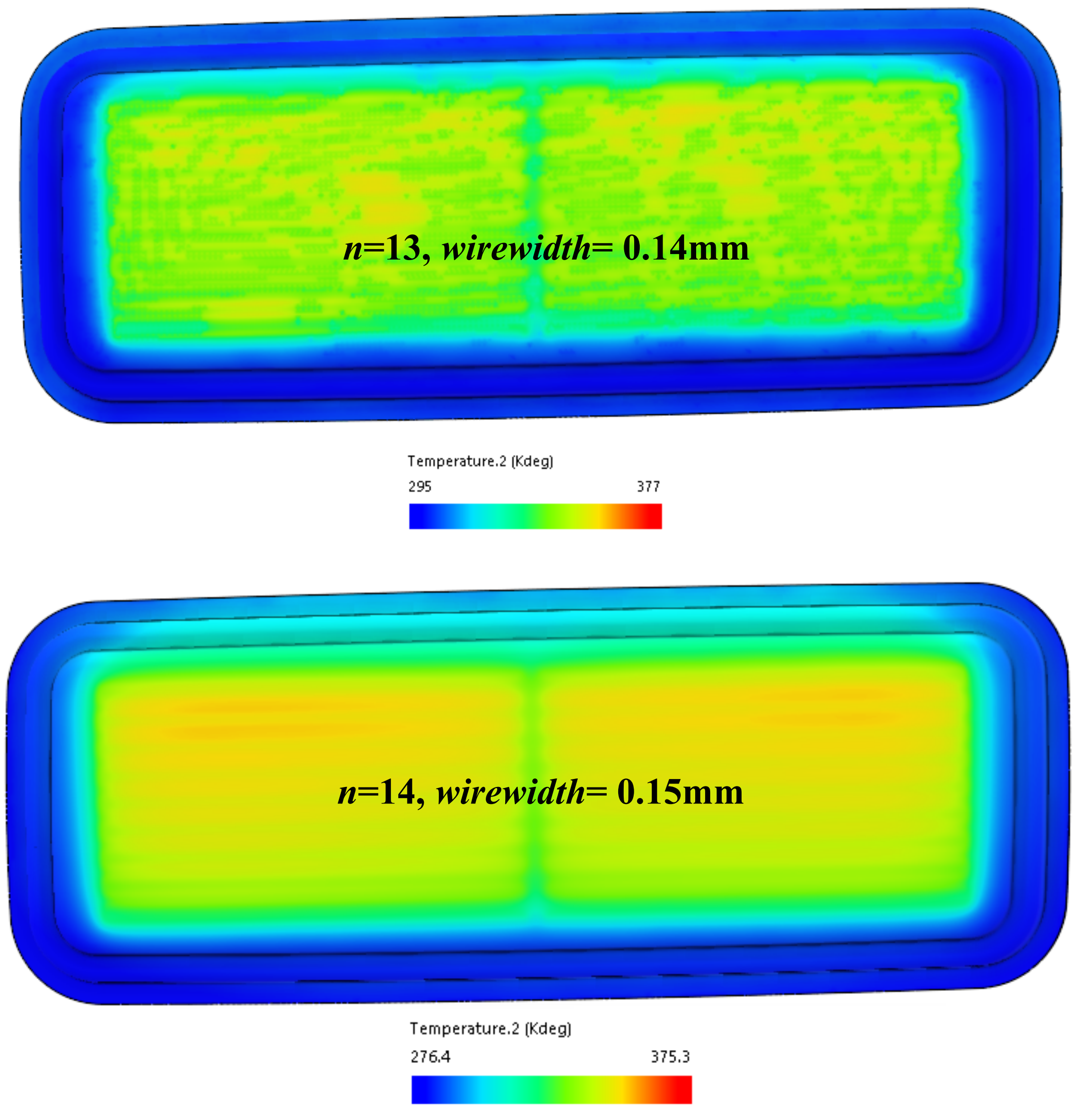

Figure 7: Material bounds simulation results

4. Conclusion

In conclusion, a MODSIM based PDS is performed to assess the influence of wire filament geometry on defrost time of a Weldex headlight. Throughout this PDS, two parameters are actively varied: *n*, which is the number of horizontal wire segments, and *wirewidth*, which is the filament's diameter. Five set-ups from the completed PDS are selected for simulation at their correct Ohmic heating value. From these five designs, two are pursued further, as they provide close to the highest average "ice layer" temperature by the end of the transient simulation, and close to the shortest inflection point time, which is deemed to be the point at which defrost has completed, while still being near the desired power rating of 30W: *n* =13 with *wirewdith*=0.14mm, and *n*=14 with *wirewidth*=0.15mm. In both cases, it is determined that, by running a steady-state room temperature simulation of 293.15K and applying a heat load generated by 16V, the Makrolon polycarbonate does not reach its melting temperature of 408.15K. Finally, this study shows that, while filament geometry has an impact on defrost time, a more noticeable impact can be achieved by being able to apply a larger Ohmic heat load.

5. Future Work

It is imperative that future work explore the possibility of varying the heat load applied to the wire filament. This could be achieved through a design-of-experiment (DOE) study implemented within a workflow automation environment that enables systematic variation of simulation parameters.

6. References

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