Smart Heating Panels to Increase Thermal Comfort and Efficiency

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Abstract The increasing electrification poses new challenges with respect to thermal comfort in vehicle passenger cabins. As waste heat in BEVs (battery electric vehicles) is mostly available on lower temperature levels, e.g. below 40 °C, it cannot effectively be used for heating. While conventional air heating with electric heaters is technically possible, it causes significant reductions in the electric driving range. Two contradicting objectives are to be achieved: Fast heat up to provide thermal comfort as well as high energy efficiency in order to maximize the driving range under all conditions.

This apparent area of conflict can be eased by the usage of low temperature radiation reducing the energy intensive heat up of the cabin air. In order to provide high energy efficiency, the emitted radiation should mostly be directed towards relevant body regions of the passengers, resulting in the necessity to redesign the passenger cabin. In this paper, a novel approach to redesign and optimize the dashboard as well as a resulting radiation heating system are presented. For the purpose of reducing computational effort of such an optimization, the complex three-dimensional geometry is sliced into simplified two-dimensional regions which are considered individually. The resulting heating system has been manufactured and integrated into the passenger cabin of a class A vehicle. Objective thermal comfort measurements as well as subjective comfort ratings have been conducted in order to validate the simulative approach and the resulting energy savings of approx. 30 %.

Keywords: Thermal Management, Thermal Comfort, Simulation, Comfort Measurement

1 Introduction

Currently, a trend for increasing electrification of the drivetrain, up to fully battery electric vehicles (BEVs), can be observed both in vehicle development as well as in customer demand. This trend is based on a variety of reasons. On the one hand, legislation, such as CO2 regulations, force OEMs to reduce fleet emissions to a level that can hardly be reached by conventional combustion engines alone. On the other hand, customer demand for electrified vehicles increases as well, due to ecological and economical aspects. In [1], different drivetrain concepts and their primary energy requirements have been compared for Germany. According to [1], the primary energy requirement for any other drivetrain concept would be at least 1.8 higher compared to battery electric vehicles. Additionally, the total cost of ownership for the customer can also be reduced due to the higher efficiency of the drivetrain and lower cost of electric energy, even if the initial invest for a BEV is higher, as shown in [2, 3].

Due to the lower energy density of current Li-Ion batteries compared to conventional fuels however, the vehicle range is limited and subject to significant variations, especially due to heating purposes in winter [4].

Therefore, a heating system reducing the impact on the overall the energy demand and simultaneous increasing thermal comfort is desirable.

One possibility to solve this conflict of objectives is the usage of radiative heating systems, e.g. presented in [5, 6]. Therefore, in this paper a novel approach to design such a heating system as well as experimental results on a prototypic implementation. Measurements show approx. 35% lower energy demand to reach thermal comfort for a class A vehicle.

2 Fundamentals

In conventional combustion engine vehicles, the waste heat of the combustion engine is used to heat the passenger cabin and thus heating has no impact on the energy demand [7]. While this waste heat can easily be used to heat up air, convection heating also is prone to losses by leakage or fresh air mode [8]. These losses are especially harmful in BEVs, where energy for cabin heating is provided by the traction battery and could otherwise be used for locomotion. Thus, conductive and radiative heating offer higher efficiencies as these technologies are not prone to the same losses as convective heating.

The overall energy balance for a vehicle cabin respecting convective, conductive and radiative heat flows can thus be stated as shown in equation (1), also including the metabolism M of the passengers.

$$\frac{dU}{dt} = \sum \dot{Q}_{convection} + \sum \dot{Q}_{conduction} + \sum \dot{Q}_{radiation} + M \tag{1}$$

Analogous to the passenger cabin, the occupants themselves as a thermodynamic system are exposed to convective, conductive and radiative heat transfer as given in equation (1). Therefore, in order to achieve the same thermal state in quasi-steady-state conditions with lower air temperatures, the conductive and the convective share are to be increased. The convective heat transfer is subject to the airflow, e.g. the air velocity, and the temperature differences between the passengers' surfaces (skin, clothes) and the surrounding air as shown in equation (2).

$$\dot{q}''_{convection} = \alpha \cdot (T_{air} - T_{surface}) \tag{2}$$

The usage of additional radiative heating elements has shown the possibility to significantly decrease the cabin temperature, e.g. by 3 K as shown in [9], or the velocity of the air and thus the mass flow, both resulting in a lower convective heat flux, cf. equation (2). In [6], subjective and objective studies have shown a reduction of approx. 30 % compared to the conventional electric heater.

A textile heating system is used for the study in [6] in order to improve the acoustic absorbance in the passenger cabin. While such a system can be easily applied to existing textile surfaces in the passenger cabin, a large portion of the passenger cabin has to be used to achieve the desired effect. Additionally, the conversion of an existing interior design to include surface heating elements is possible, but offers potential for improvement as shown below.

Therefore, in this paper, the authors will present a design fundamental for radiative surface heaters as well as a results from a prototypic implementation of a system based on these principals.

3 Design of Radiative Heating Panels

In order to ensure additional functionalities, e.g. window defogging or good air quality, are available, the radiative system will be used in combination with a conventional convective heating system. Due to lower thermal inertia, also the dynamic heat up process is improved.

The radiative heat flow of a gray body in general is given in equation (3), with σ as the Stefan-Boltzmann constant, the thermal emissivity ε, the area of the radiating surface A and its temperature Tsurface.

$$\dot{Q}_{\text{radiation}} = \sigma \cdot \varepsilon \cdot A \cdot T^{4}_{\text{surface}} \tag{3}$$

Considering two surfaces A and B, the amount of heat that is transmitted via radiation from surface A to surface B can be calculated with the corresponding view factor between these surfaces as shown in equation (4).

$$\dot{Q}_{AB} = F_{AB} \cdot \dot{Q}_{A} \tag{4}$$

With regard to equations (3) and (4), the net heat transfer from surface can thus be increased in several ways: Increase in emissivity, surface area (design and package restrictions), temperature (safety for touchable surfaces) and increase of the view factor for surface A to B.

An increase in emissivity can be achieved by choice of material and production process, although most plastic materials already show high emissivity, thus only offering minor potential of improvement. The surface area can be increased, but has to fulfill safety (visibility) and package constrictions and will be part of the design process. While an increase in temperature shows high potential (cf. equation (3)), it is restricted to safety reasons, e.g. based on [10]. Especially the view factor is important to consider as it describes the portion of heat that is emitted towards the target surface as shown in Figure 1 and thus increasing the efficiency.

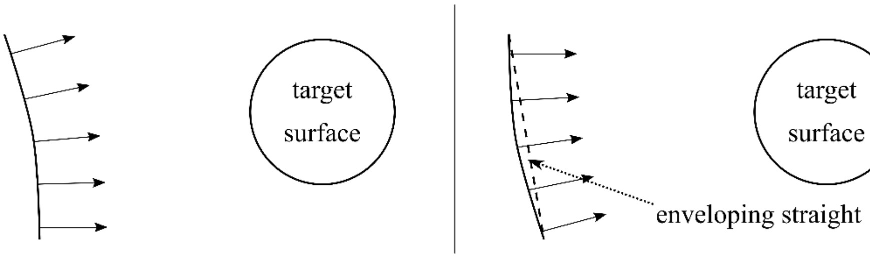

Fig. 1. Representation of convex and concave emitting surfaces.

As can be seen in Figure 1, concave surfaces offer the possibility to increase the view factor. Additionally, the view factor for the original surface (black line) and the enveloping straight result in the same view factor towards the target surface. This relation reduces the number of iterations in search for an efficient panel orientation and position, as only enveloping straights have to be considered. For the design process, a set of parameters describing the possible heating panel positions and orientations as well as feasible target surfaces have to be identified. While the former is mainly based on available surfaces and functional integration, the latter is based on a thermal comfort model with local resolution, [11]. In order to achieve a high impact via the radiative heating panels and allow for a reduction of the air temperature, target surfaces are defined on body parts sensitive for warm sensation. The areas for this study are based on the thermal comfort model in [11] and are listed in Table 1.

Table 1. Body parts selected as target surfaces.

selected body segments
head
neck
chest
upper arms
forearms
lower legs
feet

In order to reduce the degrees of freedom and parameters for a three-dimensional design, a series of principal design studies is conducted in two-dimensional planes. Figure 2 shows an example of such a design plane as a slice from a three-dimensional interior model. Panel enveloping straights, which can be manipulated in position, size and orientation, are depicted in red, a target surface for the head and shoulder region is depicted as well.

STAR-CCM+ and Optimate are used to investigate the potential heating panel designs and calculate the resulting view factors. In a finale step, the best results from the two-dimensional considerations are combined to a three-dimensional design, which can then be further detailed, e.g. as a concave surface to increase the emitting area. This design process has been used in the OPTEMUS project, results of which will be presented in the following.

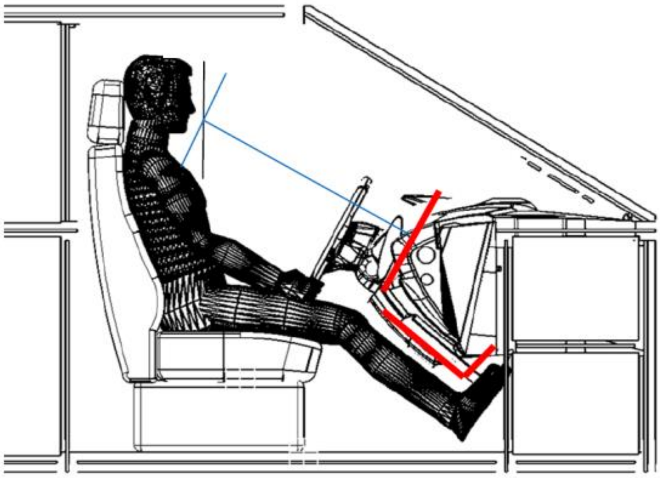

Fig. 2. Two-dimensional design space with panel enveloping straights (red) and target surface.

4 Radiative Heating Panels in OPTEMUS

The OPTEMUS (Optimised energy management and use) aims at increasing the electric range for a class A vehicle, amongst others by the use of electrical surface heating panels. Figure 2 shows the base areas, which have been considered for heating panel integration, and relevant areas for head impact. Especially the dashboard area on the passenger side is relevant for head impact investigations as shown in [12].

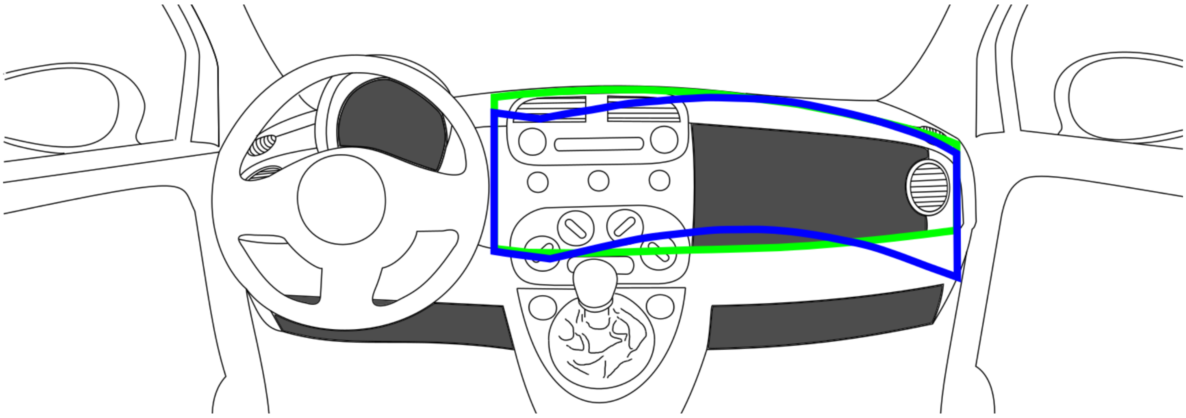

Fig. 3. Base areas for the OPTEMUS project (dark grey) and areas relevant for head impact (green: FVMSS-201, blue: ECE-R21) in a Fiat 500.

The process as described in chapter 3 has been used in order to design a radiative heating system for a Fiat 500, which simultaneously increases efficiency while heating the cabin and reduces the amount of time needed to reach acceptable thermal comfort based on the Predicted Mean Vote (PMV = 0). This newly designed radiative heating system has been implemented in a Fiat 500 alongside the convective heating system (“combined system”) and compared to a conventional convective heating system (“conventional system”), both in objective as well as subjective testing. The goal of these measurements is to replicate the measured comfort of the conventional system with the combined system, while measuring the energy demand for the heating system.

Table 2 shows the boundary conditions for these measurements. Objective comfort measurements have been used to achieve a similar behavior of the combined system compared to the conventional system. Additional information regarding the measurement setup is given in [12].

Table 2. Boundary conditions for comparison between conventional and combined heating system.

parameter	*conventional*	*combined*
ambient temperature	-10 °C	
power level surface heating (0 to 5)	0	5
blower level (0 to 5)	4	3
position air flap	100 % ambient air	
air distribution		

The measured comfort is depicted in Figure 4 (thick graphs). Since the PMV scale is limited to the range of -3 to 3, the measured comfort only increases after approx. 15 minutes, with a 3 minute benefit for the combined system. Afterwards, the combined system also shows a steeper comfort slope, increasing the temporal advantage of the combined system compared to the conventional system.

Subjective ratings are conducted for this setup as well. The offset to the measurements is noticeable, especially as the ratings start higher than the scales lower limit. This is to be explained by the expectance of worsening conditions and the tendency to avoid extreme ratings. The graphs are thus shifted compared to the measured thermal comfort. Additionally, as the PMV is by definition limited to quasi-stationary and uniform conditions, but widely used in the automotive industry (cf. [8]), thus damping the comfort measurements responses compared to the subjective ratings.

Nevertheless, the subjective ratings show a clear advantage of the combined system at approx. 5 to 10 minutes, as the radiative heat transfer with its lower thermal inertia already significantly heats the passengers and increases the comfort ratings by one unit, from “cool” to “slightly cool”.

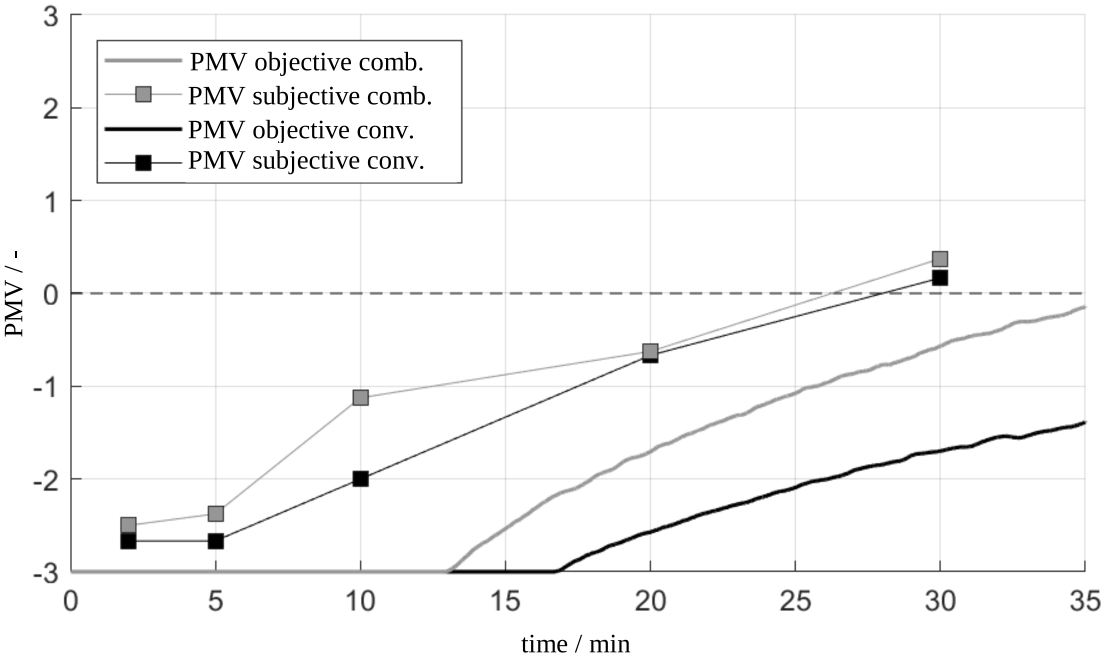

Fig. 4. Subjective ratings and objective measurements for the combined system (grey) and the convective system (black).

Additionally, the combined system shows an increased energy efficiency and performance (cf. Table 3), showing the reduced energy demand at increased comfort.

Table 3. Energy demand and time to comfort.

parameter	*conventional*	*combined*	*reduction*
energy demand to reach comfort (PMV = 0)	~ 6.3 kWh	~ 4.2 kWh	~ 33 %
time to reach comfort (PMV = 0)	~ 54 min	~44 min	~ 18.5 %

5 Conclusion

In this paper, a design process for a supplementary radiative heating system and results from measurement for such a combined convective and radiative system. The design process is based on the radiative heat transfer fundamentals and is thus applicable to a variety of applications. Additionally, by the reduction to two-dimensional considerations, the number of considered designs can be increased significantly, allowing the integration of the heating surfaces into the design of the vehicle cabin at a later stage.

Such a heating system has been designed for a class A vehicle at ika, showing promising results both in objective measurements as well as subjective ratings. Both subjective and objective comfort assessments show a faster response for the combination of radiative and convective systems with a significant reduction of the energy demand to reach comfort (approx. 33 %), resulting in an increased electrical range of the vehicle.

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