Concepts for Comfortable Air-Conditioning – Simulation Using a Zonal Cabin Model and a Metrological Evaluation Based on Equivalent Temperature

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Abstract. In the design of future electric vehicles, the air conditioning of the passenger compartment is considered as the largest auxiliary consumer. To test new climate control concepts and quantify their effectiveness in terms of user acceptance, energy efficiency and driving range, corresponding methods and tools are needed. This includes the numerical, experimental and subject-supported study regarding human thermal comfort.

New developed zonal models simulate air flow and temperature, surface temperature, pressure and also humidity in a closed environment. Predicting indoor environmental conditions in vehicle cabin is achieved in transient inhomogeneous load cases. With the combination of a radiation model, the long-wave radiation exchange between human and cabin is included in the heat balance equation with a high level of detail.

In order to improve the assessment of the local thermal conditions near the passenger, a climate measurement system (DressMAN 2.0) was developed by the Fraunhofer Institute for Building Physics (IBP). Using dedicated controllers and sensor devices the DressMAN is able to measure equivalent temperature on local segments for evaluation according to DIN EN ISO 14505-2. Based on these methods novel and existing concepts for heating have been tested with subjects in a cabin mock-up. The experiments used simulation-based methods and local climate measurement devices to compare and evaluate different climate control concepts.

Keywords: Vehicle air conditioning · Equivalent temperature sensor · Virtual test environment · Cabin mock-up · Zonal simulation model

1 Introduction

One of the challenges in the development of future electrical vehicle is to achieve an equivalent or higher level of thermal comfort and energy efficiency compared to hybrid vehicles or internal combustion engine driven vehicles. In case of combustion engine driven vehicles the inefficiency of the combustion engine offers an efficient way of

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conditioning the cabin. The waste heat from the engine could be used to heat-up the cabin and the mechanical drive from the engine could be used to drive the air-conditioning system. On the other hand in case of an electrical vehicle the efficient electric motors generate hardly any waste heat to heat-up the cabin. The mechanical drive to run the compressor is not available in an electric vehicle although the air conditioning system compressor can be powered electrically - but powering a conventional air conditioning compressor (3–5 kW) is not the most energy efficient way of climatizing, e.g. when a typical electrical vehicle consumes only 120 Wh/km [1]. Thus the use of conventional air-conditioning systems will inevitably lead to a reduction of the driving range, especially under cold outdoor conditions.

One of the solutions is the targeted use of local and close to the body climate control measures, which make it possible to increase the subjective feeling of passengers comfort. These measures should be distinguished through a direct effectiveness on the climate comfort with minimal energy consumption. The local (close to body) climate control concepts considering the human body energy balance and thermal regulation mechanism have an effect on the local and global temperature sensation and feeling of comfort.

In order to assess this potential of local climate control concept, both indoor environmental measurements and numerical evaluation methods were investigated. Subsequently four different types of local climate control measures have been examined in a vehicle mock-up and the evaluated results from measurements and numerical methods were compared to subject responses with respect to local thermal sensation and comfort perception.

2 Methodology

2.1 Comfort Measurement Using Equivalent Temperature

To determine the thermal comfort in vehicles, individual parameters of the cabin such as air temperature, air velocity and thermal radiation are often measured to detect the effect of changes in the climate design of the vehicle. Different manifestations of individual parameters can have adverse effects on each other, so that overall assessment of thermal comfort is not feasible. It would therefore be desirable to provide a measuring method by which the resulting effect of all climate parameters can be read from a single integral value. Because of the thermal inhomogeneity in a passenger compartment, for example, due to hot surfaces or strong incident airflow, locally different conditions have to be considered and identified.

The essential technical measurable parameters for assessing the expected thermal sensation of humans are in this case convection (depends on air temperature and air velocity) long wave radiation (depends on temperature of enclosed surfaces and the geometry of enclosure) and an impingement of short wave radiation due to sunlight. To research and evaluate indoor climate so called thermal manikins are utilized. Besides being expensive to procure and maintain, these manikins cannot be configured flexibly to yield a higher measurement resolution for critical zones.

As part of a research project, a comfort sensor has been developed which enables the measurement of equivalent temperatures (see Fig. 1) [2]. The equivalent temperature defined in DIN EN ISO 14505-2 [3] summarizes variables like air temperature, air velocity and thermal radiation, which determine thermal comfort, into one climate index. With the equivalent temperature as climate index, thermal environmental conditions can be described with only one numerical value, which allows a comparative evaluation of different climate scenarios. This applies even if the effects of the various individual parameters are compensated or enhanced. It is assumed that the same equivalent temperature values yield the same effect on humans with respect to the dry heat exchange between body surface and its surroundings.

Fig. 1. Equivalent temperature sensor and system software of DressMAN 2.0

A novel equivalent temperature sensor has been developed by the Fraunhofer IBP and integrated to the DressMAN 2.0 system. Measured local equivalent temperatures can be linked to comfort ratings in accordance with DIN EN ISO14505-2. To be able to detect also locally prevailing factors influencing the thermal sensation, commercially available sensors for air temperature and air velocity are provided.

2.2 Numerical Evaluation Based on Zonal Cabin Models and Manikin Models

For capturing the impact of various climate measures on humans, a computational analysis was conducted parallel to the empirical studies. To avoid long computation times of computational fluid dynamics (CFD), the VEPZO model (VElocity Propagating ZOnal Model) is implemented in Modelica [4]. The zonal modelling approach is an intermediate approach between CFD and a single node modeling. The zonal models provide a better resolution of airflow distribution in an enclosure than the perfectly mixed air volume of nodal models. A VEPZO model typically subdivides a room into 10^1-10^2 zones. In the zones, the conservation of mass and enthalpy are implemented. The VEPZO model is using the airflow velocity as a property of a zone and a viscous loss model in order to better match the physics of airflows. This allows a rapid prediction of local temperature distributions considering the location and intensity of heat sources and air vents. As an extension of the VEPZO model, the RADZO model has been developed which is able to calculate the heat radiation on the zonal grid [5]. In addition, the Thermal Model Generation Tool has been developed to automatically build up a VEPZO model, thermal enclosure models and a RADZO model from a CAD geometry export. Space boundaries are subdivided into small areas in accordance with the zonal grid [6].

Zonal simulations predict the effect of cooling or heating surfaces on the air temperature distribution as well as their radiation effect. Local measures, such as radiant heating surfaces, can be evaluated for their energy efficiency as well as their influence on passenger comfort.

For evaluating the thermal comfort in a vehicle, geometric models of the cabin surroundings and of the human body are needed. For this purpose, a vehicle mock-up was modelled for zonal simulation. In addition, a virtual manikin with ten body segments was implemented in the thermal vehicle model to numerically predict the thermal comfort. The view factors of local body segments were determined for the surrounding cabin and for all body segments involved in radiant heat exchange. The view factors determine the thermal influence of temperatures enclosing inner surfaces on the manikin and thus serve alongside the surface temperature and emissivity of the surrounding surfaces as an output variable for calculating the radiation heat exchange between the local body segments and the environment.

While the view factors strongly affect the radiative heat exchange, the convective heat transfer coefficient of the local body segments together with the local air temperature determine the convective heat exchange. The coefficients were determined in this study as a function of the air velocity at the ventilation outlets through CFD and segmentally transferred to the zonal model (Fig. 2).

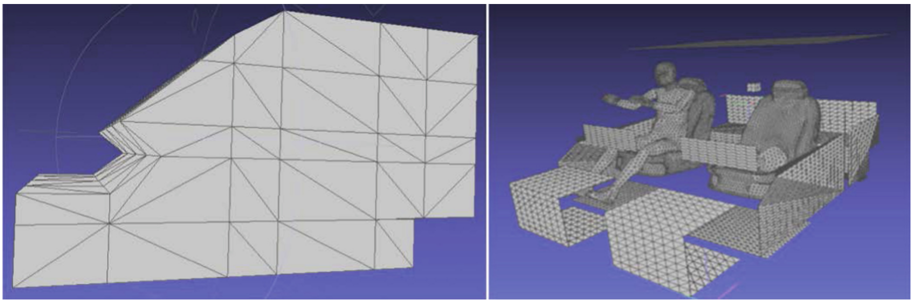

Fig. 2. Zonal geometry and virtual manikin with heating segments in the cabin mock-up model

3 Experimental Study in a Vehicle Mock-up

3.1 Vehicle Mock-up

The vehicle mock-up at Fraunhofer IBP is generic mock-up made of wood and plexiglas, thus enabling a vendor neutral form with defined geometry and a high level of flexibility in the creation of new surface heating and cooling systems. Thus, both the heating of the cabin via electrical heating foils, as well as the cooling of the cabin via a secondary refrigerant circuit are possible. For the control system, the internal surfaces were divided into 11 different segments like door, floor, roof, footwell, dashboard, etc. The volumetric air flow rate can be varied in four stages. The ventilation air is exhausted from two openings in the rear shelf.

In the passenger compartment, two conventional vehicle seats are installed in beige fabric. A seat heater with flexible control of heat flow or the contact surface temperature was fabricated.

A total of 37 PT100 sensors were installed in the interior for measurement of air and surface temperatures. In addition, six sensors were attached to the outer surfaces of the mock-up. In support, the air velocities in the vehicle cabin and the heat flow on the seat were measured. The climate measuring system DressMAN 2.0 is used for the measurements of temporary cabin climate states.

3.2 Test Design for Experimental Study

In test conditions with subjects, the different climate measures were implemented with different proportions to convective-heating, radiation-heating and seat heating in the vehicle mock-up and evaluated energetically and climatically. In all test cases, an equivalent cabin climate was targeted to make the resulting energy consumption and comfort evaluation comparable. Five climate measures with different proportions to convective, radiative and seat heating were evaluated energetically and climatically in several test runs (Fig. 3). The reference cabin climate was an acceptable climate for the driver in winter, which means that the subjects on the driver's seat should assess the indoor climate in the vehicle cabin between a bit cool to neutral and rate it as acceptable.

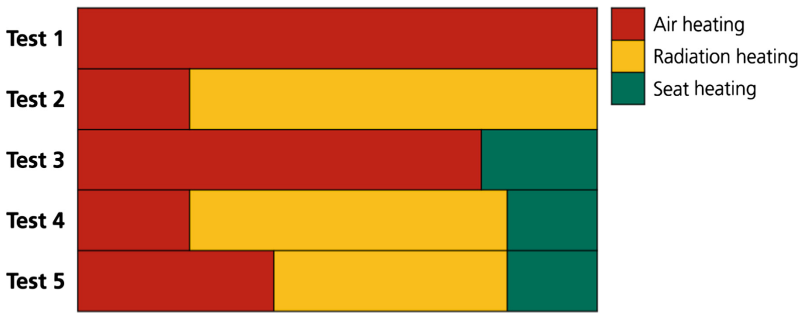

Fig. 3. Schematic representation of the proportions of different heating systems used in the test design, Test 1: reference system

3.3 Execution of the Tests in the Vehicle Mock-up

The experiments were conducted over a five days period in the vehicle mock-up at the Fraunhofer IBP in Holzkirchen. Every day a different climate control measure was tested. The outer boundary condition of the vehicle mock-up for all tests was held constant at 7 °C. For stable indoor climate conditions, the climate chamber and the vehicle mock-up were conditioned four hours before the tests started. For the study, 10 to 12 people between 25 and 32 years of age participated. The proportion of women was 25%. On all tests, the same participants attended to better asses the difference in the boundary conditions.

The participants were wearing individual but the same clothing in five trials according to the instructions on the clothing insulation value (about 1.0 clo). They stayed for 20 min for acclimatization in a room. There was only one person in the vehicle mock-up per trial. In order to have the activity level of a participant similar to the activity level of driving (1.2 met, 70 W/m^2), the participants had to steer in a driving simulator. Subsequently, the participants evaluated the indoor climate by means of electronic questionnaires, in which the complete thermal sensation, the overall comfort, the local feeling as well as the local discomfort were requested.

4 Results

4.1 Evaluation Using DressMAN 2.0 Measurement

Figure 5 shows the results of the DressMAN 2.0 measurement on all local body segments. For comparison, the air temperature measurements are shown for two height levels in degrees Celsius during the experiments in the cabin mock-up (Fig. 4).

The air temperature varied within 2 K at 0.1 m during test 2, which suggests a variable boundary condition and correspondingly different thermal perceptions within one experiment. In exception to test 2, the other four studies showed stable thermal boundary conditions in all trials. The thermal evaluation of the subjects can thus be compared well with one another and a further analysis with mean values is possible, while the mean value of test 2 should be considered carefully.

The temperature variation of test 2 during the experiment impacts also the subject comfort evaluation. The overall thermal sensation votes of test 2 varied from slightly cool to slightly warm in the range of two scale points, while other tests showed mainly variation of only one scale point. According to the comfort assessments, the condition in Test 5 with a combination of air-, radiation- and seat heating system yields the highest satisfaction of subjects (Fig. 5).

While the air temperature reaches the required 21 °C at 1.1 m in test 1 (air heating), the equivalent temperature is shown at almost all body segments below 20 ° C, which indicates increased air velocity and thus increased convective heat loss. In particular, the equivalent temperature in the footwell is exceeding largely the temperature range, at least 22.3 °C are recommended in DIN EN ISO 14505-2 (see Fig. 6).

If the temperature profile in the vehicle mock-up is taken into account during convective heating, the set temperature should not be 21 °C at 1.1 m but above 24 °C in order to meet the required temperature in the footwell. The air heating systems (Test 1 and Test 3) show few variations between local segments as opposed to radiant heaters (Test 2, 4, 5), where the left hand and the foot-well are much warmer than the other body segments due to the asymmetrical panel heating (left door and foot well).

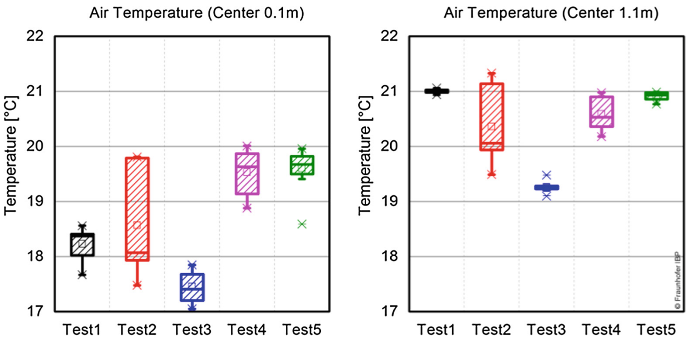

Fig. 4. Box plot of the room air temperature in the middle of the vehicle mock-up in five trials at a height of 0.1 m and 1.1 m (large box with strips: 25%–75% range, small box within large box: mean value).

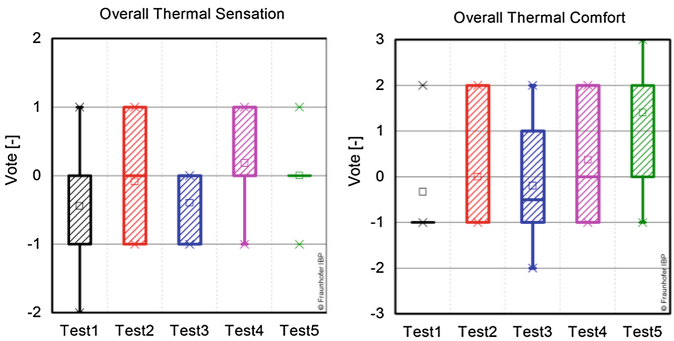

Fig. 5. Subject assessment: overall thermal sensation (1: slightly warm, 0: neutral, −1: slightly cool); overall thermal comfort (3: satisfied, −3; dissatisfied)

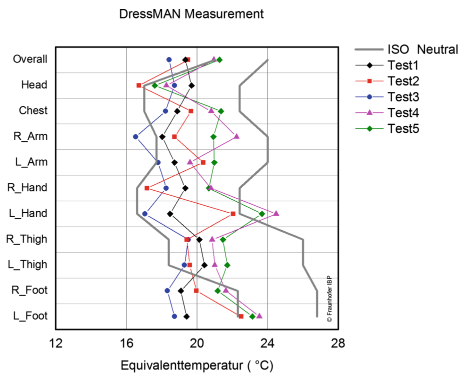

Fig. 6. Local thermal sensation of the five climate control concepts using the DressMAN 2.0 measurement; ISO neutral: Comfortable area according to DIN EN ISO 14505-2.

The total equivalent temperature, which in this study is area-weighted by local equivalent temperatures, meets the requirement of DIN EN ISO 14505-2 only for test 5, whereby test 4 misses the requirement only closely. No measurement was performed on the seat and back during the DressMAN measurement. Therefore, the examined local position varies from the participant's question.

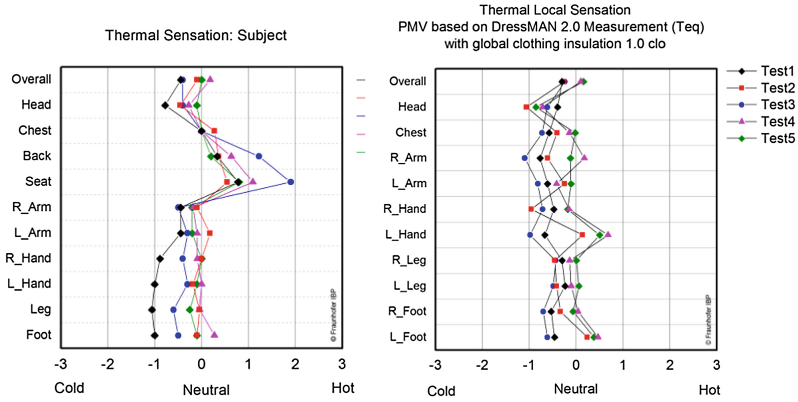

Fig. 7. Local thermal sensation of the five air-conditioning concepts based on the subject's evaluation and local PMV calculation from the equivalent temperature of DressMAN measurements with global clothing insulation values

4.2 Comparison of Subject Responses with Numerical Models and Measurements

Figures 6 and 7 show the local thermal sensation in five tests with different evaluation methods; subject evaluation, evaluation using DressMAN 2.0 measurement and numerical evaluation.

Since the DIN EN ISO 14505-2 does not provide a quantitative evaluation option but only a qualitative evaluation (comfortable or not), the results of the measurement (equivalent temperature) of DressMAN 2.0 were transferred to a predicted mean vote (PMV) calculation based on local heat exchange and quantified. There was a strong influence of the local clothing insulation values on the local heat balance. The uncovered parts of the body, such as the head and hands, are rated very cold, while the body parts with high insulation values such as the chest and back are rated slightly warm in all the tests.

In order to reduce the influence of local clothing insulation values, evaluations with uniform clothing insulation values of 1.0 clo were carried out. This resulted in a reduced variation between local segments. The contact heat transfer between the seat and manikin was additionally taken into account for all evaluations. If the driver's seat (0.26 clo) is taken into account for the clothing insulation value, which would be correct for the heat balance evaluation according to the literature in [7, 8], all ratings are moved by 0.4 in the direction of the warm area in the right figure of Fig. 8.

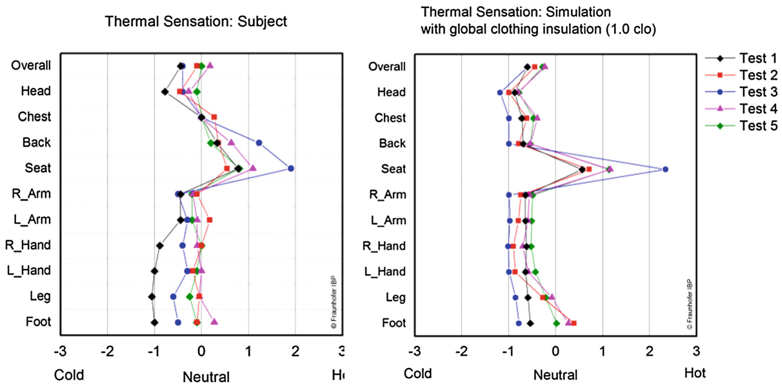

Fig. 8. Local thermal sensation of the five air-conditioning concepts based on the subject's evaluation and Thermal local sensation of the five air-conditioning concepts according to the numerical evaluation.

According to the subject evaluations, the climate control measures dominated by air heating (Test 1 and Test 3) show a strong difference in the leg area compared to other solutions. In Test 1, the leg area, hands and head are rated "slightly cool". Interestingly, in Test 3, where a strong seat heating is used and the air temperature is almost 2 K and the equivalent temperature 1 K lower than in Test 1, all local segments are judged to be a bit warmer than in Test 1. The radiant heating of the footwell and that of the left door in test 2, 4 and 5 has a significant effect on the leg area as desired.

Regardless of the application of the seat heating, the seat contact surfaces and the back have always been rated as slightly warm or warm. These results are reproducible because the questionnaires were only carried out after 20 min and thus the strong heat loss from the body to the seat through heat conduction faded. If the proportion of the air heating is increased compared to the radiant heating, the evaluation in the head area (test 5 compared to test 2) improves. The evaluation in the upper body area hardly differed in all experiments; especially the chest was always rated as "neutral".

Comparing all evaluations, the DressMAN measurements show better agreement with subject responses than the simulation result. All PMV ratings based on the heat balance calculation and the DressMAN measurement show a slight deviation of 0.2 on the ASHRAE scale [9] (7-point scale from cold (−3) to hot (+3)) compared to subject questionnaires. The simulation always evaluates a little cooler from 0.2 to 0.4 points on the ASHRAE scale. The deviations are more prevalent in trials with radiant heating than in trials with air heating.

Although the difference of thermal evaluation between individual participants was not high, being −0.4 to 0.2 on the ASHRAE scale, the simulation model was still able to predict the order of thermal sensation votes of the test boundary conditions. A 0.1 ASHRAE scale difference correlates to approx. 0.5 K operative temperature difference by near to neutral (neither cold nor warm) indoor environment with normal indoor winter clothing (1.0 clo). The local equivalent temperature measurements as well as the thermal computational simulation seem to be well suited for the evaluation of the cabin environment even for local measures close to the body (Fig. 9).

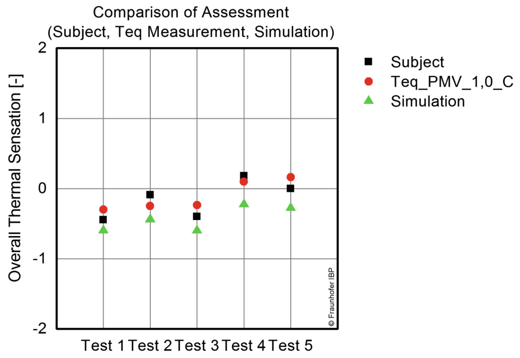

Fig. 9. Comparison of evaluation methods for thermal overall temperature sensation (Test: Thermal, average overall feeling of participants, Teq_PMV_C: PMV calculation based on DressMAN measurement taking into account the heat flow on the seat).

4.3 Evaluation of Energy Demand

Since the measured energy consumption of the vehicle mock-up in the air heating system was strongly dependent on the efficiency of the fan and the thermal perceptions were not identical in all experiments, the energy efficiency between test variants was evaluated by the simulation.

According to the simulation results Fig. 10, the reference system (pure air heating, test 1) consumes more energy compared to other climate control concepts in order to achieve similar thermal sensation. A seat heating (test 3) will effectively reduce the energy requirement, if real subjects' local perception is ignored and only the heat balance of the manikin is considered. Although the conduction heating is most effective for the heat balance of a human, a powerful seat heating like test 3 will cause high local discomfort in real tests. The powerful radiant heating and weak air heating (test 2) is

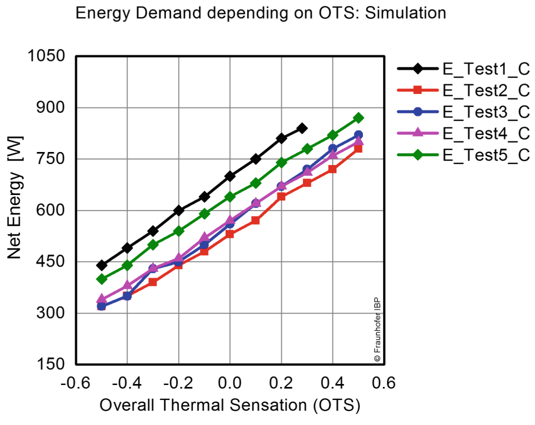

Fig. 10. Comparison of energy demand depending on the predicted thermal sensation for different climate control concepts (simulation results)

even more effective than the combination of air and seat heating (test 3). The greater the proportion of radiant heating, the lower the energy demand for the vehicle mock-up is.

According to the results of the numerical evaluation, a climate control concept which is local and close to the body can reduce the net energy demand compared to the pure air heating system. The concept study in test 2 with strong radiant heating showed a 24% lower energy demand, test 5 with air, radiation, and seat heating resulted in a reduction of 9%.

5 Conclusion and Outlook

We investigated the potentials of local climate control concepts in experimental studies. Given detailed evaluations from subjects on local thermal sensation and overall comfort, the ratings are compared with measurements of equivalent temperatures and with numerical results from refined numerical simulation models.

The results of the study show that the local, near-body climate control measures are more energy-efficient and more comfortable than conventional heating systems in the vehicle. For this purpose, the applied assessment methods, namely a local, directed equivalent temperature measurement and the thermal comfort simulations, have a good suitability for the evaluation of cabin climate control systems (also in the case of local and near-body measures).

It can be concluded, that any local discomfort should be avoided for a high comfort in vehicle cabin. In the case of air heating, the foot area represents a discomfort zone, while the head was perceived to be too cold during the air conditioning with a high proportion of radiation. Only a combination of conventional air heating, as well as radiation and seat heating can provide a homogeneous thermal perception (non-homogeneous temperature) in a vehicle cabin and thus high comfort. As already shown in previous studies, it is affirmed that locally warmer climate in the foot region and a colder area in the region of the head of subjects are preferred. The conventional air heating in the vehicle cannot produce such optimal local boundary conditions. Thus a different climate control concept is required for a high degree of comfort. The energetic and cabin climatic evaluation of the local climate control measures in the real vehicle may differ from existing results, since the vehicle mock-up has other insulation and hermetical properties to a real vehicle. Nevertheless, this study shows the potential of the near-body measures in the vehicle as well as the assessment methods of such measures.

With the combination of measurement and simulation data, it is now possible to thoroughly test new architectures for innovative thermal management. The aim is to minimize the risks of design and configuration in vehicle air conditioning at an early stage. After having invested in establishing a virtual test environment, the study showed that costs for developing and testing novel concepts are minimized and evaluation of solutions is less time-consuming.

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