Title
Virtual thermal comfort engineering

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Publication Date
2001

**SAE TECHNICAL
PAPER SERIES**

2001-01-0588

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Printed in USA

2001-01-0588

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ABSTRACT

Simulation of passenger compartment climatic conditions is becoming increasingly important as a complement to wind tunnel and field testing to help achieve improved thermal comfort while reducing vehicle development time and cost. Delphi Harrison Thermal Systems has collaborated with the University of California, Berkeley to develop the capability of predicting occupant thermal comfort to support automotive climate control systems. At the core of this Virtual Thermal Comfort Engineering (VTCE) technique is a model of the human thermal regulatory system based on Stolwijk's model but with several enhancements. Our model uses 16 body segments and each segment is modeled as four body layers (core, muscle, fat, and skin tissues) and a clothing layer. The comfort model has the ability to predict local thermal comfort level of an occupant in a highly non-uniform thermal environment as a function of air temperature, surrounding surface temperatures, air velocity, humidity, direct solar flux, as well as the level of activity and clothing type of each individual. VTCE takes into account the geometrical configuration of the passenger compartment including glazing surfaces, pertinent physical and thermal properties of the enclosure with particular emphasis on glass properties. Use of Virtual Thermal Comfort Engineering (VTCE) will allow for exploration of different climate control strategies as they relate to human thermal comfort in a quick and inexpensive manner.

INTRODUCTION

Thermal comfort is an important concern for occupants in an enclosed environment such as the passenger compartment of a vehicle. However, the tendency to use more glass in vehicle styling, tightening fuel-economy constraints, changing to environmentally safe refrigerants and reduced condenser air flow, particularly at idle, hampers achieving occupant thermal comfort. In order to counter these challenges, reducing the heat loads that enter passenger compartments has become an important issue in the early stage of vehicle design. Since HVAC system capacity can not continue to increase at the rate glass area is increasing, it has become necessary to develop tools that can predict the impact of various design choices on passenger thermal comfort early in the design process. Thermal comfort is the ultimate goal of HVAC systems for vehicles. However, assessment of the thermal comfort in a vehicle is very complex due to fast transient behaviors of soak and cool-down, and also highly asymmetric thermal environments associated with highly non-uniform air velocity and temperature distribution, localized solar flux, and radiation heat load from the windshield and instrument panels. Analysis tools for the temperature and velocity distributions in passenger compartments coupled with the thermal comfort predictions can guide design directions during the early stage of vehicle development process [1,2].

Virtual Thermal Comfort Engineering has been developed jointly with UC Berkeley to predict the passenger compartment thermal environment and passenger thermal comfort. This present paper describes basic methods of VTCE and demonstrates the capabilities including the effects of solar load for various solar incidence angles, glass properties, and also surrounding radiation heat, air velocity magnitude, and air temperatures on the thermal comfort of the occupants in a simplified passenger compartment. In the vehicle environment, many of these parameters are dependent on each other and the relationship among them is complex and not known exactly. This makes an experimental parametric study a nearly impossible task. However, with VTCE tools, these parameters under investigations can be analyzed very easily so that it is possible to vary only one parameter without influencing other parameters. The elements of VTCE process, as shown in Figure 1, will be described in the following sections.

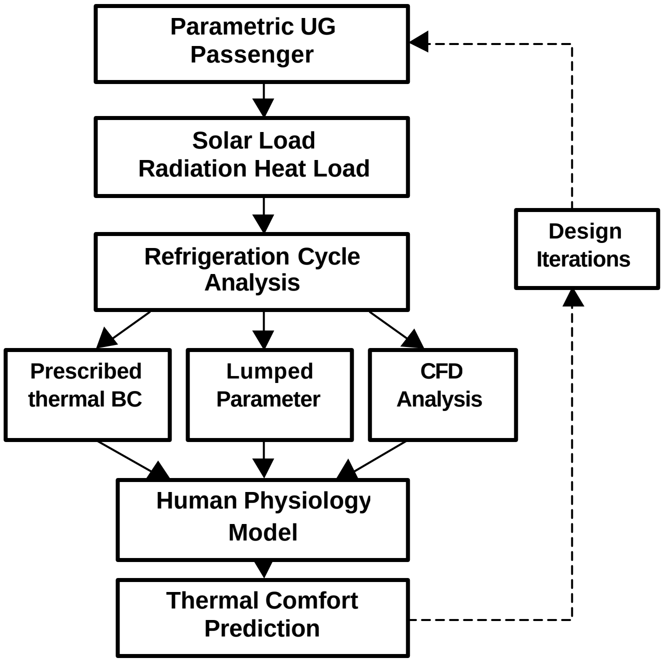


Figure 1. Schematic of Virtual Thermal Comfort Engineering Process

VIRTUAL THERMAL COMFORT ENGINEERING

PARAMETRIC UG MODEL

The geometry of the passenger compartment is controlled by key design parameters that were carefully selected from early stage vehicle architectural design parameters. The parametric model can potentially cover a wide range of vehicle shapes and sizes for sedan types. The key design parameters, such as A/C outlet location and size, windshield angle, body vents location, and many other parameters can be varied easily to accommodate potential design changes. The creation of the parametric model requires careful planning for a sedan type topology that can cover a wide range of potential design changes with key design parameters and their interactions. Once these parametric models are available, the benefits of these parametric models are tremendous. Due to readily available water-tight surface geometry from these parametric solid models, the mesh generation time can be drastically reduced compared to the traditional CFD process. Due to the parametric solid model, the design iterations become trivial exercise. For example, the effect of solar load into the cabin for various windshield angles, shape, and orientations can be analyzed very easily. The following parametric model, as shown in Figure 2, for a sedan type has been developed by collaboration with GM NAO Car group.

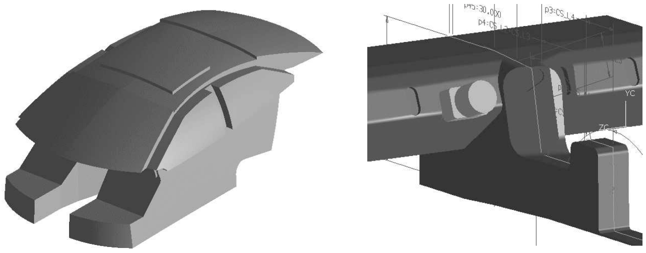


Figure 2. Parametric solid model representation of a sedan

SOLAR LOAD PREDICTION

The solar load on the vehicle compartment is dependent on glass properties, solar incidence angle, and incident solar spectrum. The absorptivity, transmissivity, and the reflectivity of the glass vary depending on the incident angle of the sun and the wavelength distribution of the incident radiation. A solar load program [3] that considers these effects has been integrated into VTCE. Similar capability will be also available in FLUENT CFD code as a result of joint collaboration between Delphi and GM. The solar intensity varies depending on the time, date, location, and vehicle orientation. The overall solar intensity can be obtained from the NREL's SOLPOS code [4] and NREL's hourly solar database. The solar load through the glass into the passenger compartment was modeled by separating the heat flux into short-wave and long-wave radiation. Short-wave radiation is absorbed based on skin or clothing absorptance and long-wave radiation is absorbed based on the skin or clothing emittance. The solar load program keeps track of the reflection from the glass, absorption by the glass, transmission into the cabin, and also incident radiation on the occupants in the cabin. The amount of solar load absorbed by the occupant influences the thermal comfort of the occupant by increasing clothing and skin temperatures. A database of various automotive glass properties has been incorporated and the effect of solar absorbing and reflecting automotive glasses on thermal comfort can be assessed.

RADIATION HEAT LOAD

Radiant heat exchange occurs between the occupant and its surroundings. During a vehicle cool-down or warm-up process, the radiation heat load has as great an influence as the air temperature on the occupant thermal comfort. Radiation heat transfer can be calculated using a linearized model based on mean radiant temperature (MRT) specified for each body segment or using an explicit model using the Stefan-

Boltzmann law. Using a realistic 3-D model of the occupant, we calculate shape factors between each of the 5000 polygons that define the body geometry and any arbitrary set of environmental surfaces. Each of these environmental surfaces is described by its position, surface area, temperature and emittance. This method is significantly more accurate than the MRT approach for non-uniform environments [5]. The heat gain/loss by radiation from the occupant is computed using view factors between the occupant and the surrounding interior surfaces. View factors between 16 body segments and the interior surfaces can be computed either from FLUENT code or an in-house radiation view-factor calculation program [3]. These view factors are very important to accurately assess the effect of radiation heat load on the thermal comfort.

REFRIGERATION CYCLE ANALYSIS

The system airflow rate and the discharge air temperature for cool-down and warm-up analysis can be specified from the A/C system simulation code [6]. The system airflow rate and the discharge air temperature at A/C outlets and heater outlets provide the boundary condition for the lumped parameter model and also for CFD analysis of passenger compartment.

CABIN THERMAL ENVIRONMENT

The cabin thermal environment can be either prescribed from tunnel data or can be computed directly with a lumped parameter model or with CFD. Each method has it's own merits and has various levels of approximations associated with efforts to achieve more accurate simulations.

1. Prescribed Thermal Boundary Conditions

The transient history of the interior surface temperatures, air temperatures, and velocity magnitudes around the occupant can be specified from the tunnel test data. These boundary conditions can be specified either a tabular form or a functional form with a time constant. This approach is very attractive to assess the isolated effects of these variables on the thermal comfort without influencing other variables. A user-friendly graphical interface allows to specify various cabin thermal environment. In order predict cabin thermal environment, the following approaches are recommended.

2. Lumped Parameter Model

A simple lumped parameter model has been developed in-house with 12 lumped nodes that are distributed in the cabin. The transient response of the cabin thermal environment can be simulated with a prescribed air flow distribution. The air temperature and air velocity distributions around 16 body segments of the occupant in the cabin has been measured from the vehicle test with a manikin, as shown in Figure 3. These air temperatures and the velocity distributions around 16 body segments were linearly scaled with the system airflow rate and the discharge temperatures. This approach is useful during the early stage of vehicle development when the passenger compartment geometry is not available. In order to predict detailed airflow distribution in the cabin, CFD approach is recommended.

Figure 3. Vehicle test set up with a manikin

3. Computational Fluid Dynamics

The flow and temperature field in the passenger compartment is calculated with Fluent. The CFD compartment geometry is directly generated from our parametric UG model as shown in Figure 2. This geometry can be directly imported to Gambit, Fluent pre-processor, and the time and effort for preparation of clean surface geometry for 3-D mesh generation were drastically reduced.

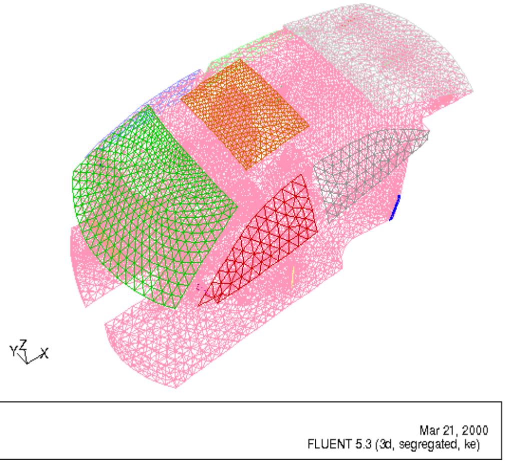


Figure 4. Passenger compartment mesh

For CFD analysis, as shown in Figure 4, the physical domain of the compartment is subdivided into finite volumes and the Reynolds-averaged Navier-Stokes equations are solved simultaneously with the conservation of energy equation to predict airflow, temperature, and humidity distribution around occupants. CFD approach provides detailed information for various airflow distributions in the cabin and also around the occupants. Figure 5 shows airflow distributions around the chest of the human body and path-lines from the A/C outlets.

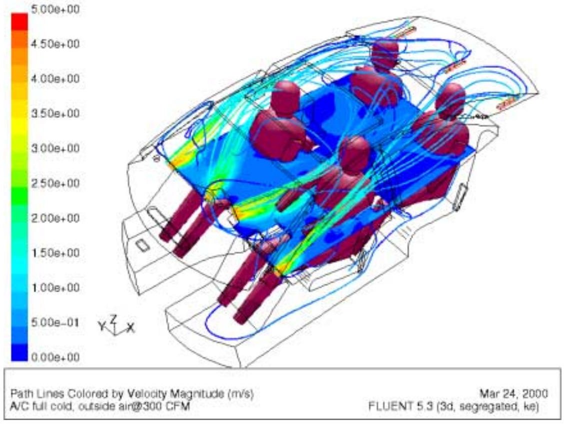


Figure 5. Passenger compartment CFD result at outside air mode.

Currently, FLUENT code exchange air temperatures and air velocity information around 16 body segments with the occupant body surface temperatures computed from UC Berkeley physiological model. Due to the limited space of the present paper, the details of validation and vehicle applications of the CFD analysis will be presented in our future paper.

PHYSIOLOGICAL MODEL

The Berkeley Comfort Model is based on the Stolwijk model [7] as well as on work by Tanabe [8], but includes several significant improvements over the Stolwijk model. The Stolwijk model is based on six body segments: head, torso, arms, hands, legs, and feet. The current Berkeley model can simulate an arbitrary number of segments. Each of these segments consists of four body layers (core, muscle, fat, and skin tissues) and a clothing layer. A separate series of nodes represent arteries and veins and provide for convective heat transfer between segments and tissue nodes and the countercurrent heat exchange between the arteries and the veins. The model computes heat transfer between each node using a standard finite-differencing algorithm with variable time-stepping to optimize computational resources while preserving numerical stability.

1. Segmentation

In the VTCE application, we use sixteen body segments, as shown in Figure 6a, corresponding directly to the UC Berkeley segmented thermal manikin [9]. The manikin can accurately measure heat transfer coefficients [10] and clothing insulation values for individual body parts, and we can then use these data directly in the comfort model. The radiative heat transfer is calculated by the view factors for 5000 polygons that defines the occupant 16 body segments, as shown in Figure 6b.

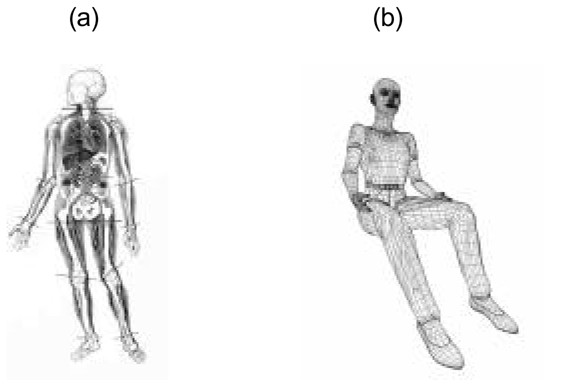


Figure 6 Typical segmentation used in the model are: head, chest, back, pelvis, right and left upper arms, right and left lower arms, right and left hands, right and left thighs, right and left lower legs, and right and left foot

2. Blood flow model

Human body thermal regulation is mainly achieved by regulating blood flow, so a realistic blood flow model is important for any dynamic model of human thermal comfort. It is by vasoconstriction and vasodilatation that the body regulates blood distribution in order to control skin temperature and increase or decrease heat loss to the environment. Veins and arteries are paired, even down to very small vessels, and veins carry heat from the arteries back to the core. This counter-current heat exchange, as shown in Figure 7, is a major process in decreasing heat loss and maintaining core temperature in cold environments. Nodes exchange heat with their adjacent nodes via conduction and as well as with blood flows.

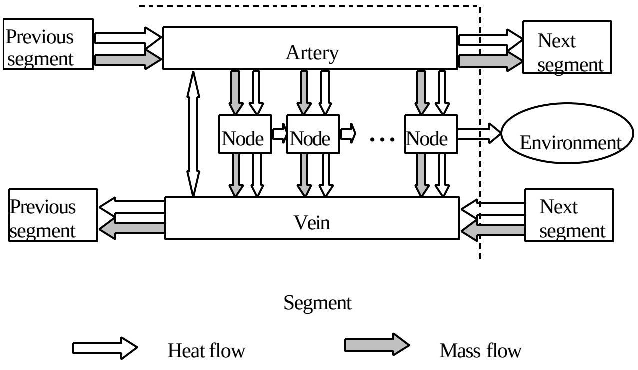


Figure 7. Segment blood flow model

3. Clothing Model

The current model includes a clothing node to model both heat and moisture capacitance of clothing. Heat capacity of the clothing has been demonstrated to be important when considering transient effects [11]. Moisture capacitance is important to correctly model evaporative heat loss from the body through clothing. The moisture model uses the regain approach [12] to calculate the amount of moisture that a specific fabric will absorb at a given relative humidity.

4. Contact surfaces

In almost any environment, the body is in contact with solid surfaces and loses heat via conduction. In the vehicle, the seat contacts a considerable fraction of the body and this must be considered to accurately model the occupant. The current model includes a contact surface for each segment. The thermal properties of the contact surface are used to simulate its surface temperature. Each body segment includes the fraction of exposed skin and clothed skin in contact with the surface.

5. Physiological variation

Human physiology varies significantly among individuals, and these differences can affect perceptions of thermal comfort; e.g., higher metabolic rate or increased body fat can cause people to feel warmer. Remarkably, comfort models have not generally considered such variation. The current model maps six descriptive characteristics of the human body (height, weight, age, gender, skin color, and body fat) to the physiological data used by the comfort model. The simulations show that a change in body fat from 14% to 28% can result in a skin temperature change of nearly 1°C.

VALIDATION OF PHYSIOLOGY MODEL

As an initial validation of the model, we compared simulated skin and core temperatures with a number of physiological studies [13,14,15]. These studies include several steady-state conditions and three transient environmental conditions. Werner performed 86 climatic chamber experiments with air temperatures ranging from 10°C to 50°C at 40% relative humidity. Comparison of the measured data from the above experiments and the simulated results from the current model are presented in Figure 8. Under steady-state conditions, the core temperature prediction is very close to the measured values (within 0.5°C) (Figure 8a). For most segments (Figure 8b and 8c), the skin temperature simulation is within 1°C. Adding the countercurrent blood flow model greatly improved the agreement between limb skin temperatures predicted by the current model and the experimental data. The current model validations show that the model is able to predict both core and extremity skin temperatures with reasonably accuracy under a range of environmental conditions. More detail validations for transient conditions can be found in [16].

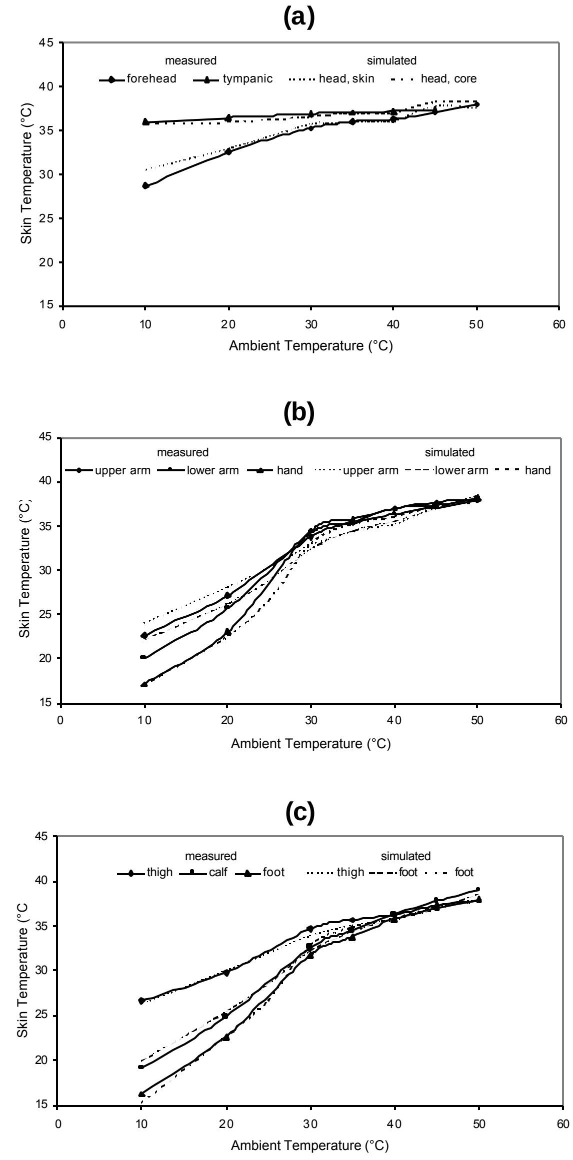


Figure. 8. Comparison of measured (Werner 1980) and simulated temperatures during steady-state conditions ranging from 10°C to 50°C. (a) Head skin and core. (b) Upper arm, lower arm and hand. (c) Thigh, calf and foot.

THERMAL COMFORT

The human sense of thermal comfort is very complex. It relates both the physiological and the psychological states of a person under specific conditions. The well known variable for estimating the global thermal comfort of persons is the PMV (Predicted Mean Vote) index introduced by Fanger [17]. However, for strongly inhomogeneous conditions such as a passenger compartment, PMV method may not be valid. Most well-validated models of predicted subjective response [17,18] are limited to uniform thermal environments. Bohm accepted the 'Equivalent Homogenous Temperature' (EHT) proposed by Wyon [19] for assessing non-uniform environments and developed limits [20]. We calculate EHT for each body segment and generate a diagram plotting these within limits established for segments by Bohm as shown in Figure 11. A statistically determined comfort range between the cold and warm borderline indicated as bold lines for 16 body segments, in which 90% of the people would feel comfortable. More research is required to develop a whole-body comfort index for non-uniform environments in transient conditions.

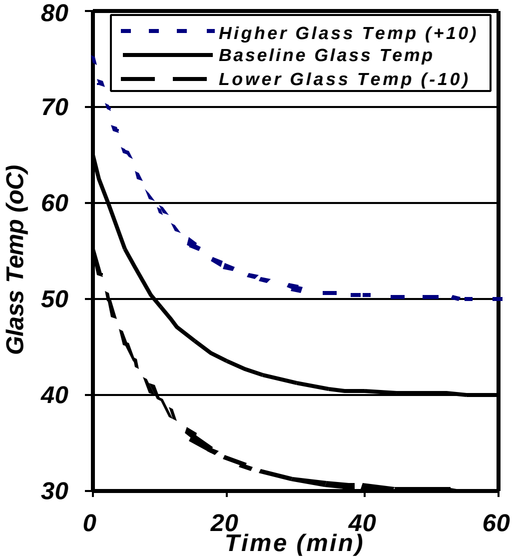


Figure 9. Glass temperatures for 3 different test cases

RESULTS

In the present study, we tested the model for various thermal environments on a simplified solar buck [21]. The comfort simulator can be easily set up for the following test cases, as shown in Table 1. The interior and other thermal boundary conditions for surface temperatures and glass temperatures were specified as a simple decay function with a time constant for a hot soak and cool-down simulations, as shown in Figure 9. The baseline test case are defined in Table 1, and a standard Stolwijk model are specified for the human physiology with a metabolic rate of 60 w/m^2 and a standard summer clothing was specified for a soak and cool-down simulation. Each simulation cases as listed in Table 1, only one parameter was varied to avoid the effects of coupling with multiple parameters.

Table 1. Test cases for a solar buck

Simulation cases	Air Velocity (m/s)	Glass temp (^{o}C)	Interior temp (^{o}C)	Solar Angle	Glass Property	Humidity(%)
Baseline	0.2	65-40	60-30	(45,-45)	Ppg 7010	50
High Air Velocity	0.3	65-40	60-30	(45,-45)	Ppg 7010	50
Low Air Velocity	0.1	65-40	60-30	(45,-45)	Ppg 7010	50
Higher Glass Temp	0.2	75-50	60-30	(45,-45)	Ppg 7010	50
Lower Glass Temp	0.2	55-30	60-30	(45,-45)	Ppg 7010	50
Higher Interior Temp	0.2	65-40	70-40	(45,-45)	Ppg 7010	50
Lower Interior Temp	0.2	65-40	50-20	(45,-45)	Ppg 7010	50
Soft-ray glass	0.2	65-40	60-30	(45,-45)	Ppg soft-ray	50
Solar off	0.2	65-40	60-30	(45,-45)	Ppg 7010	50
High Noon Solar	0.2	65-40	60-30	(90,0)	Ppg 7010	50
Front Solar	0.2	65-40	60-30	(45,0)	Ppg 7010	50
Very Low Humidity	0.2	65-40	60-30	(45,-45)	Ppg 7010	5
Low Humidity	0.2	65-40	60-30	(45,-45)	Ppg 7010	25
High Humidity	0.2	65-40	60-30	(45,-45)	Ppg 7010	75

BASELINE

For the baseline case with solar incidence angle of 45 degrees Altitude and –45 degrees Azimuth, the computed solar load distribution inside the solar buck and the driver was shown in Figure 10. Direct solar intensity of 750 w/m^2 and diffused solar intensity of 100 w/m^2 were specified. Due to the solar incidence angle of 45 degrees altitude angle and 45 degrees azimuth angle, the front-left side of the body receives more solar load. The effect of the solar incidence angle on the driver influences the local thermal comfort and produced higher EHT values as shown in Figure 11. Due to the strong solar load, the overall comfort for the baseline case was a marginal, slightly warm thermal sensation. In the following, we tested the effects of various thermal environments on the driver's thermal comfort.

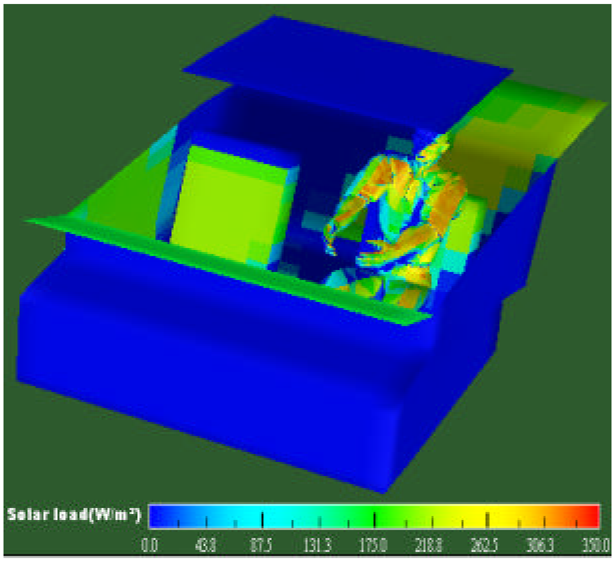


Figure 10. Computed solar loads in the cabin for the baseline case (45 Altitude, -45 Azimuth)

EFFECTS OF AIR VELOCITY

Figure 11 shows the effect of air velocity magnitude on the thermal comfort based on EHT. A large effect of air velocity was found on the body segments of head, arm, and hand. Very little effects on plevis, back, and thigh were found. This is because the large portion of these body segments was contacted with a seat.

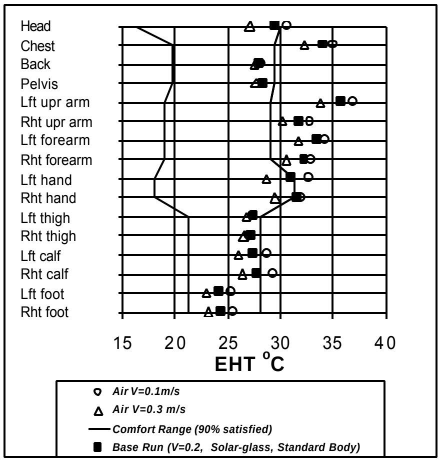


Figure 11. Thermal comfort diagram for the effects of air velocity

EFFECTS OF GLASS TEMPERATURES

Radiant heat exchange occurs between the driver and the surrounding glass. During a vehicle cool-down or warm-up process, the radiation heat load has as great an influence as the air temperature on the occupant thermal comfort. As shown in Figure 12, the higher glass temperatures influenced the upper arm segments and head due to large view factors between these body segments and the front and side glasses. EHT for the left upper arm increased by roughly 4 °C when the glass temperature increased by 10 °C. Very little effects on the lower body segments were found that is due to relatively small view factors between these surfaces

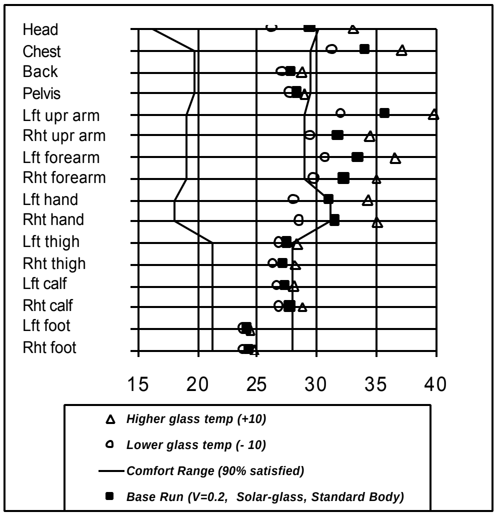


Figure 12. Thermal comfort diagram for the effects of glass temperatures

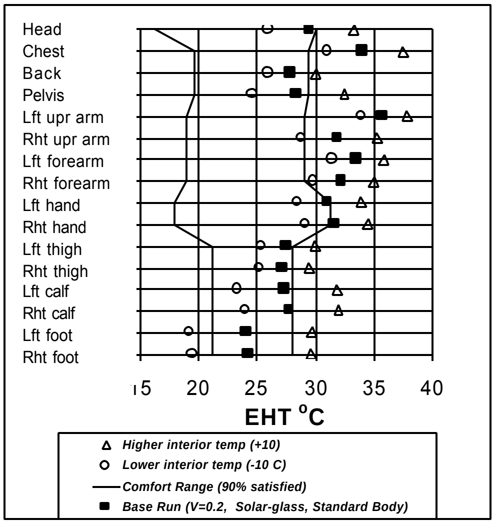


Figure 13. Thermal comfort diagram for the effects of interior surface temperatures

EFFECTS OF INTERIOR SURFACE TEMPERATURES

As shown in Figure13, the higher interior surface temperatures influences the most of the body segments due to a relatively large view factors between these body segments and the interior surfaces. Relatively less influence was found near the upper arm segments, particularly for the left upper arm segments due to a relatively small view factors between the upper arm and the interior surfaces that excludes glass surfaces. The left-upper arm was influenced significantly by the neighboring side window glasses as described in the previous section.

EFFECTS OF SOLAR LOAD AND GLASS TYPE

EHT values improved significantly without solar load into the cabin, as shown in Figure 14. Particularly, EHT for the left upper arm decreased by roughly 7 °C when there is no solar load into the cabin. The effects of solar load are dominant mostly on the upper portion of the body segments because the solar load for the lower portion of the body segments was blocked by IP and side doors. In order to understand the effect of glass properties, PPG soft-ray glass was also tested and compared with the baseline with a solar absorbing glass (PPG 7010). Solar absorbing glass has some improvements on the upper portion of the body segments and EHT for the left upper arm increased roughly by 2 °C with the soft-ray glass.

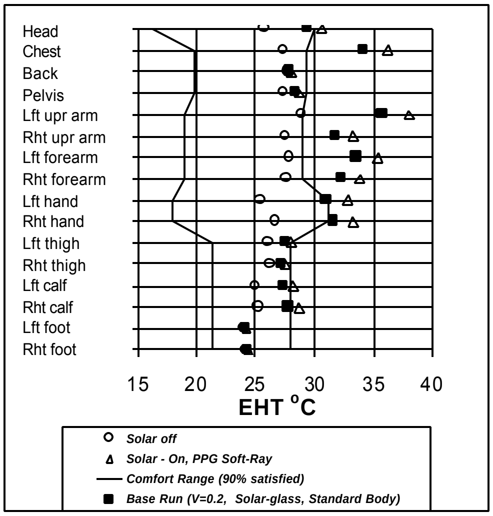
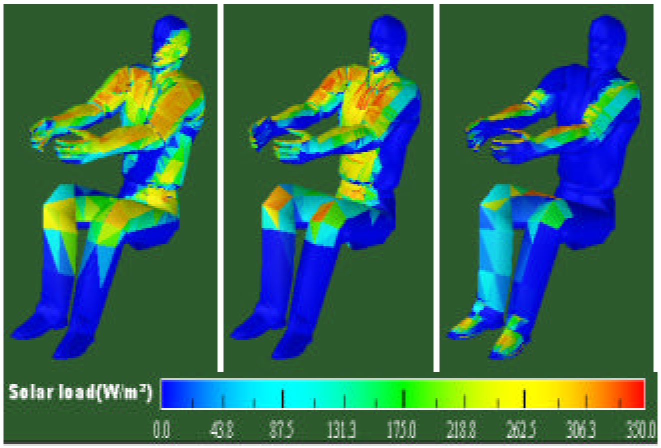


Figure 14. Thermal comfort diagram for the effects of solar load and glass property

EFFECTS OF SOLAR INCIDENCE ANGLE

In order to understand the effects of solar angles on the driver, two different solar angles (45° altitude, 0° azimuth) and (90,0) were tested and compared the baseline with a solar angle (45,-45). As shown in Figure 15, the subsequent solar loads on the driver depend largely on the incident solar angles. The corresponding EHT values are simulated and shown in Figure 16. For the case of the front solar incidence angle (45,0), the chest area had fairly high EHT values (38 °C). It is a challenge to reduce asymmetric thermal load to the occupants in the cabin under cases of extreme solar gain.



(a) (45,-45) (b) (45,0) (c) (90,0)

Figure 15. Solar load on the driver for 3 different solar incidence angles

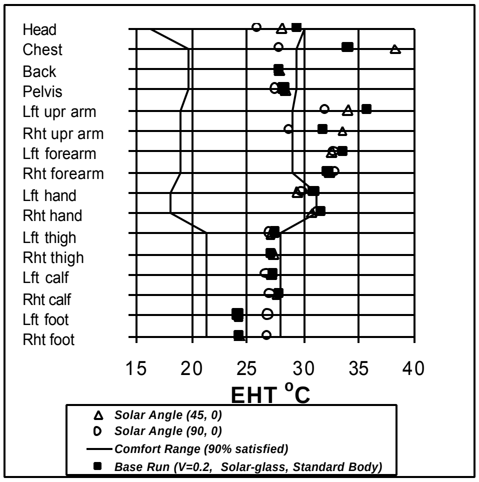


Figure 16. Thermal comfort diagram for the effects of solar incidence angles.

PMV COMPARISON

The human sense of thermal comfort is very complex. The well known variable for estimating the global thermal comfort of persons is the PMV (Predicted Mean Vote) index introduced by Fanger [17]. For strongly inhomogeneous conditions such as a passenger compartment, PMV method may not be valid. Therefore, only relative comparisons of the test cases in the present study were attempted. As shown in Figure 17, the air velocity, glass and interior temperatures are very sensitive to the occupant thermal sensation. The effect of solar angles is also important to assess the overall thermal sensation of the occupants. It was found that the effect of relative humidity in the cabin was less sensitive to PMV values.

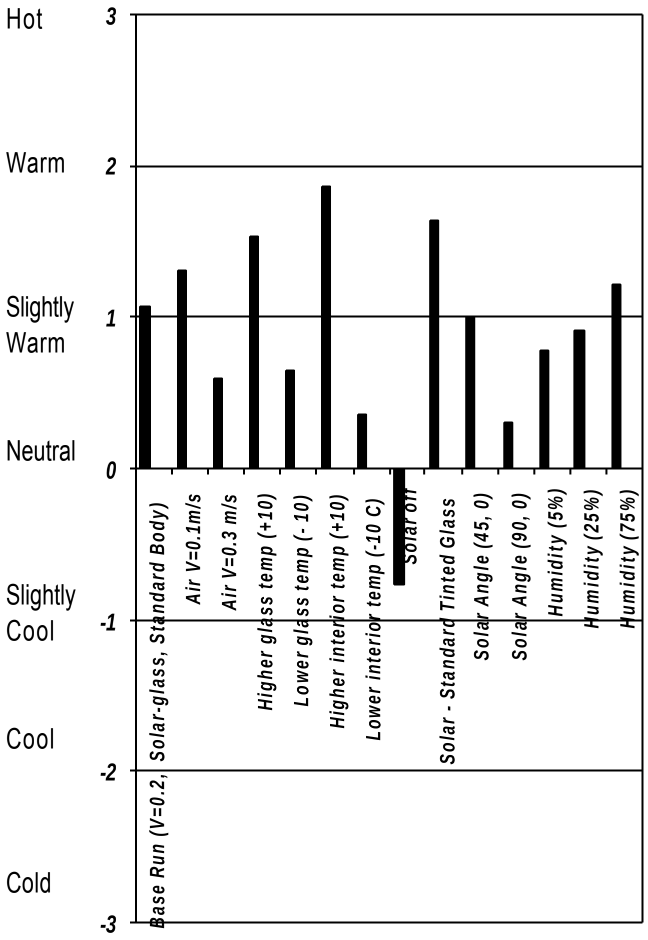


Figure 17. Comparison of PMV values for the test cases

MANIKIN FIELD TEST

In order to validate VTCE, the UC Berkeley segmented thermal manikin, as shown in Figure 3, was put in a stationary vehicle in an outdoor test facility near Richmond, California. The measured indoor environmental parameters include:

- air temperature and velocity for each of the 16 body segments
- interior surface temperatures
- air temperature and humidity (front and back, breathing level and waist level)
- diffuser outlet temperature and humidity
- solar radiation on the dash

The measured environmental parameters (air temperature, velocity, surface temperature, solar radiation, and humidity) were then put into the VTCE to predict heat loss from the manikin. The heat loss was converted into EHT values and the comparison was made between the predicted and measured EHT during the cool down process. As shown in Figure 18, the simulated EHT values for the test case predicted very well with the measurements with the manikin.

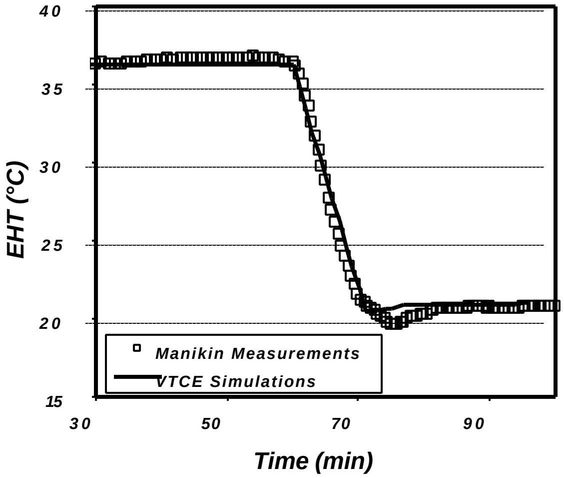


Figure 18. Comparison of simulated EHT values with the manikin measurements for cool-down process.

CONCLUSION

The presented VTCE is suitable for the evaluation of heat load in a passenger compartment and local thermal comfort of its occupants. The simulation tool allows the rapid assessment of various parameters with respect to thermal comfort during the early stages of vehicle development. The use of EHT to quantify thermal comfort makes it possible to obtain results in inhomogeneous thermal environments. Further work should include validation of thermal comfort predictions based on a wide range of human subject test under asymmetric thermal environments and transient conditions. More research is required to develop a whole-body comfort index and dynamic comfort zone for EHT under rapid transient conditions with highly non-uniform thermal environments.

AKNOWLEDGEMENT

The authors would like to thank Edward Arens, Tom Duan, and Tiefeng Yu from UC Berkeley for many useful discussions. The project supports of Karma Sangwan and Jim Giardino are also gratefully acknowledged.

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