

Analytical Model for Human Thermal Comfort in Passenger Vehicles

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ABSTRACT

An analytical model, which takes care of thermal interactions of human body with surroundings via basic heat transfer modes like conduction, convection, radiation and evaporation, is compiled. The analytical model takes measurable inputs from surroundings and specific human parameters. Using these parameters a quick calculation entailing all heat transfer modes ensues in net heat exchange of human body with surroundings. Its magnitude and direction decides the qualitative indication of thermal comfort of concerned human being. The present model is scaled on actual human beings by noting the subjective assessment in comfortable as well as uncomfortable surroundings. As a part of validation, it is implemented in an actual Climatic Wind Tunnel Heater test, where temperatures and other parameters on different parts of the body are noted down and fed to the model as input. Output of the equation is then compared with the subjective assessment of human beings. A realistic concurrence of the output and test data validates the analytical model in the complex geometry like passenger cabin for thermal sensation prediction in a heater test. This model helps in predicting the human thermal comfort in early design stage and supporting HVAC component design for better performance and will save the cost, time and efforts for human comfort assessment road trials.

INTRODUCTION

Human Thermal Comfort is defined as state of mind that expresses satisfaction with thermal environment. A lot of Research has been done to predict the human thermal comfort analytically as well as computationally apart from traditional subjective assessment techniques. Human thermal comfort becomes important aspect of design when it comes to automobile passenger cabins and demands precise design of

Heating Ventilation and Air Conditioning (HVAC) components. This is because; airflow and temperature distribution in a mobile automobile is dynamic and complex. Analytical models and Computational Fluid Dynamics (CFD) exercises help in improving the Air conditioning units, cabin design for better thermal comfort before actual tests on prototype vehicles are carried out.

Orosa [1] and Hensen [2] discussed about different models for analytical prediction of human thermal comfort. The models include Fanger model and development of subsequent Predicted Mean Vote (PMV). The term, Percentage of People Dissatisfied (PPD) was also discussed along with the widely accepted temperature range for maximum thermal comfort. A three dimensional relation between temperature, humidity and acceptance level was plotted and was concluded that low temperature and low humidity conditions were preferred over others for better human thermal comfort. Along with Fanger model, other models like adaptive models, which are generally used for civil engineering purpose, were also discussed.

Han *et al.* [3] stated that models like Fanger and adaptive models mostly deal with steady state environments. In a complicated and unsteady environment like that in a passenger car, those may not be valid. They described another method of thermal comfort calculation in a non-homogeneous environment, which is known as Equivalent Homogeneous Temperature (EHT). EHT averages all the convection and radiation heat exchange spatially and then computes a uniform value of temperature. This uniform value or EHT was then compared with the actual temperature values from a test or simulation and thermal sensation can be predicted. This method however has drawbacks like non-inclusion of biological heat generation and evaporation heat exchange in the EHT calculation.

Mezrhab and Bouzidi [4] developed a code, which takes care of radiation, convection and conduction and computes nodal heat transfer, which can be applied to a complex geometry like a passenger cabin. With the use of external climate data and thermo-physical and radiative properties like heat transfer coefficients, the analysis was carried out to find feasibility of use of excessively glazed surfaces in the vehicle geometry, which increased the load on Air conditioning system. To study effect of these surfaces on temperature variation inside the cabin surfaces, this exercise proved very useful. Alternatively physical test data also helps to predict the temperature required in the passenger cabin for short and long haul vehicles as done by Lin *et al.* [5]. Kaynakli *et al.* [6] independently developed a model based on heat exchange of human body with surroundings in a passenger car in a hot soak process. The human body was divided into 16 different body segments and approximate area of each part was measured. Value of this area was then used to calculate the percentage area of total body. They used Thermal Sensation (TS) to find out extent of thermal comfort of human body in that part. This theoretical study was supported by experimental measurements.

Chian *et al.* [7] utilized the analytical model in the Computational Fluid Dynamics Exercise for a sample automobile cabin. For a typical event of cabin pull down, temperatures and velocities over manikins were evaluated and the same values were used as input for 'Predicted Mean Vote' (PMV) measured for different body parts. Han *et al.* [8] [9] [10] carried out similar study for a passenger cabin of a Sports Utility Vehicle (SUV). Integration of the CFD exercise with Physiological model in an organized algorithm was called as Virtual Thermal Comfort Engineering (VTCE). They studied effects of various thermal loads, extent of clothing and varying air velocity on temperature contours over manikin surfaces. These temperatures were then normalized using EHT scale and used to predict the local thermal comfort in sixteen different parts of body. In another study by Han and Luang [11], hot soak and cool down performance of a passenger cabin was validated using test data. Unsteady state hot soak and cool down of a passenger cabin modeled by CFD was compared with experimental results. Different locations on surfaces of virtual manikins were chosen for this comparison. In similar studies by Aroussi *et al.* [12] and Zhang *et al.* [13], velocity pattern inside the cabin and that over the manikin surface obtained from simulations were compared with test data.

Keeping in mind the previous research done by these scientists and engineers, the present work is sectioned into two parts. First part discusses about the theory and process of compilation of the simple analytical model for human thermal comfort, which is compared with real life assessment of numerous educated subjects for scaling. Second part describes the detailed validation part of the present mathematical model in a cabin-heating event where air

velocity and temperature values over body surfaces are used in the analytical model mentioned before and feasibility of this theoretical model in the complex environment is deliberated.

ANALYTICAL MODEL: THEORY AND COMPILATION

Thermal comfort of human body is the outcome of optimum heat exchange of body with the surrounding environment. It is well known that human being gets the energy from food, which is subsequently converted to Adenosine Triphosphate (ATP) and ATP is burnt to produce energy. The latter part of this process is called human metabolic activity. Part of this energy is used to do the required work and rest of the heat has to be dissipated to keep the body in thermal equilibrium. That is where the thermal comfort of human being comes in the picture. The heat, which has to be dissipated, can opt for one or more of the paths, which are described in details.

The idea of thermal comfort lies in the heat balance of the human body. Thermal equilibrium equation of human body can be written as follows,

$Q_s = \text{Heat generated in the body} - \text{Heat dissipated from the body} \pm \text{other thermal load}$

Expanding the term heat dissipated by modes of heat transfer,

$$Q_s = (Q_{\text{met}}) - (\pm Q_{\text{rad}} \pm Q_{\text{conv}} \pm Q_{\text{cond}} + Q_{\text{evap}}) + Q_{\text{solar}} \quad [14] \quad (1)$$

Where,

Q_s = Heat stored in the body as result of thermal imbalance

Q_{met} = Metabolic heat produced by body,

Q_{rad} = Heat loss or gain by radiation,

Q_{conv} = Heat loss or gain by convection,

Q_{cond} = Heat loss or gain by conduction,

Q_{evap} = Heat loss by evaporation,

Q_{solar} = Direct solar load, if applicable.

To obtain thermal comfort, value of Q_s , the heat stored in body should be as low (near to zero) as possible. The mechanisms by which extra heat is dissipated can have their magnitudes more or less depending upon external factors & the internal human system that regulates this heat balance is called as vasomotor control system. The different heat transfer modes are now discussed in details,

A. DIFFERENT HEAT TRANSFER MODES FROM HUMAN BODY TO SURROUNDINGS

1. Heat Transfer by Radiation

Heat transfer by radiation is governed by temperature of surrounding surfaces of enclosure around the human body. The average value of the temperature of surrounding surfaces, which eventually depends upon solar load and other factors in case of automobiles, is defined as Mean Radiant Temperature. For example, the temperature of car inner surface like dashboard can go up to 70° C in a hot soak and cool down test, in that case the person sitting in the cab undergoes heat gain by radiation. For calculation of heat loss by radiation, view factor plays an important role. However in case of heat exchange from a mass locked in a closed volume, it may be safe to assume view factor to be one. The heat energy can be calculated from the following formula.

$$Q_{\text{rad}} = F \varepsilon \sigma A_s (T_s^4 - T_{\text{surr}}^4) \quad (2)$$

Where,

ε = emissivity,

σ = Stefan-Boltzmann Constant = 5.6703×10^{-8} (W/m²K⁴),

T_s = Avg. outer surface temp,

T_{surr} = Surrounding surface temp,

A_s = Surface area of body,

F = View factor

2. Heat Transfer by Convection

Heat transfer by convection can be clearly understood to be a major function of air velocity around the human body. However, the heat transfer equation can be written as follows,

$$Q_{\text{conv}} = h A_s (T_s - T_{\text{surr}}) \quad (3)$$

Where,

T_s = Avg. outer surface temperature.

T_{surr} = Surrounding surface temperature.

A_s = Surface area of body.

h = convective heat transfer coefficient.

At lower temperatures, temperature difference between body surfaces and air around body increases, which subsequently increases magnitude of heat transfer by convection. Hence, high air velocity would certainly ensue in more thermal discomfort as it would carry away most of the heat by convection only.

3. Heat Transfer by Conduction

When the person in discussion has different external surfaces attached to his/her skin, air entrapment inside the gap and subsequent heat transfer by convection abates. In that case heat transfer by conduction takes place on account of temperature difference between skin and attached surfaces. The direction of heat flow can be either towards or away from the body. Heat Transfer by conduction can be written as,

$$Q_{\text{cond}} = K A (T_{\text{skin}} - T_{\text{Surface}}) / b, \quad (4)$$

Where,

K = Thermal Conductivity of insulating surface

b = Thickness of insulating surface

4. Heat Transfer by Evaporation

Body always excretes sweat from sweat glands as enhance heat transfer from body to surroundings. However, in dry conditions the sweat is evaporated so quickly that its trace cannot be noticed. In addition, when humidity and temperature increase inability of circumstances to get rid of the sweat makes the person uncomfortable. Interestingly, unlike the other modes, this mode carries heat from body to surrounding only and not the other way round. This happens because of vapor pressure difference between skin and air. As the body temperature (37° C approximately) is fixed, vapor pressure corresponding to this temperature is fixed. This enhances the heat transfer from body to surrounding. The magnitude of heat transfer goes to zero when outside temperature becomes equal to body temperature and air becomes fully saturated.

In this heat exchange process, sweating is accelerated because of vapor pressure difference. Body heat is used to vaporize this sweat and ultimately carry away the heat in latent form. The gross equation of heat energy carried away in this form can be expressed as,

$$Q_{\text{evap}} = m_{\text{vap}} h_{\text{fg}} \quad (5)$$

Where,

m_{vap} = rate of evaporation from body (kg/s)

h_{fg} = enthalpy of vaporization of water (KJ/kg).

The mass flow rate of perspiration depends upon coefficient of mass diffusion per unit surface area per unit saturation pressure difference. It can be sensed that if the saturation pressure difference were more, that would draw more water out from skin surface and would subsequently add to more heat transfer from body in latent format. The detailed heat transfer equation for evaporation can be written as,

$$Q_{\text{evap}} = C_d A (p_s - p_v) h_{\text{fg}} \quad (6)$$

Where,

C_d = Mass diffusion coefficient.

p_s = saturation vapor pressure corresponding to skin temperature.

p_v = vapor pressure of air temperature.

5. Assumptions in the Model

1. The skin surface is assumed to be in constant contact with clothing insulations. It means uneven air gap between skin surface and clothing is neglected. This assumption helps to include simplicity in calculations of conduction resistances.

2. Heat to be transferred by radiation from the body is completely assumed to go to the surrounding enclosures. View factor in this case is one. This assumption holds good for closed volumes like cabin. This assumption helps in way as view factor calculation is a time consuming as well as resource consuming process. In addition, if view factors really need to be calculated then the analytical nature of the model becomes no longer valid. It would then become an exercise of 3D CFD.

3. Hemispherical total emissivity is considered for calculating the radiation transfer. Dependence of wavelength on emissivity is neglected. A typical value for total emissivity for human skin is 0.95 and that for a cotton fabric is 0.77.

4. The diffusion coefficient of skin surface is taken for a normal person. It may vary from person to person depending upon skin physiology of every individual.

5. Skin is assumed in fully saturated condition at that temperature. This assumption helps to avoid nature of sweat glands and their response to outer surroundings in calculation and increasing biological complexity and dependence.

6. Body temperature remains 37°C for the sake of calculation, which is core temperature.

B. COMPILATION OF ALL HEAT TRANSFER MODES

All these heat transfer equations need to be clubbed together to find out total heat transfer from human body in [equation \(1\)](#). Hence the equations need to be rewritten in terms of known or measurable parameters like temperature velocity and humidity. In this process, some of the parameters in the heat transfer equations can be simplified. Anecdote of all these simplifications is delineated below.

1. Clothing Resistance and Clothing Surface Temperature

The Conduction and Convection resistances can be clubbed together to form a resistance circuit. For a clothed body, conduction resistance offered by clothes can be summed up with heat transfer coefficient to form an Overall heat transfer coefficient (U). For a point of measurement, it can be written that

$$1/U = 1/h_c + R_{\text{clothing}} \quad (7)$$

R_{clothing} can be determined for each type of garments. It depends upon thermal conductivity of fabric and standard thickness of sample garments. The resistance circuit can also be used to find out clothing surface temperature.

$$(T_{\text{skin}} - T_{\text{air}}) / (h_c^{-1} + R_{\text{clothing}}) = (T_{\text{clo}} - T_{\text{air}}) * h \quad (8)$$

Heat transfer coefficient can be written in terms of velocity by many empirical relations. We used the following stipulated by ASHRAE (1989).

$$h_c = 8.3 V^{0.6} \quad (9)$$

The temperature of clothing thus found can be used in the heat transfer calculation for dissipation through covered surface specifically by radiation.

2. Radiative Heat Transfer Coefficient

Radiation heat transfer equation in [\(2\)](#) seems to be infeasible to be incorporated in simple heat exchange calculation. Using normal body temperature as a reference, we can segregate the nearly constant parameters in [equation \(2\)](#) and calculate a constant value for simplistic calculations.

$$Q_{\text{rad}} = \epsilon \sigma A_s (T_{\text{sk}}^4 - T_{\text{surf}}^4) = \epsilon \sigma A_s (T_{\text{sk}}^2 + T_{\text{surf}}^2) (T_{\text{sk}} + T_{\text{surf}}) (T_{\text{sk}} - T_{\text{surf}}) \quad (10)$$

Hence,