

New Evaluation Method of Transient and Non-Uniform Environment in a Passenger Compartment

Kenjiro Imai, Takuya Kataoka, Takafumi MASUDA and Tomohiro Inada
DENSO Corp

ABSTRACT

Development of new passenger-car climate control systems that contribute to improved comfort and decreased fuel consumption requires quantitative evaluations of thermal sensation and comfort. Therefore, a new evaluation method of the transient and non-uniform passenger-compartment thermal environment has been developed. Vehicle occupant's local thermal sensations are evaluated by using the local standard new effective temperature (SET*) that is calculated using a human thermoregulation model. The occupant's whole-body thermal comfort is then evaluated by local thermal sensation. The theory of the method and some example application results are introduced in this paper.

CITATION: Imai, K., Kataoka, T., MASUDA, T. and Inada, T., "New Evaluation Method of Transient and Non-Uniform Environment in a Passenger Compartment," *SAE Int. J. Passeng. Cars - Mech. Syst.* 5(2):2012, doi:10.4271/2012-01-0633.

INTRODUCTION

Since the thermal environment in a vehicle passenger compartment is transient and non-uniform, it is important to improve occupants' comfort by improving the thermal distribution in the compartment during heating/cooling. At the same time, with CO₂ regulations becoming increasingly stringent in recent years, lower fuel consumption is also a high-priority requirement for automobiles, and so car air-conditioning systems are required to satisfy occupants' comfort expectations while using the minimum energy.

To meet these requirements, technologies for efficient thermal transfer to occupants are expected to be developed in the future, such as task/ambient air-conditioning systems and direct heating/cooling systems.¹ In order to realize these technologies for improving comfort or decreasing fuel consumption, quantitative evaluation of occupants' thermal sensations and comfort is indispensable.

To quantitatively evaluate vehicle-compartment thermal environment, engineers have attempted evaluations using a thermal manikin,² and with skin temperature and standard new effective temperature (SET*).^{3,4} The thermal-manikin method takes account of an occupant's body shape, clothing and skin temperature and can evaluate the equivalent temperature based on sensible heat transfer, but has difficulty in evaluating a hot or transient environment. Recently, therefore, engineers have come to focus on the SET*-based method which uses SET* for each body segment (local

SET*) calculated based on various thermal parameter measurements.

The authors measured the air temperature and velocity, radiation temperature, and humidity in a transient and non-uniform passenger-compartment environment using an amenity manikin, and calculated the local SET* by using a 16-body-segment 128-node human thermoregulation model in order to evaluate occupant's local thermal sensations. The authors then determined the distribution of local thermal sensation votes at which the occupant felt comfortable, and estimated the occupant's whole-body comfort based on the difference between this distribution and the distribution of thermal sensations evaluated in the target environment. This paper gives an overview of the local SET* calculation procedure and presents an application example of the present evaluation method to evaluate occupant's thermal sensations and comfort in steady-state and transient passenger-compartment environments.

CALCULATION OF PARTIAL SET*

CONCEPT OF LOCAL SET*

Since the present evaluation method is an expansion of the concept of the generally known SET*, this paper first gives an overview of the SET*.

The amount of heat radiation per unit skin surface area of a human body to the environment can be expressed by the following equation:

$$\dot{Q}_{sk} = F_{cl}(h_c(T_{sk} - T_a) + h_r(T_{sk} - T_r)) + F_{pcl}\kappa h_c\omega(P_{sk} - \Phi_a P_a) \quad (1)$$

In the equation, the first term on the right side represents the amount of convection heat transfer, the second term the amount of radiant heat transfer, and the third term the amount of latent heat transfer by sweating. Although radiant heat value of the second term is usually proportional to the difference of the 4th power of human body skin temperature and wall temperature, it approximates to linear expression like an upper equation when the difference in human body skin temperature and wall temperature is less than about 30 °C. T_{sk} , T_a , and T_r are skin temperature, air temperature, and radiation temperature, respectively; h_c and h_r are convection heat transfer coefficient and radiant heat transfer coefficient, respectively; F_{cl} is the heat transfer coefficient of clothing; P_{sk} and P_a are the saturated vapor pressure of moist air at skin temperature and around human body, respectively; Φ_a is relative humidity; ω is the percent wet area of the skin surface in sweating; and F_{pcl} is the moisture permeation efficiency factor of clothing. κ represents a coefficient, known as the "Lewis ratio," which is derived from the similarity relation between mass transfer coefficient and convection heat transfer coefficient. The Lewis ratio is 0.0165°C/P_a.

Meanwhile, the amount of heat radiation in a standard environment can be expressed as:

$$\begin{aligned} \dot{Q}_{sk} = & F_{cls}(h_c(T_{sk} - SET^*) + h_r(T_{sk} - SET^*)) \\ & + F_{pcls}\kappa h_{cs}\omega(P_{sk} - 0.5P_{SET^*}) \end{aligned} \quad (2)$$

From the equivalence relation between these radiation amounts, the following equation can be derived. SET* can be determined by solving this equation:

$$\begin{aligned} F_{cl}(h_c(T_{sk} - T_a) + h_r(T_{sk} - T_r)) + F_{pcl}\kappa h_c\omega(P_{sk} - \Phi_a P_a) \\ = F_{cls}(h_c(T_{sk} - SET^*) + h_r(T_{sk} - SET^*)) \\ + F_{pcls}\kappa h_{cs}\omega(P_{sk} - 0.5P_{SET^*}) \end{aligned} \quad (3)$$

in which P_{SET^*} represents the saturated vapor pressure of moist air at the SET*. The skin temperature, which is a human physiological value, and the percent wet area of skin surface (amount of sweat) can be calculated using Gagge's 2-node human thermoregulation model.⁶

Thus, the SET* represents the equivalent temperature in a standard environment where the human physiological value is assumed to be equal to the amount of heat radiation from a human body into the environment. The SET* has been confirmed as having a good correlation with thermal sensations.

The present evaluation method expands this concept of SET* to estimate a vehicle occupant's local thermal

sensations. Specifically, the skin temperature and sweat rate of each segment of a human body is determined using a human thermoregulation model that models each body segment, thereby calculating the local SET* and evaluating occupant's local thermal sensations. The following section describes the local SET* calculation procedure.

OVERVIEW OF HUMAN THERMOREGULATORY MODEL

The human thermoregulatory model has evolved since Gagge developed a two-node model, and a multi-node model is available today that models each segment of a human body in detail.^{7,8} For ease of use in daily evaluation of an air-conditioned environment, we employed a small-calculation-load node model.

The human thermoregulatory model is composed mainly of heat transfer between body tissues, including blood flow, heat transfer between the human body and the environment through the skin surface, and thermoregulatory response of blood flow, sweating, and metabolism. The following paragraphs give details of the model that we developed for our study.

Fig. 1 shows the thermoregulatory model divided into multiple body segments. It is divided into 16 segments: head, neck, chest, abdomen, upper arms, forearms, hands, thighs, calves, and feet. Fig. 2 shows a model of the tissues and blood flows of each body segment. Each segment comprises two tissues of skin and core, and six blood pools in the main artery, main vein, and capillary arteries and veins of skin and core, respectively. The thermoregulatory model is composed of 128 nodes in total.

The blood vessel system carries blood from the chest to the head, arms, and feet, and back to the chest. Blood pools are grouped into those in the main artery and vein which carry blood across different body segments, and those in the capillary artery and vein, which circulate blood within each body segment.

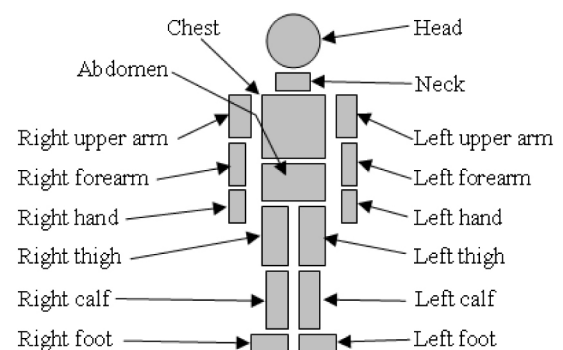


Fig. 1. Divisions of human thermoregulatory model

The human body has arteriovenous anastomosis (AVA) blood vessels that facilitate blood return through the superficial veins in the extremities to the center of the body when the ambient temperature is high.⁹ function simulating

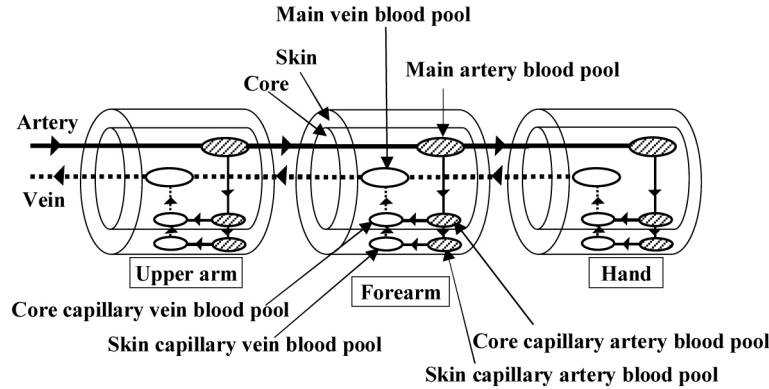


Fig. 2. Tissues and blood flow model

the AVA blood vessels has also been incorporated in our thermoregulatory model.

This model is expressed by the following equations:

Core tissues:

$$\rho_1 c_1 V_1 \frac{dT_1(t)}{dt} = -\frac{\lambda}{d} A(T_1 - T_2) + \rho_1 c_b C_b(T_3 - T_1) + V_1 \{H_{a1}(T_3 - T_1) + H_{v1}(T_4 - T_1)\} + M_{B1} + M_{shiv} - Q_{res}$$

Skin tissues:

$$\rho_2 c_2 V_2 \frac{dT_2(t)}{dt} = \frac{\lambda}{d} A(T_1 - T_2) + V_2 \{H_{a2}(T_5 - T_2) + H_{v2}(T_6 - T_2)\} + M_{B2} - Q_{R+C} - Q_E - Q_S$$

Core capillary artery blood pools:

$$\rho_b c_b V_3 \frac{dT_3(t)}{dt} = (q_1 + q_2) \rho_b c_b (T_7 - T_3) - V_1 H_{a1}(T_3 - T_1) - H_{av34}(T_3 - T_4)$$

Core capillary vein blood pools:

$$\rho_b c_b V_4 \frac{dT_4(t)}{dt} = q_1 \rho_b c_b (T_1 - T_4) + q_2 \rho_b c_b (T_6 - T_4) - V_1 H_{v1}(T_4 - T_1) + H_{av34}(T_3 - T_4)$$

Skin capillary artery blood pools:

$$\rho_b c_b V_5 \frac{dT_5(t)}{dt} = q_2 \rho_b c_b (T_3 - T_5) - V_2 H_{a2}(T_5 - T_2) - H_{av56}(T_5 - T_6)$$

Skin capillary vein blood pools:

$$\rho_b c_b V_6 \frac{dT_6(t)}{dt} = q_2 \rho_b c_b (T_5 - T_6) - V_2 H_{v2}(T_6 - T_2) + H_{av56}(T_5 - T_6)$$

Main artery blood pools:

$$\rho_b c_b V_7 \frac{dT_7(t)}{dt} = \rho_b c_b \{q_{vin} T_{vin} - (q_{aout} + q_1 + q_2) T_7\} - H_{av78}(T_7 - T_8)$$

Main vein blood pools:

$$\rho_b c_b V_8 \frac{dT_8(t)}{dt} = \rho_b c_b \{q_{vin} T_{vin} - (q_1 + q_2) T_4 - q_{vout} T_8\} + H_{av78}(T_7 - T_8)$$

Where, ρ is density, c is specific heat, V is volume, T is temperature, λ is thermal conductivity, d is the thickness of insulation between skin and core, A is surface area, H_a is heat transfer coefficient between artery and tissues, H_v is heat transfer coefficient between vein and tissues, H_{av} is heat transfer coefficient between artery and vein, M_B is metabolic heat rate, M_{shiv} is heat generation by shivering, Q_{res} is heat loss by respiration, Q_{R+C} is convective and radiate heat loss from skin, Q_E is latent heat loss by sweating, Q_S is heat loss for seat in contact area and q is skin blood flow rate. The subscript 1 shows core, 2 shows skin, 3 shows core capillary artery blood pool, 4 shows core capillary vein blood pool, 5 shows skin capillary artery blood pool, 6 shows skin capillary vein blood pool, 7 shows main artery blood pool, 8 shows main vein blood pool, b is blood.

As a thermoregulatory-response-related control system, the model also incorporates the blood flow rate, sweat rate, and heat generation control equations.

Body temperature is regulated by controlling the blood flow rate, sweat rate, and heat generation. It is known that each of these three parameters can be expressed as a function of skin temperature and body temperature. As the function expressions, the following equations proposed by Yokoyama⁹ were used:

Skin blood flow rate:

$$q_{sk,i} = \zeta_i \left\{ 0.694(T_{core} - 36.7) + 0.074(T_{sk,m} - 34.0) + 0.149 \right\} \frac{100V_{sk,i}}{6\rho_b}$$

Amount of latent heat transfer by sweating:

$$E_i = \varepsilon_i A_i + \left\{ 197(T_{core} - 36.7) + 23(T_{sk,m} - 34.0) + 7212\delta_i \left(\frac{dT_{sk,m}}{dt} + 0.00317 \right) \right\} \times \exp\left(\frac{T_{2,i} - 34.0}{10} \right) + A_i E_{base}$$

Equation for heat generation control by metabolism: