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Authors
Huizenga, Charlie
Hui, Zhang
Duan, Thomas
et al.

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AN IMPROVED MULTINODE MODEL OF HUMAN PHYSIOLOGY AND THERMAL COMFORT

Charlie Huizenga, Zhang Hui, Thomas Duan, Edward Arens
Center for Environmental Design Research
University of California, Berkeley 94720-1839, USA

ABSTRACT

The UC Berkeley Multinode Comfort Model is based on the Stolwijk model of human thermal regulation but includes several significant improvements. Our new model uses sixteen body segments (compared to six in the Stolwijk model) corresponding to the UC Berkeley segmented thermal manikin. Each segment is modeled as four body layers (core, muscle, fat, and skin tissues) and a clothing layer. Physiological mechanisms such as vasodilation, vasoconstriction, sweating, and metabolic heat production are explicitly considered. Convection, conduction (such as to a car seat or other surface in contact with any part of the body) and radiation between the body and the environment are treated independently. The model is capable of predicting human physiologic response to transient, non-uniform thermal environments. This paper describes the physiological algorithms as well as the implementation of the model.

INTRODUCTION

Stolwijk's 25 node model of thermoregulation (Stolwijk and Hardy 1966) set out the fundamental concept, algorithm, physical constants and physiological control sub-systems for many contemporary multinode models (Hwang and Konz 1977). The Berkeley Multinode Comfort Model is based on the Stolwijk model as well as on work by Tanabe in Japan (Tanabe, Stuzuki et al. 1995), 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 Berkeley model (like the Tanabe model) uses sixteen body segments corresponding to the Berkeley segmented thermal manikin (Tanabe, Arens et al. 1994). Each segment in the model is modeled as four body layers (core, muscle, fat, and skin tissues) and a clothing layer. Blood is modeled as a separate series of nodes that provide convective heat transfer between segments and tissue nodes. 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.

The treatment of time as a series of discrete "phases" of variable length enables the model to simulate almost any combination of environmental, clothing and metabolic conditions. Effects of transient and spatially asymmetric conditions that are completely lost in whole-body models such as the 2-node PMV model can be predicted by the model. An example simulation might be a person walking from an air-conditioned building to hot summer outdoor conditions and then getting into a car that has been sitting in the sun, turning on the air-conditioning and driving as the car begins to cool off. Applications include evaluating thermal comfort in spaces with asymmetric or transient thermal environments including automobiles, buildings or outdoors.

MODEL OVERVIEW

The Berkeley model simulates an arbitrary number of sequential sets of environmental and physiological conditions, called phases. The phases are specified either interactively or through text files to facilitate use of the model with other software. Each phase consists of the following data:

- Duration
- Metabolic rate
- Physiological constants
- Clothing* (insulation level and moisture permeability)
- Air temperature*
- Mean radiant temperature* (or a list of surface temperatures, emissivities and angle factors)
- Air velocity*
- Relative humidity*
- Contact surface thermal properties*

**This data is specified for each of the sixteen segments*

Phases would most commonly be used to represent segments of time where environmental conditions are constant or vary linearly with time. Since the length of the phase is arbitrary, non-linear transients can be simulated by short, linear approximations. All of the physiological constants embedded in the Stolwijk model can also be changed through the input data.

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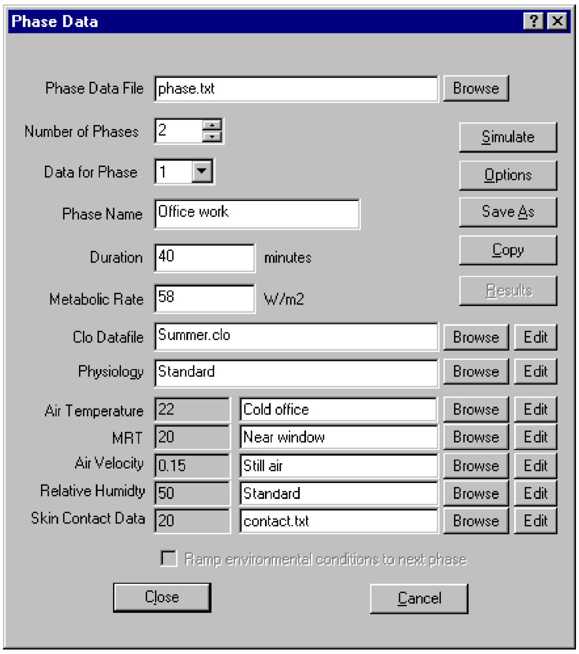
This allows the user to change not only obvious physical data such as height, weight, basal metabolic rate, and heat transfer coefficients but also more detailed physiological data such as tissue properties, thermal conductivities, hot/cold receptor properties, vasoconstriction and vasodilation coefficients. These properties can even be changed during the simulation to correct for changing conditions such as posture (e.g. seated vs. standing).

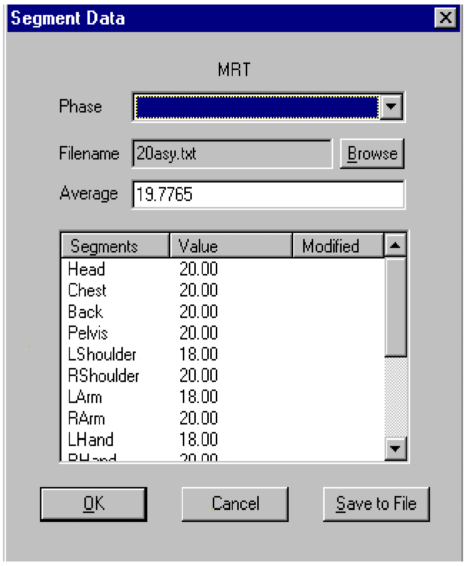


Phase Data File: phase.txt
Number of Phases: 2
Data for Phase: 1
Phase Name: Office work
Duration: 40 minutes
Metabolic Rate: 58 W/m2
Clo Datafile: Summer.clo
Physiology: Standard

Air Temperature	22	Cold office
MRT	20	Near window
Air Velocity	0.15	Still air
Relative Humidty	50	Standard
Skin Contact Data	20	contact.txt

☐ Ramp environmental conditions to next phase

Figure 1. The Phase Data dialog box. In this example screen there are four phases, the first of which lasts 2 hours, with a metabolic rate of 58.2 W-m2 (1 met) and a clothing ensemble as described in another external file called summer.clo.



MRT

Phase:

Filename: 20asy.txt

Average: 19.7765

Segments	Value	Modified
Head	20.00	
Chest	20.00	
Back	20.00	
Pelvis	20.00	
LShoulder	18.00	
RShoulder	20.00	
LArm	18.00	
RArm	20.00	
LHand	18.00	

Figure 2: A sample of the Edit dialog box for Air Temperature. Each segment can be exposed to different environmental conditions.

The following improvements have been made over the Stolwijk model:

- Increase in number of body segments from six to sixteen
- Improved blood flow model, including counter flow heat exchange in the limbs
- Addition of a clothing node to model both heat and moisture capacitance
- Addition of heat loss by conduction to surfaces in contact with the body
- Improved convection and radiation heat transfer coefficients
- Explicit radiation heat transfer calculation using angle factors
- Addition of a radiation heat flux model (e.g. sunlight striking the body)

Segmentation. The use of sixteen body segments in the model provides two important advantages. First, it improves the model's ability to predict the effects of thermally asymmetric environments. The Stolwijk model combined left and right body segments, making it difficult to examine the effects of a lateral asymmetry such as a cold window. The second important advantage is that the model segmentation corresponds directly to the UC Berkeley segmented thermal manikin. This device provides us with the ability to accurately measure heat transfer coefficients and clothing insulation values for individual body parts, and we can use this data directly in our comfort model. The manikin measures heat flux to the environment for each segment, providing valuable data for validating the model.

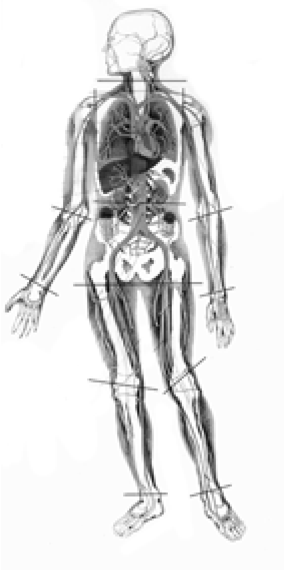


Figure 3. The 16 body segments of the Berkeley model are: head, chest, back, pelvis, right and left upper arms, right and left lower arms, right and left hands, right and left thighs, right and left lower legs, and right and left feet.

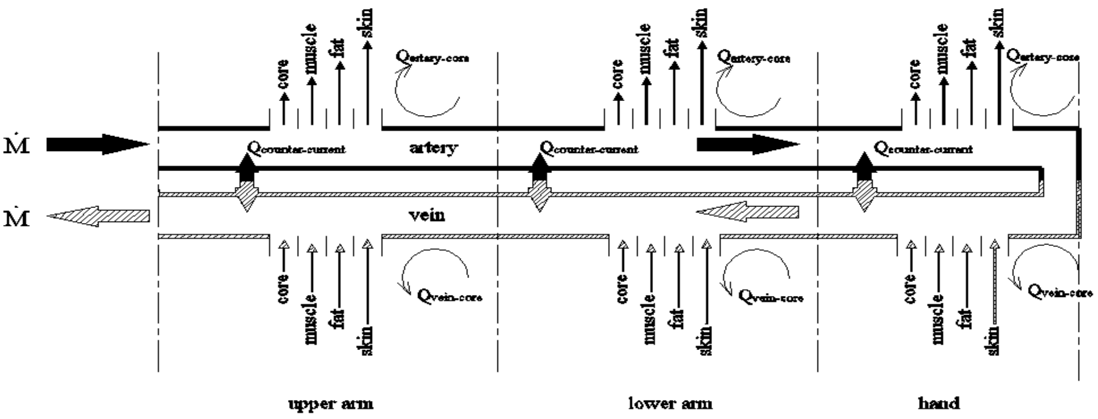


Figure 4. Extremity blood flow model.

Improved blood flow model. Human body thermal regulation is mainly conducted through blood flow regulation, and 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. During exercise or work, the extra heat produced is carried to the body surface by the blood where higher skin temperatures increase heat loss through convection and radiation. Skin temperatures and, more importantly, hypothalamus temperature control this regulation as well as the opening of sweat glands to release additional heat by evaporation. During cold stress, cutaneous vasoconstriction shunts blood to more deeply located veins which are closer to the arteries. In addition, 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 is a major strategy to decrease heat loss and maintain core temperature in cold conditions.

The original Stolwijk model assumes that the arterial blood temperature is the same throughout the body. The heat exchanges between local tissues and local blood are thus simplified as heat exchanges between local tissues and blood at this core temperature. This assumption is basically sound for modeling the head and trunk. In the body, the brain receives a relatively large and constant blood flow that accounts for about 15% of the total blood flow of the body. With the high blood flow rate and relatively short vessel length, the heat exchange effectiveness is small and the blood temperature entering the brain is effectively the same as the core blood temperature. Similarly, large blood vessels in the trunk have relatively little heat transfer with surrounding tissues due to the high blood flow rates and incomplete contact with tissues (Chato 1980; Chen and Homes 1980).

In the limbs, Stolwijk's assumption is less valid. Based on Chato's data we calculate that arterial blood flowing to the hands will reach a temperature about halfway between the temperature of the blood entering the upper arm and the temperature of the surrounding tissue. For this reason, we decided that we could improve on Stolwijk's model by including the change in blood temperature as it flows through the extremities.

Figure 4 shows the blood flow model for an arm (the leg has the same structure) indicating both heat and mass transfer. The mass transfer is the radial blood flow which leaves the central artery, goes through the transverse terminal arteries, and the capillary beds to distribute blood to core, muscle, fat, and skin tissues. It is then taken up by the transverse terminal veins and returns to the central vein. The heat transfer includes the heat exchange between the vessels and their contacting tissues as well as the counter-current heat exchange between arteries and veins. The blood temperature returning to the central vein is assumed to be at the tissue temperature from whence it came.

In the extremities (upper arm, lower arm, hand, thigh, lower leg, foot), entering artery blood temperature of a segment is set equal to the leaving artery blood temperature of the preceding segment. All blood returning from the veins is mixed together to determine the returning core blood temperature.

Clothing Node. Stolwijk considered clothing as insulation without mass. The addition of a clothing node in the Berkeley model is used to model both heat and moisture capacitance of clothing. Heat capacity of the clothing has been demonstrated to be important when considering transient effects (Burch, Ramadhyani et al. 1991). Moisture capacitance is needed to correctly model evaporative heat loss from the body through clothing. The moisture model uses the regain approach (Morton and Hearle 1993) to calculate the amount of moisture that a specific fabric will absorb at a given relative humidity.

Contact surfaces. In almost any environment, the body is in contact with solid surfaces and loses heat via conduction. The most common contact surface for the body is a chair. Under steady-state conditions, this can be treated as increased insulation and modeled as clothing. Under transient conditions, the clothing model does not work well since the chair can have significant thermal mass. Many other situations involve conduction heat loss including sitting in a car seat with hands on the steering wheel or resting arms on a counter. The Berkeley model allows the description of a contact surface for each segment. This description includes an initial temperature, thermal conductivity, specific heat and depth of the material. A far-field temperature and heat transfer coefficient is specified as a boundary condition. For each segment, the fraction of exposed skin and clothed skin in contact with the surface are also specified.

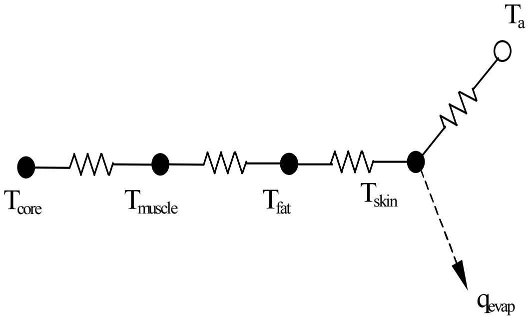


Figure 5. Stolwijk model node structure.

Convection and radiation heat transfer. Stolwijk used a combined convection and radiation heat transfer coefficient for each of the six segments in his model. The Berkeley model separates convection and radiation heat transfer. Convective and radiative heat transfer coefficients are based on test results from the Berkeley segmented thermal manikin for both seated and standing posture (de Dear, Arens et al. 1997). Convective heat transfer is calculated based on the air temperature, and radiative heat transfer is calculated based on MRT, each specified by body segment.

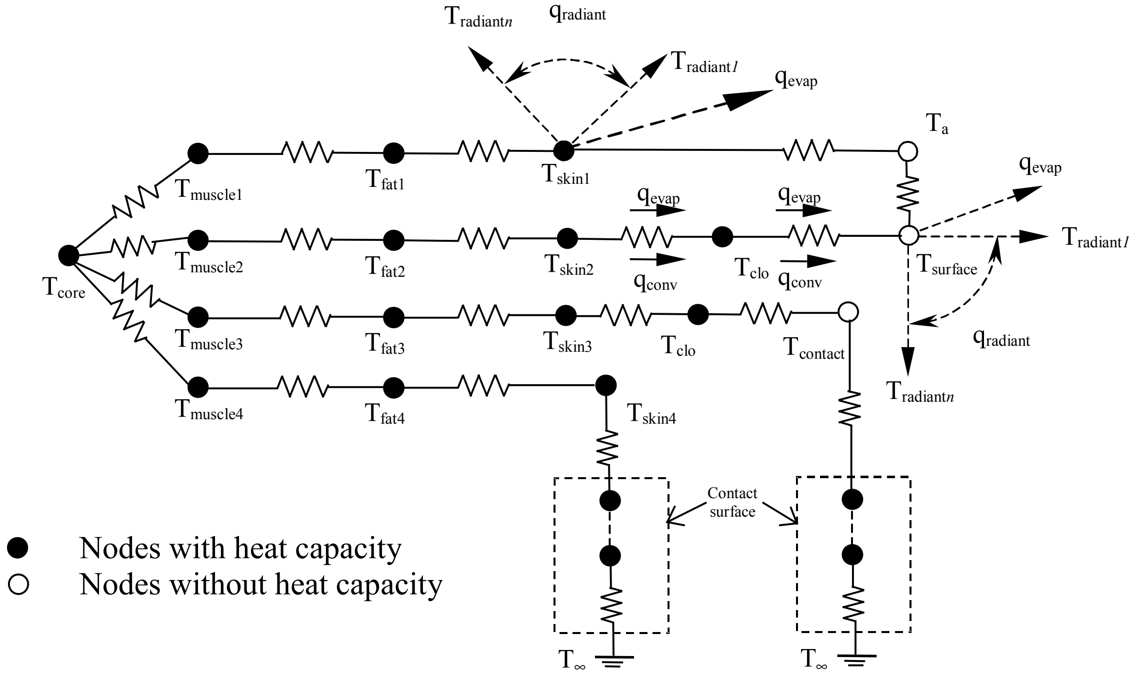


Figure 6. Typical segment node structure showing four parallel heat paths: top, exposed skin with convective and radiant heat loss; second from top, clothed skin with convection and radiant heat loss; third, clothed skin with conductive loss to contact surface; bottom, bare skin

In addition to the linearized radiation approach, the Berkeley model can optionally calculate radiation heat transfer using the Stefan-Boltzmann law. In this option, shape factors are required for each of the 16 segments and an arbitrary set of environmental surfaces. Each of these environmental surfaces is described by its surface area, temperature and emittance. This option is significantly more accurate than the MRT approach for highly non-uniform environments such as automobiles (Corrado, Pretti et al. 1995).

Radiation Heat Flux. In addition to longwave radiation heat transfer with surrounding surfaces, the body is often exposed to radiation from the sun, heat lamps or other sources. The model includes a radition heat flux component that allows the user to specify the heat flux for each segment. A two-band model is used, separating this heat flux into shortwave and longwave radiation. Shortwave radiation is absorbed based on skin or clothing absorptance and longwave radiation is absorbed based on the skin or clothing emittance.

IMPLEMENTATION

The model has been implemented in an object-oriented (OO) approach using C++. Much effort has been spent to make the data structure and simulation procedure resemble the physical model as much as possible. In addition, we have kept the internal model structure very flexible, so that changes to the model can be implemented easily, often without recompiling the code. For example, the node structure is read from text input files so that adding a node or reconfiguring existing nodes only requires modifying program input. The choice of an object-oriented language has greatly simplified this approach.

Several objects are defined to represent each element of the physical model. The *node* object is the basic unit in this object structure. All the actual simulation procedures – heat production, heat transfer and regulating control mechanism -- are done within node objects. Multiple nodes are organized into a tree-like structure which is maintained by a higher level object, the s*egment* object. A segment also has a *blood* object which contains an *artery* and a *vein*. Figure 7 shows the relationship of these objects. The *body* consists of several *segments* that are connected with each other via blood. Nodes exchange heat with their adjacent nodes via conduction and as well as with blood.

Nodes in each segment form a linked tree. Multiple parallel branches may be included in each segment to simulate different heat flow paths. The structure of each segment does not need to be identical. This provides the capability to model different body parts having quite different physical structures and/or non-identical environmental conditions. For example, if the subject is wearing shorts, the model will generate both a clothed and a bare-skin path for the thigh segment. If the subject is wearing long pants, only the clothed path will be generated.

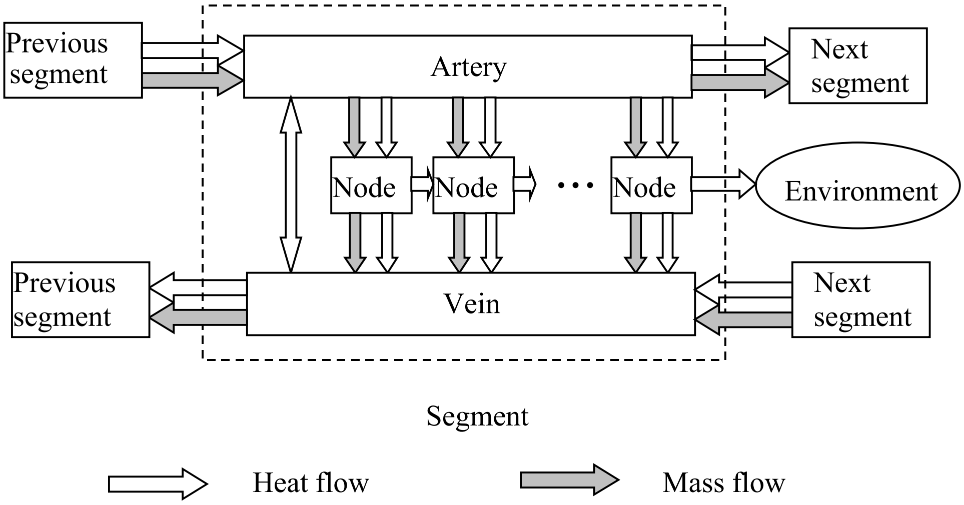


Figure 7. Segment object schema

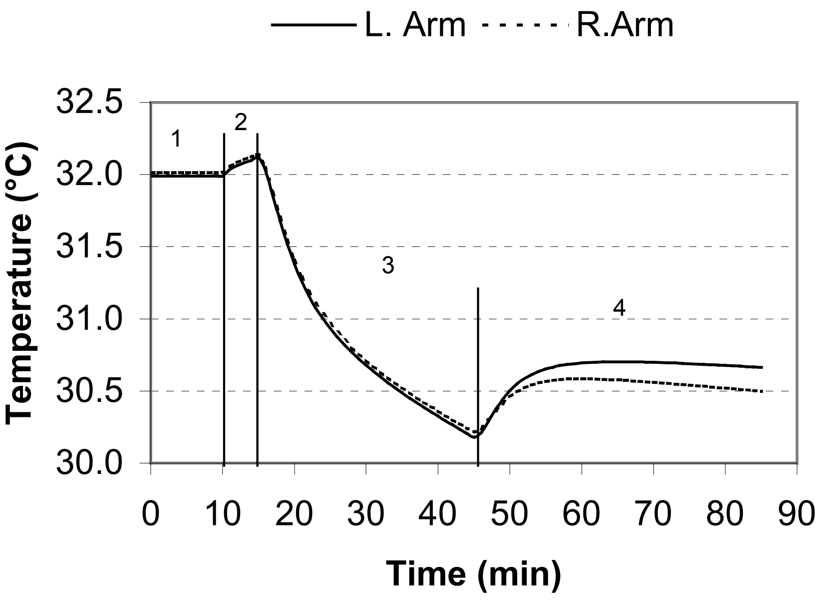


Figure 8. Simulation results showing left and right lower arm temperatures for a transient set of conditions with four phases. The subject is sitting in an office (phase 1), then puts on a coat and walks through the building (phase 2), exits the bulding on a cool day and walks outside (phase 3) then enters a different (cooler) building and sits near a cold window (phase 4). The effect of the cold window is seen in the lower skin temperature of the right arm.

APPLICATIONS

Its flexible input structure and its ability to evaluate transient, non-uniform thermal environments make the Berkeley model useful for a wide range of applications. An obvious example is evaluation of occupant comfort in automobiles, where the environment can be very transient and can have highly non-uniform radiant loads. Other examples include evaluation of innovative HVAC approaches for buildings such as task/ambient systems or displacement ventilation that provide non-uniform or stratified environments. The input structure of the Berkeley model allow it to be connected to building simulation programs and to evaluate thermal comfort in a much more rigorous manner than is currently being done.

EXAMPLE SIMULATION

To demonstrate the capabilities of the model, an example simulation was done of the following scenario. A person puts on a coat after sitting in their office, walks outside on a cold day, enters another building, walks up some stairs, removes their coat and sits down near a window. The second building is cooler than the first and the cold window surface results in additional radiant heat loss on the right side. Figure 8 shows average the left and right lower arm temperatures as predicted by the Berkeley model.

FUTURE WORK

Our next objective is to perform a detailed validation of the model using experimental data in the literature as well as our own data taken in our controlled environment chamber. In addition to validating the physiologic behavior of the model, we will validate the ability of the model to predict human subjective responses to the thermal environment.

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REFERENCES

Burch, S. D., S. Ramadhyani, and J. T. Pearson, “Analysis of passenger Thermal Comfort in An Automobile under Severe Winter Conditions,” ASHRAE Transactions **97, pt.1**, 1991.

Chato, J. C., “Heat transfer to blood vessels,” ASME Journal of Biomechanical Engineering **102**: 110-118, 1980.

Chen, M. M. and K. R. Homes, “Microvascular Contribution in Tissue Heat Transfer,” NYAS

(Annals of the New York Academy of Science) **335**: 137-150, 1980.

Corrado, J. V., M. Pretti, and A. Sacchi, “Routine for the Calculation of Angle Factors between Human Body and Car Drivers' Cabin,” SAE Technical Paper Series 95A1054: 421-429, 1995.

de Dear, R. J., E. Arens, H. Zhang, and M. Oguro, “Convective and Radiative Heat Transfer Coefficients for Individual Human Body Segments,” International Journal of Bio-Meteorology **40, No. 3**: 145-156, 1997.

Hwang, C. and S. A. Konz, "Engineering Models of the Human Thermoregulatory System - A Review," IEEE Transactions on Biomedical Engineering **BME-24, No. 4**: 309-325, 1977.

Morton, W. E. and J. W. S. Hearle, Physical Properties of Textile Fibres, Manchester, UK, The Textile Institute, 1993.

Stolwijk, J. A. J. and J. D. Hardy, “Temperature Regulation in Man - A Theoretical Study,” Pflugers Archiv Ges. Physiol., **291**: 129-162, 1966.

Tanabe, S., E. Arens, F. Bauman, H. Zhang, and T. Madsen, “Evaluating Thermal Environments by Using a Thermal Manikin with Controlled Skin Surface Temperature,” ASHRAE Transactions **100, Pt. 1**: 39 - 48, 1994.

Tanabe, S., T. Stuzuki, K. Kimura, and S. Horikawa, “Numerical Simulation Model of Thermal Regulation of Man with 16 Body Parts of Evaluating Thermal Environment (Part 1 Heat Transfer at Skin Surface and Comparison with SET* and Stolwijk Model),” Summaries of Technical Papers of Annual Meeting, Architectural Institute of Japan, 1995.