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***Yazar (Author)**: Üzeyir PALA*

ORCID: 0000-0001-6231-0846

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Investigation of Thermal Comfort for Bus Passengers During a Cooling Test Inside a Climatic Chamber

Araştırma Makalesi/Research Article

Üzeyir PALA

Engineering Faculty, Industrial Engineering Department, Halic University, Turkey

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ABSTRACT

In this current work, thermal comfort for a cooling process inside a bus was described in a combined theoretical and experimental form. The bus was heated to 40℃ for 7 hours within climatic chamber and AC unit was turned on at the beginning of the test. Temperatures, humidity of air and air velocities were measured at certain points to observe effects of ambient conditions on passengers' thermal comfort and physiology. Human body was assumed to be one complete piece which is composed of mainly core and skin compartments. Transient Energy Balance Model by Gagge was used for calculation of changes in thermal conditions. Transient heat and mass transfer between bus interior environment and passenger bodies during cooling period were calculated by a mathematical model. Effects of fast transient conditions on either sensible or latent heat transfer from body, temperatures of core and skin, thermal discomfort and thermal sensation which are all factors for human ergonomics were investigated in detail. The aim in this study is to describe a testing and thermal comfort calculation methodology for assessment of thermal comfort of a bus AC system's cooling performance.

Keywords: Thermal comfort, thermal sensation, bus, cooling period, climatic chamber.

Klimatik Odada Yapılan Bir Soğutma Testi Sırasında Otobüs Yolcuları Termal Konfor Değişiminin Araştırılması

ÖZ

Bu çalışmada, otobüs yolcuları için bir soğutma testi sırasındaki ısıl konfor değişimi teorik ve deneysel olarak ele alınmıştır. Otobüs klimatik oda içinde 7 saat boyunca 40℃ 'ye ısıtılmış ve AC ünitesi test başlangıcında açılmıştır. Ortam koşullarının yolcuların termal konforu ve fizyolojisi üzerindeki etkilerini gözlemlemek için sıcaklıklar, hava nemi ve hava hızları belirli noktalarda ölçülmüştür. İnsan vücudunun esas olarak gövde ve deri bölümlerinden oluşan tek bir parça olduğu varsayılmıştır. Isıl şartlardaki değişimlerin hesaplanmasında Gagge tarafından geliştirilmiş olan Geçici Enerji Dengesi Modeli kullanılmıştır. Soğutma testi sırasında otobüsün iç ortamı ile yolcular arasındaki geçici ısı ve kütle transferi matematiksel bir model ile hesaplanmıştır. Hızlı geçici koşulların, insan ergonomisi açısından önemli faktörler olan vücuttan duyulur veya gizli ısı transferi, vücut ve deri sıcaklıkları, termal rahatsızlık ve termal duyu üzerindeki etkileri detaylı bir şekilde incelenmiştir. Bu çalışmada amaç, bir otobüs AC sistemi soğutma performansının yolcuların termal konforu açısından değerlendirilebilmesi için bir test ve termal konfor hesaplama metodolojisi ortaya koymaktır.

Anahtar Kelimeler: Isıl konfor, ısıl duyu, otobüs, soğutma testi, klimatik oda.

1. INTRODUCTION

Thermal comfort is an important aspect in human factors engineering, i.e. ergonomics which is the science of refining the design of products to optimize them for better and easier human use. In this work, the system to refine and optimize is the AC system of a bus. For this reason, the results of all experimentation and computational efforts are to be checked at the end and the vehicle AC system is to be revised accordingly for a better thermal comfort sensation inside, which leads to comfortable use of buses for especially long distance travelers. This will also increase passenger's efficiency to do other activities during travelling like reading, doing office work, communicating, etc. inside vehicle environment. Therefore, comfort of vehicle passengers inside is an important topic in automotive and thermal comfort models take care of thermal interactions in between.

Thermal comfort and physiological control mechanisms was first investigated by Gagge et al. (1971) (ASHRAE 1997). Thermal comfort models were afterwards evaluated by Doherty and Arens (1988) (ASHRAE, 1997) from physiological bases point of view. Parsons (1993) worked additionally on Human Thermal Environments (ASHRAE, 1989). Parsons (2000) has studied thermal environment effects on comfort, health and working efficiency. Jones (2002) has investigated thermal comfort models regarding their capabilities and limitations, compared several model outputs and at the

**Sorumlu yazar (Corresponding Author)*
e-posta : uzeyirpala@halic.edu.tr

end demonstrated that there exist considerable differences among models' predictions. Different vehicular thermal comfort models developed were comprehensively reviewed to predict vehicular cabins' thermal comfort by Alahmer et al. (2011) in detail by use of different experimental techniques.

Guan et al. (2003a) examined experimentally human thermal comfort inside a car under highly transient conditions and used an acclimatized room for simulation of 16 typical environmental conditions. Guan et al. (2003b) discussed also thermal sensation modeling in another paper. Using environmental and personal input parameters they combined physiological and psychological factors in a mathematical model to investigate physiological responses. Alahmer et al. (2012) used Berkeley and Fanger models to analyze thermal sensation and comfort state inside vehicle cabins with relative humidity (RH) and temperature control.

A model of computation during both heating and cooling processes for mass and heat transfer between human and car interior was presented by Kaynakli et al. (2002). They based their model on body heat balance equation with additional empirical equations describing sweat rate and mean skin temperature. Kaynakli et al. (2003a) calculated all heat losses either sensible or latent, skin temperature and wettedness, PMV and PPD values by simulation. Kaynakli et al. (2003b) worked also on a computational thermal interactions model between body segments and their environment. In another work, Kaynakli et al. (2004) investigated thermal comfort for both heating and cooling processes for a car using heat balance equation in combination to empirical expressions for mean skin temperature and sweat rate and investigated thermal comfort inside a car during both heating and cooling processes. Finally, Kaynakli and Kilic (2005) studied experimentally, thermal interactions and thermal comfort inside a car during heating again. Transient heating effects on thermal comfort by changing temperature, air velocity and RH parameters for vehicle was investigated. Predictions obtained were compared with experimental results.

Kilic and Akyol (2009) studied experimentally together the parameters affecting thermal comfort in the environment for two different ventilation modes by using Gagge Model.

Pala (2014) investigated effects of a heating period for a bus inside a climatic room on thermal comfort by using Gagge's Transient Energy Balance Model for the analysis. In the study, a bus was instrumented to measure all necessary feet and head level temperatures as well as humidity and ambient temperature. An extreme, transient and non-uniform heat-up period of -20℃ to +20℃ in 90 minutes was applied until nearly steady-state conditions reached. Sensible (convection, conduction, radiation) and also latent heat transfer means were all taken into consideration during calculations. At the end of the work, Thermal Sensation and Thermal Discomfort Levels were calculated depending on all measured parameters. In the study, body was taken as one complete piece.

Velt and Daanen (2017) determined the optimal internal temperature in an electric bus during a cool day necessary for thermal comfort of passengers, where energy efficiency is of prime importance as well.

The current paper is based on Gagge's Transient Energy Balance Model describing body heat balance, including also empirical equations to define mean skin temperature and sweat rate. Cooling process effects on passengers' thermal comfort were investigated in detail under transient conditions depending on temperature, RH, air velocity and passengers' clothing ensemble. A data acquisition system inside the room collected the data. Mathematical model was explained step by step in detail for future investigations.

2. MATERIAL and METHOD

HVAC system performance for a vehicle is measured with its ability to reach to an adjusted temperature level during cool-down, warm-up and regulation periods.

Air temperature, velocity of air over passenger bodies, mean radiant temperature and RH are the main environmental factors which are effective on thermal comfort. However, there are also subjective personal factors such as clothing, human metabolism and body weight. Due to these parameters and also thermal transients and non-uniformities, complex physiological thermoregulatory reactions may be observed in human body such as shivering, sweating and vascular constriction and dilation for control of blood flow.

A cool-down process from +32℃ to +25℃ in 60 minutes according to GBK (Gütegemeinschaft BusKomfort E.V.) Standard is a non-uniform and transient phase for passengers exposed to changes on temperature, air velocity and humidity.

Thermal comfort is more critical for long distance travelers; however such studies are usually found for buildings in the literature. Nevertheless, some directly related papers exist on these topics in automotive area, but they were mostly conducted on cars.

Thermal comfort parameters' investigation and definition of the testing and calculation methodology used for AC system development process of a bus is the main aim of this paper. With the help of the analytical model developed, it is possible to see how thermal sensation and discomfort curves vary under given conditions. Necessary optimizations for vehicle AC system can accordingly be done with further iterations.

A standard raw test data from +32℃ down to +25℃ within 60 minutes was used here. Room ambient temperature was kept constant at around +40℃.

Test data does not include core and skin temperatures. Therefore, they were calculated starting from neutral levels (i.e. 33.7℃ for skin and 36.8℃ for core).

Opposite to a heating test, conduction heat transfer between passenger bodies and seats and back supports was not taken into consideration due to relatively lower temperature differences in between.

In this study, heat storages in body core and skin compartments were both considered according to Transient Energy Balance Model and MATLAB code was written for all calculations. The main reason for choosing this model is that, unlike other steady-state models, it has transient nature and considers heat storages in both body core and skin compartments.

The value of clothing ensemble was taken as 0,5clo for bus passengers assuming summer clothing during cooling test (ASHRAE 1989). The gender of the passengers was not taken into consideration during the study.

Either the human body was considered as monolithic or as a whole consisting of 16 parts as in Kaynakli et al. (2004), the resulting differences were studied in the literature and it was determined that there were no significant differences between the two. The main difference here is mostly the local chilling of less clothed left and right feet and fibula regions of the body. However, the monolithic acceptance of the human body generally does not lead to a considerable error in the calculations and is in good agreement.

3. MATHEMATICAL MODELING

Human body interacts with its environment thermally and this can be expressed as follows for core and skin compartments separately according to Gagge Model:

$$S_{cr} = M - \widehat{W} - Q_{res} - Q_{cr,sk} \quad (1)$$

$$S_{sk} = Q_{cr,sk} - (Q_{cd} + C + R + E_{sk}) \quad (2)$$

Note that the meanings of all parameters in the equations are given in Nomenclature Table and the values for all constant parameters commonly used in the literature are given in Table 1.

Table 1. Constant Parameters Used for Calculations

Constant Parameter		Value	Dimension
Ab	Body surface area	1.751	m^2
$c_{p,a}$	Specific heat of air	1005	J/kg K
$c_{p,b}$	Specific heat of body	3470	J/kg K
cp,bl	Specific heat of blood	4145	J/kg K
fcl	Ratio of clothed to nude body area	1,05	-
hfg	Heat of vaporization	2.43*10^6	J/kg
hr	Irradiative heat transfer coefficient	4,7	W/m^2.K
K	Effective heat transfer coefficient between core and skin	5,28	W/m^2.K
m	Body mass	70	kg
m ̇res	Mass flow rate of air inhaled corresponding to 6L/min	0.0001296	kg/sec
Mmet	Standard metabolic heat production rate for a human body	131 W or 75 W/m^2 (Olesen, 1982)	Watt or W/m^2
ηe	Evaporation efficiency	0,85	-
ηcl	Permeation efficiency of summer clothing	0,80	-
nclo	Clothing value	0,5	clo
Qcd	Heat transfer by conduction	0	J
Rcl	Thermal resistance of clothing for one clo	0,155	m^2 K/W
Tcr	Initial body core temperature	36,8	°C
Tex	Temperature of exhaled air	35	°C
Tmilhcr	Core temperature border of mild hypothermia	35	°C
Tmodhcr	Core temperature border of moderate hypothermia	32	°C
Tsevhcr	Core temperature border of severe hypothermia	28	°C
Tsk	Initial skin temperature	33,7	°C
V	Air velocity	0,35	m/s
W	External work done	0	Watt
Wex	Exhaled air humidity ratio	0,95	-

Instantaneous temperature changes are caused by heat storages both in body core and skin compartments and are expressed by:

$$\frac{dT_{cr}}{dt} = \frac{S_{cr}\, A_b}{(1-\alpha)\, m\, c_{p,b}} \quad (3)$$

$$\frac{dT_{sk}}{dt} = \frac{S_{sk}\, A_b}{\alpha\, m\, c_{p,b}} \quad (4)$$

where α is the ratio of skin weight to the weight of total body described by the formula:

$$\alpha = 0.0418 + \frac{0.745}{3600\, \dot{m}_{bl} + 0.585} \quad (5)$$

Change in the core and skin temperatures can be calculated by two formulae below starting from their initial values.

$$T_{cr} = T_{cr} + 10\,(\frac{dT_{cr}}{dt}) \quad (6)$$

and

$$T_{sk} = T_{sk} + 10\,(\frac{dT_{sk}}{dt}) \quad (7)$$

During the test, measurement intervals were 10 seconds.

Heat losses through convection and irradiation from body to environment can be given as:

$$C + R = \frac{T_{sk} - T_o}{R_{cl} + 1/[(h_c + h_r)\, f_{cl}]} \quad (8)$$

Operative temperature (T_o) in the above equation is given as:

$$To = \frac{h_r\, \overline{T_r} - h_c\, T_a}{h_r + h_c} \quad (9)$$

$\overline{T_r}$ is body mean radiant temperature and it is empirically defined as:

$$\overline{T_r} = 0.94\, T_a - 1.38 \quad (10)$$

h_c is the coefficient of convective heat transfer and given as:

$$h_c = 8.3\, V^{0.6} \quad (11)$$

Sweating and natural diffusion of water through skin cause both latent heat losses from skin and it is calculated with the following formula:

$$E_{sk} = E_{rsw} + E_{dif} = \frac{w\,(P_{sk,s} - P_a)}{(R_{cl}/\eta_{cl}\, LR) + (1/h_c\, f_{cl}\, LR)} \quad (12)$$

LR is Lewis ratio and it is the ratio of evaporative heat transfer coefficient divided by convective heat transfer coefficient.

$$LR = 15.15 \frac{(T_{sk} + 273.2)}{273.2} \quad (13)$$

Partial pressure of saturated water vapor at temperature of skin can be calculated as:

$$P_{sk,s} = 610.78\, e^{\left(\frac{17.2694\, T_{sk}}{T_{sk} + 238.3}\right)} \quad (14)$$

and partial pressure of water vapor in ambient air is calculated by:

$$P_a = \frac{RH}{100}\, P_{sk,s} \quad (15)$$

During respiration, body loses either sensible or latent heat through evaporation and convection of water vapor inside inhaled air through respiratory tract.

Heat losses by convection (C_{res}) and evaporation (E_{res}) due to respiration is given by:

$$Q_{res} = C_{res} + E_{res} = \dot{m}_{res} \frac{[c_{p,a}\,(T_{ex} - T_a) + h_{fg}\,(W_{ex} - W_a)]}{A_b} \quad (16)$$

The following expression gives heat transfer between core and skin:

$$Q_{cr,sk} = \left(K + c_{p,bl}\, \dot{m}_{bl}\right)(T_{cr} - T_{sk}) \quad (17)$$

Blood flow rate is given as:

$$\dot{m}_{bl} = \frac{1}{3600}\left(\frac{6.3 + 200\, WSIG_{cr}}{1 + 0.5\, CSIG_{sk}}\right) \quad (18)$$

where $WSIG_{cr}$ and $CSIG_{sk}$ can be expressed as:

$$WSIG_{cr} = T_{cr} - 36.8 \quad (19)$$

$$CSIG_{sk} = 33.7 - T_{sk} \quad (20)$$

Production of metabolic energy due to shivering can be calculated with the following empirical equation:

$$M_{shiv} = 19.4\, CSIG_{sk}\, CSIG_{cr} \quad (21)$$

where $CSIG_{cr}$ is calculated from

$$CSIG_{cr} = 36.8 - T_{cr} \quad (22)$$

Total body heat production rate is then:

$$M = M_{met} + M_{shiv} \quad (23)$$

Sweat production rate per unit area of skin is calculated with the following empirical equation:

$$\dot{m}_{rsw} = 4.7 * 10^{-5}\, WSIG_b\, e^{\left(\frac{WSIG_{sk}}{10.7}\right)} \quad (24)$$

where $WSIG_b$ and $WSIG_{sk}$ are given by:

$$WSIG_b = T_b - 36.49 \quad (25)$$

$$WSIG_{sk} = T_{sk} - 33.7 \quad (26)$$

In the literature, mean body temperature T_b is given as:

$$T_b = \alpha\, T_{sk} + (1 - \alpha)\, T_{cr} \quad (27)$$

Polynomial expressions obtained with curve fit for T_a and RH parameters are as shown below.

$$T_a = 3.752 * 10^{-28}\, t^8 - 1.195 * 10^{-23}\, t^7 + 1.569 * 10^{-19}\, t^6 - 1.101 * 10^{-15}\, t^5 + 4.497 * 10^{-12}\, t^4 - 1.100 * 10^{-8}\, t^3 + 1.641 * 10^{-5}\, t^2 - 0.016\, \mathrm{t} + 39.680 \quad (28)$$

$$RH = 2.522 * 10^{-51}\, t^{15} - 1.655 * 10^{-46}\, t^{14} + 4.875 * 10^{-42}\, t^{13} - 8.522 * 10^{-38}\, t^{12} + 9.838 * 10^{-34}\, t^{11} - 7.894 * 10^{-30}\, t^{10} + 4.512 * 10^{-26}\, t^9 - 1.851 * 10^{-22}\, t^8 + 5.414 * 10^{-19}\, t^7 - 1.106 * 10^{-15}\, t^6 + 1.516 * 10^{-12}\, t^5 - 1.295 * 10^{-9}\, t^4 + 5.870 * 10^{-7}\, t^3 - 7.099 * 10^{-5}\, t^2 - 0.028\, \mathrm{t} + 44{,}523 \quad (29)$$

TSENS and DISC comfort prediction indices given by Gagge et al. are, on the other hand, expressed as follows:

$$TSENS = \begin{cases} 0.4685\left(T_b - T_{b,c}\right) & \text{if } T_b < T_{b,c} \\ \dfrac{4.7\eta_e\left(T_b - T_{b,c}\right)}{T_{b,h} - T_{b,c}} & \text{if } T_{b,c} \le T_b \le T_{b,h} \\ 4.7\eta_e + 0.685\left(T_b - T_{b,h}\right) & \text{if } T_{b,h} < T_b \end{cases} \quad (30)$$

$$DISC = \begin{cases} 0.4685\left(T_b - T_{b,c}\right) & \text{if } T_b < T_{b,c} \\ \dfrac{4.7(E_{rsw} - E_{rsw,req})}{(E_{max} - E_{rsw,req} - E_{dif})} & \text{if } T_{b,c} \le T_b \end{cases} \quad (31)$$

Mean body temperature T_b is compared with the levels of upper and lower evaporation control temperatures.

$$T_{b,c} = (0.194/58.15)\left(\mathrm{M} - \widehat{W}\right) + 36.301 \quad (32)$$

$$T_{b,h} = (0.347/58.15)\left(\mathrm{M} - \widehat{W}\right) + 36.669 \quad (33)$$

E_{rsw} is heat loss due to sweat evaporation and given as:

$$E_{rsw} = \dot{m}_{rsw}\, h_{fg} \quad (34)$$

$E_{rsw,req}$ is the required E_{rsw} that assures thermal comfort and is given as:

$$E_{rsw,req} = 0.42\left(\mathrm{M} - \widehat{W} - 58.15\right) \quad (35)$$

A maximum total value of latent heat loss from skin by diffusion and sweating together is E_{max} and it is given by:

$$E_{max} = \frac{P_{sk,s} - P_a}{(R_{cl}/\eta_{cl}\, LR) + (1/h_c\, f_{cl}\, LR)} \quad (36)$$

Note that, it is the case, where w=1 in Eqn. 12.

Body wet portion required for sweat evaporation can be expressed as:

$$w_{rsw} = E_{rsw}/E_{max} \quad (37)$$

Skin wettedness (w) can be calculated empirically by:

$$w = 0.06 + (0.94\ E_{rsw}/E_{max}) \quad (38)$$

Evaporation by diffusion is given as:

$$E_{dif} = 0.06\ (1 - w_{rsw})\ E_{max} \quad (39)$$

Note that (1- w_{rsw})= w_{dif}

The scale for both Thermal Sensation and Discomfort indices is: (+5) : extremely hot and not bearable; (+4) : very hot; (+3) : hot; (+2) : warm; (+1) : slightly warm; (0) : **neutral**; (-1) : slightly cool; (-2) : cool, (-3) : cold; (-4) : very cold; (-5) : extremely cold and not bearable.

4. EXPERIMENTAL SETUP

The passenger compartment of a bus is relatively a big space in which there exist non-uniform, 3D, unsteady turbulent flows and variations of internal temperature during both cooling and heating processes. Therefore, due to serving for long distances with so many passengers, AC performance of a bus is crucial.

Capacities of cooling elements of the bus are:

1- AC Unit at the Roof = 35 kW (not tropical version)

2- Defroster AC Unit = 8 kW

Total vehicle cooling capacity = 43 kW

Window and aisle air exits from main air duct have openings with constant cross sections and are not adjustable. However service sets just over passenger heads are on the contrary adjustable depending on passengers' comfort needs.

Shape of air inlet/outlet nozzles together with their locations, average air flow rate over passengers, direction of ventilated air and distribution of passengers, etc. are all effective parameters for ventilation characteristic in a passenger bus. In this respect, a non-uniform internal air and temperature distribution under hot ambient conditions may cause sweating and therefore discomfort of the occupants inside.

The test was carried out with 54 seats, 3-axle bus. Air temperatures and velocities inside and relative humidity either inside or outside of the bus were all measured with proper sensor instrumentation. Types and points of measurements are shown in Figure 1. Air temperature measurements were also performed for head levels on the given locations. These values were then averaged in order to use for the rest of calculations.

Figure 1. Measurement Points on the Pasenger Bus

A cooling data collected at every 10 seconds for all temperature and RH parameters was used in this thermal comfort investigation work. Outside RH data were measured additionally. The data was saved for 128 minutes, which is much longer than normal test duration of 60min. according to GBK Standards for cooling tests; however instead of required +32℃ as the initial chamber temperature, +40℃ was used and at the end cooling amount was observed as temperature difference. According to release condition of GBK Standard, a temperature difference of 7℃ within 60min. must be achieved by means of bus AC system.

K Type thermocouples (Measurement range: -200℃ - +1370℃; Accuracy: +/- 0.3℃; Resolution: 0,1℃) were used for temperature measurements and Rotronic HC2-S sensors (Measurement range: 0–100% relative humidity; Accuracy: 0.8%; Resolution: 0,01℃) were used for inside and outside RH measurements.

Air velocities were separately measured by Testo 435 Anemometer (Measurement range: 0–20 m/s; Accuracy: +/- 0.03 m/s + 4% of measurement value) and 0.35 m/s average air velocity value was used for calculations.

The experiment was conducted according to GBK Standard with the following conditions:

- Ambient temperature is +40℃ (Normally start temperature is 32℃ according to GBK Standard, but a temperature difference of 7℃ within 60min. will be aimed for AC system release for 3-5 star certification).
- Vehicle shall wait min.7 hours under +40℃ for homogeneous temperature distribution without engine running.
- RH inside the bus is tried to be kept constant starting from 40% RH at the beginning.
- Each passenger is simulated by 131W heat load and 25% humidification, i.e. 40gram/hour steam per person during the test. For each meter of bus length, 4 persons are taken into consideration for a 4 star seat layout.
- Doors and flaps opening to outside are all to be closed before starting the test and circulating mode is adjusted.
- Vehicle shall not move during the test; it is stationary.
- Temperature deviations of max. +/-3K between measured and set values are allowed and cannot be exceeded in the chamber.
- Acclimatized room should be equipped accordingly for measurements.
- Wind speed inside the chamber shall be 80 km/h during the test.
- Defrosting Unit of the vehicle is set at min. temperature value and runs with 100% fan speed.
- Defrost flaps shall be in circulation position.
- Cooling system is to be set to min. Tset value, i.e. maximum cooling performance.
- Service sets and nozzles must be all opened completely before the test in circulation mode.
- Engine rpm level shall be fixed to 1500 rpm during the test by using a special tool to fix it for a constant compressor operation.
- During cooling test max. 2 persons is allowed inside the bus.
- Testing time starts immediately after vehicle engine and then AC compressor is started.
- The temperature measurements for heads shall be performed at 150 cm height from vehicle ground level.
- The average of average temperatures of heads shall be the main evaluation criterion for complete vehicle.
- Test shall continue until steady-state condition is reached, which is longer than standard 60min. test.

Each heavy vehicle brand defines its own testing procedure and test set-up and they may differ to some extent in this respect. The test-setup and procedure used in this work were both standard and they served for comparison purposes among different vehicle AC System configurations only. Therefore one-to-one direct comparison according to different load drive cycle was intentionally ignored in this work.

Release Condition for a Passenger Bus:

The internal temperature of the bus must decrease from +32℃ to +25℃ within 60 minutes according to the main requirement by GBK for busses. This means that within 60min. of measurement time, a temperature decrease of 7℃ must be achieved. Temperatures inside and outside of the vehicle were both around +40℃ and RH value was around 41% at the beginning of the test and note that there was also a humidification inside the bus to simulate release of water vapor from passenger bodies.

5. RESULTS AND DISCUSSION

Initial temperature level within bus compartment was +40℃ at the beginning of cooling test. Raw measurement data for all channels was collected with respect to independent time variable. The average head level temperatures were taken as internal temperature data of the vehicle for further calculations. Chamber temperature i.e. the ambient temperature of the bus was kept constant at around 40.2℃ throughout the test.

In Figure 2 variations of internal temperature and RH inside the vehicle are shown together. Test data was normally longer, however only a regular portion of 7720 seconds was used as the test data. A minimum temperature level of 26℃ was reached at the end of test time. After 60min. from test start, internal temperature of the bus was measured to be 28.8℃, which means that a temperature decrease of 11.2℃ from 40℃ down to 28.8℃ was achieved by means of bus AC system. This means that according to this temperature decrease result and considering GBK Standard, the bus cooling system can be released. Initial RH value was almost 41% and it varied around 47% especially to the end of cooling process. Multi degree polynomials were fit to the measured data with Eqns. 28 and 29 for further calculations in MATLAB.

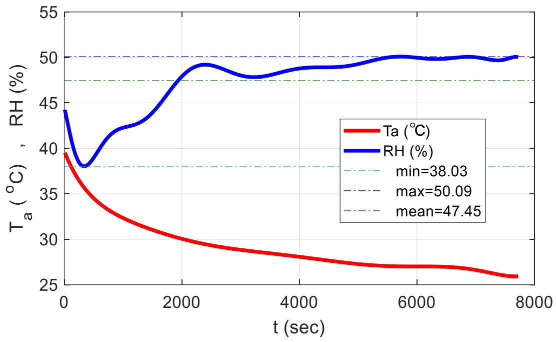

Figure 2. Bus Internal Temperature and RH inside the Bus

Heat loss through respiration is dependent directly on ambient temperature inside the vehicle and it is calculated by Eqn. 16. By continously decreasing bus internal temperature, respiration heat loss decreases also due to decreasing temperature gradient. Min. respiration heat energy loss was 81.37, max. is 102.4 and the mean was 85.97 W/m^2.

In Figure 3 warm and cold signals from core, skin and complete body are observed. Skin cold signal exceeds 12℃ as maximum value and 8.6℃ as mean value. For $CSIG_{cr}$, a max. value of 0.1943℃ was observed. A very small value of max. 0.0001376℃ was measured for core warm signal ($WSIG_{cr}$). $WSIG_{sk}$ and $WSIG_b$ values were measured to be both zero.

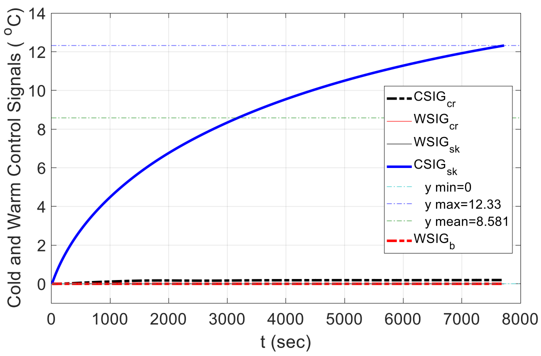

Figure 3. Control Signals (Cold and Warm)

Heat produced by body shivering, in addition to body constant metabolic heat production of 131 W/person, has a max value of 46.4 W/person.

As the internal temperature inside the bus and therefore skin temperature decreases, rate of blood flow between core and skin tends to stabilize to the end of the test. Its max. value is 0.00175, min. value is 0.0002443 and the mean value is 0.0003846 kg/s.m^2.

Core and skin temperatures and blood flow in between calculated by Eqn. 18 are influential on energy flow between core and skin. The variation of this energy flow is shown in Figure 4. As expected, it increases continuously after test start. To compensate the heat loss due to decreasing ambient temperature, body generates heat within body core and this energy is transferred to the skin compartment. By decreasing internal bus temperature, it continues to increase and it exceeds normal metabolic heat generated by the body of 75W/m^2 which is equal to 131 W/person divided by total body surface area of 1.751m^2 of a person. The reason behind is normally due to shivering effect.

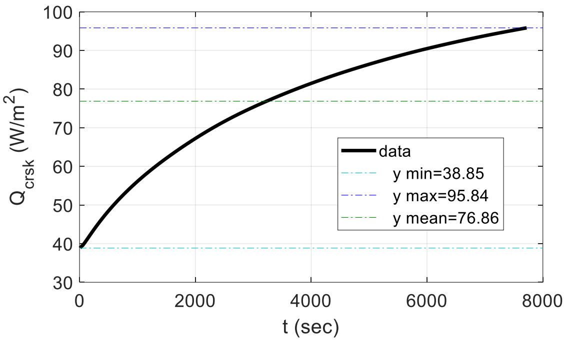

Figure 4. Heat Energy Flow between Core and Skin

Heat transfer by convection and radiation cumulatively decreases by decreasing bus internal temperature. A good reason behind this fact should be that the passengers have 0.5clo clothing and although bus internal temperature was 40℃ at beginning of the test with relatively higher temperature gradient between bus ambient and skin temperature, this gradient decreases by time throughout the test. Its max. value is 189.2, min. value is 121.5 and the mean value is 142 W/m^2.

During test time bus internal temperature decreases continuously by cooling performance of AC system and therefore heat transfer through evaporation decreases as well. There is relatively small amount of heat loss here in comparison to heat losses through convection and radiation, as expected. Its max. value is 31.04, min. value is 13.89 and the mean value is 18.51 W/m^2.

Energy stored in core and skin compartments are respectively depicted in Figure 5. As seen from the graphs, equilibrium conditions are observed around zero level in both cases. It can be noted that body core experiences an extreme change at the beginning of the test to react sudden changes and then stabilizes around zero to the end. In case of the skin however, a relatively higher amount of energy is stored to compensate decreasing ambient temperature. As the bus internal temperature decreases by means of cooling, it stabilizes again around zero level due to energy balance of the body.

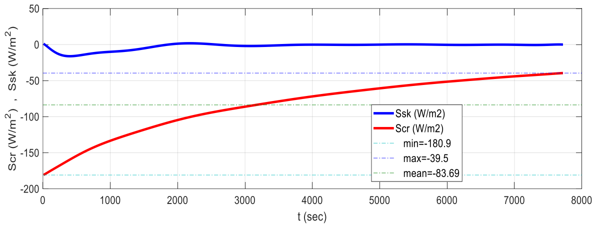

Figure 5. Heat Energy Stored in the Body Core and in the Skin

As a human physiology rule, body keeps core temperature always at T_{cr}=36.8°C constant level with relatively small variations which is a thermoregulatory function. During complete cooling process, there is a maximum decrease of 0.19°C in core temperature from its neutral value. Core temperature is calculated as always above mild, moderate and severe hypothermia temperature limits. These physiologically accepted levels are in turn 35°C, 32°C and 28°C. Skin temperature however decreases relatively much more due to directly being exposed to ambient conditions as observed in Figure 6. According to the mathematical model, decrease in skin temperature is bigger than 12°C.

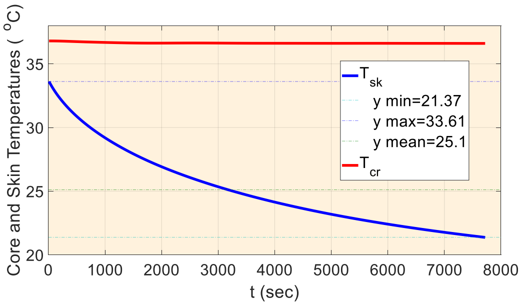

Figure 6. Temperatures of Skin and Core

Mean, low, high body control temperature levels are given in Figure 7. It is seen that a decline of > 12°C in the skin temperature causes also a related decline in body mean temperature as well according to Eqn. 27.

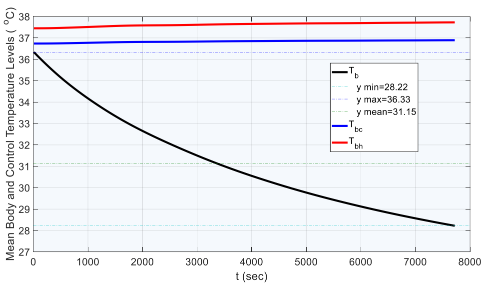

Figure 7. Body Control Temperature Levels (Low, Mean and High)

In Figure 8, a comparison of all heat losses by radiation, convection, respiration and evaporation is shown together. Heat loss under these test conditions is observed mostly by convection and radiation, then by respiration and then by finally evaporation through skin. Min. total heat loss is 216.9, max. is 313.2 and the mean is 246.5 W/m^2.

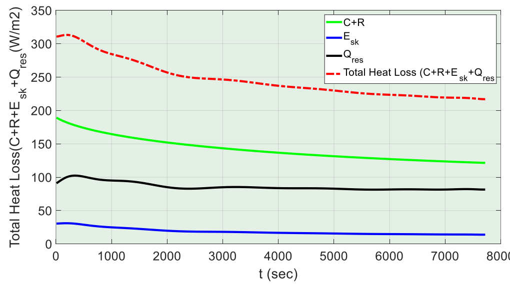

Figure 8. Total Heat Losses as overall (C+R+Qcd+Qres+Esk)

Certain boundary conditions in the data set led TSENS and DISC graphs to be the same exactly as observed in Figure 9.

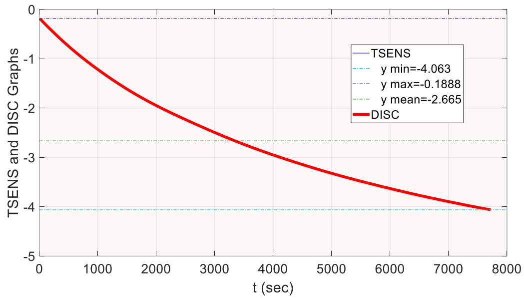

Figure 9. Thermal Discomfort and Thermal Sensation Graph

At the beginning of the test, body starts with neutral thermal comfort feeling since we start the analysis with neutral core and skin temperatures. TSENS starts with -0.19 which is a negative value, but as the hot environment is experienced by the body of bus passenger right at the beginning and skin temperature decreases more than 12°C down to 21.37°C, it falls down until -4.063 till to the test end. Considering only the final TSENS or DISC value, this is a thermal sensation scale between cold-very cold with 0.5clo summer clothing. However, when considering the average index value of -2.665 throughout the test duration, it can easily be concluded that the passengers inside the vehicle experienced a thermal sensation between cool and cold as overall.

6. CONCLUSIONS

A description of thermal comfort during a cooling process inside a bus in a climatic chamber was studied here in a combined theoretical and experimental form. A similar situation may occur normally during ride conditions of busses between cities in our daily lives in summer seasons.

In Pala (2014) study, the heating performance of the vehicle from -20°C to +20°C and the thermal comfort of the passengers were investigated. In this study however the cooling performance of the vehicle and the thermal comfort of the passengers are investigated. In this respect, both studies complement each other because they deal with completely opposite cases.

Effects of changing internal temperature, AC cooling capacity, clothing ensemble, RH, average air velocity, etc. can directly be checked by means of MATLAB algorithm iterations already developed for this purpose. In case if any problem detected in the cooling system design at the end of testing phase, HVAC design and testing team can analyze and accordingly detect where and how to make the required revisions, improve the system and retest it for thermal comfort validation for a better passenger ergonomics inside the vehicle.

In the literature, no other holistic study suitable for product design benchmarking was found which details the method step by step in terms of cooling test in buses.

Human body was taken as one complete piece instead of 16 sedentary pieces for a good approximation for these types of works where we have dynamic ambient and also difficult experimental conditions.

The current study provides a standard test and computation model for bus cooling system design and test engineers in order to assess a bus AC system performance and it is also valid either for heating or regulation tests.

There seems to be no need to measure skin and core temperatures for cooling test in Transient Energy Balance Model, because neutral temperatures can easily be used for calculations.

$T_b < T_{b,c}$ is always satisfied in cooling test as observed also in Figure 7. For this reason, the first option of index equations (Eqns. 30 and 31) of $TSENS = DISC = 0.4685(T_b - T_{b,c}) \quad if\ T_b < T_{b,c}$ was always satisfied. Therefore TSENS and DISC graphs were calculated to be exactly the same. Important changes in thermal sensation calculation results could be expected, when the second and the third options of TSENS index formula was also used depending on testing conditions. This would probably lead to a completely different TSENS and DISC graph; however such a situation did not occur during the current test.

It can be noted that minus TSENS and DISC values found here may be similar to some heating test results with minus temperature degrees. However, this could be possible considering that clothing ensemble is completely different in each case. For winter heating test clothing ensemble is normally taken as 1.5clo, whereas for summer cooling test clothing ensemble is taken as 0.5clo; which directly affects all calculation results.

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