Isı Bilimi ve Tekniği Dergisi, 32, 1, 101-107, 2012
J. of Thermal Science and Technology

ISSN 1300-3615

TRANSIENT EFFECTS OF DIFFERENT HEATING MODES ON TEMPERATURE AND HUMIDITY INSIDE THE AUTOMOBILE CABIN DURING HEATING PERIOD

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(Geliş Tarihi: 30. 11. 2010, Kabul Tarihi: 12. 01. 2011)

Abstract: The aim of this study is to investigate the transient effects of heater on temperature and humidity in an automobile cabin under transient heating period. Interior volume of an automobile is relatively small to other indoor environments, so that temperature and humidity values can rapidly change under highly transient conditions. Studies that are investigating the effects of heater on automobile cabin environment in real car conditions are restricted. Experiments were carried out in a parked car inside a laboratory at nights to prevent the possible wind and solar irradiation effects. In the experiments only plane vents were operated with three different air velocity levels. Temperature and relative humidity differences between air velocity levels were obtained, relations between time, temperature and relative humidity were calculated. From this study it is understood that temperature and relative humidity values inside a car vary directly from air velocity values. The obtained results can be used to improve other thermal comfort studies inside automobiles and also CFD analyses can be validated under transient conditions.
Keywords: Automobile, Heating period, Thermal comfort.

ISITMA SÜRECİNDE FARKLI ISITMA MODLARININ OTOMOBİL KABİNİ İÇERİSİNDEKİ SICAKLIK VE BAĞIL NEME OLAN ANLIK ETKİLERİ

Özet: Bu çalışmanın amacı ısıtıcının bir otomobil kabini içerisindeki sıcaklık ve bağıl neme olan anlık etkilerinin incelenmesidir. Otomobil kabini diğer iç ortamlara göre daha küçük olduğundan sıcaklık ve bağıl nem değerleri geçici rejim koşullarında çok hızlı bir biçimde değişmektedir. Isıtıcının otomobil kabini içerisindeki etkilerini gerçek kabin ortam koşullarında inceleyen çalışmalar oldukça sınırlıdır. Deneyler olası rüzgar ve güneş ışınımı etkilerini önlemek için laboratuarda park edilmiş bir otomobil içerisinde gerçekleştirilmiştir. Deneylerde üç ayrı hava hız düzeyi olan konsol menfezleri çalıştırılmıştır. Sıcaklık ve bağıl nem değerlerini hava hız düzeylerine göre farklılıkları ve zamana göre sıcaklık, bağıl nem değerleri arasındaki bağıntılar elde edilmiştir. Bu çalışmadan anlaşıldığı üzere araba kabini içerisindeki sıcaklık ve bağıl nem değerleri hava hızı değerlerinden doğrudan etkilenmektedir. Bu çalışmadan elde edilen sonuçların, otomobillerdeki ısıl konfor çalışmalarının geliştirilmesinde ve geçici rejim koşullarında gerçekleştirilen sayısal hesaplamalı akışkanlar dinamiği analizlerinin doğrulanmasında kullanılabilir.
Anahtar Kelimeler: Otomobil, Isıtma süreci, Isıl konfor

NOMENCLATURE

clo	clothing insulation [$0.155\ m^2°C/W$]
met	metabolic rate [$60\ W/m^2$]
Rh	relative humidity [*%*]
t	time [*s*]
T	temperature [*°C*]
V	air velocity at vent outlet [*m/s*]

INTRODUCTION

Passenger and the driving thermal comfort has been always a concern since the development of modern cars, and thermal comfort inside the automobile cabin affects the driver's awareness and ability to concentrate (Bhatti, 1999 a,b). Climate control systems in vehicle compartments result in non-uniform temperature distributions, with the occurrence of considerable spatial temperature gradients of over 10°C. For instance, obtained spatial temperature differences from 7 °C under an environmental of 26.7 °C (summer conditions) and increasing up to 13°C in winter conditions while the environmental temperature became as low as -20 °C (Zimney et. al, 1999). This heat stress not only influences the visibility (Nasr, 2000) but also affects the mental condition of the driver (Cisternino 1999).

Aroussi and Aghil (2000), indicated that the need to improve the climatic comfort in passenger vehicles is crucial not only to passenger comfort but also to their safety, and to make progress in this area, a good understanding of the flow behavior inside the passenger compartment is required. Daanen et al. (2003), simulated the effects of warm, cold and thermoneutral ambient conditions on driving performance. They obtained that driving performance was affected from cold and hot ambient conditions. Jones (2002), compared several thermal sensation model outputs with the measured data for a typical winter automobile warm-up conditions and showed that the models differed widely in their predictions.

Kaynakli et al. (2002), presented a computational model of heat and mass transfer between a human and the vehicle interior environment during heating and cooling periods. Their model was based on the heat balance equation for human body, combined with empirical equations defining the sweat rate and mean skin temperature. Kaynakli and Kilic (2005), also investigated the thermal comfort inside an automobile during the heating period and compared their simulation model and showed that the data obtained from their experimental studies were in good agreement with their simulation model. Guan et al. (2003a), presented an experimental study to examine human thermal comfort under highly transient conditions inside an automobile. In their study, they used a climatic chamber to simulate 16 different winter and summer conditions and thermal sensation modeling was investigated in their other paper (Guan et al., 2003b). In their mathematical model, physiological and psychological factors were combined, environmental and personal parameters used as inputs to determine the physiological responses.

Guan et al. (2003c), also presented a literature review on current advances in thermal comfort modeling for both building and vehicle HVAC applications. Walgama et al. (2006), presented a wide review of passenger thermal comfort in vehicles and they presented various empirical, thermal comfort and computational models. Quanten et al. (2007), made a comparison of thermal comfort performance of two different types of road vehicle climate systems, two cars which have an un-air-conditioned heating cooling device and an air-conditioning climate control unit. They encountered temperature gradients in un-air-conditioned car up to 8-9°C, on the other hand air-conditioned car had temperature gradients of 5-6°C for the same condition. Yamashita et. al. (2007), investigated summertime thermal conditions for cars in a climatic chamber. They reproduced the thermal conditions such ambient temperature, passenger seat temperature and radiation panels then they observed the effects of these parameters. They concluded that ambient temperature is the only factor that influenced thermal acceptance. Cassetta and Musto (2006), assessed thermal comfort in a car cabin which has sky-roof. They made the first experimental study on this subject by using four different sky-roofs and compared the performances of them with on the road experiments.

Hodder and Parsons (2007), determined the effects of solar radiation on thermal sensation in a test chamber. They used metal halide compact source iodide lamps to create artificial sunlight during the experiments. In their study they performed three cases with different intensity of solar radiation, spectral content of solar radiation and glazing types. A linear relationship was found between solar radiation and the thermal sensation. Korukçu and Kilic (2009), used IR-thermography to determine instant surface temperature distribution and facial skin temperatures of the driver inside an automobile cabin during transient heating and cooling periods. They also investigated different air velocity levels that are provided by the vents. Ambs (2002), analysed a car cabin during transient cooling period by using finite element method. In his model thermal comfort level and local temperature values of virtual mannequins were obtained. From his study local discomfort regions and thermal sensation for virtual passengers were also determined.

Akyol and Kilic (2010), modeled thermal loads inside the automobile cabin. In their model they calculated the interactions between the passenger and the ambient that is affected by solar irradiation. They also investigated the effect of colours and windows’ optical properties such as transmissivity, reflectivity and absorptivity coefficients on thermal comfort. Mezrhab and Bouzidi (2005), developed a numerical model for thermal comfort inside car compartment under transient conditions with combined conduction, convection and radiation heat transfer. They also investigated effects of solar radiation, different glazing types, car colours and radiative properties of materials inside the compartment. Kilic and Sevilgen (2009), performed a three-dimensional transient numerical analysis inside an automobile cabin during heating period. They added a virtual manikin with real dimensions and physiological shape into the vehicle cabin. The manikin surfaces were subjected to either constant heat flux or constant temperature. They calculated three-dimensional fluid flow, temperature distribution, and heat transfer characteristics inside the cabin.

In this study, the effects of different air velocity levels on temperature and relative humidity inside the cabin for 10°C outside temperature were obtained. The correlations between temperature and relative humidity were calculated and the effects of air velocity levels were investigated.

METHODOLOGY

The experiments were carried out in a parked FIAT Albea 2005 inside a laboratory to prevent the possible interactions such wind, rain or other weather conditions between the test car and the environment. All of the experiments were done at nights to eliminate the possible effect of solar radiation. The vents were located on the plane, which have 3 levels of air velocity.

The data were collected during the February 2008 with 27 experiments, there is only one healthy male subject chosen to omit the individual responses inside the compartment. The characteristics of the subject were as follows: age = 28 yr, height = 183 cm, weight = 95 kg. The mean outside temperature of the car inside the laboratory was measured in every 10 seconds and the mean values were: 10.5°C (±0.8).

The initial temperature and the relative humidity inside the compartment were adjusted to 14°C and %45 respectively for the heating period at the beginning of all experiments. The indoor conditions such temperature, relative humidity and the air velocity measurements were made by a Testo 350 M/XL 454 probe in every 10 seconds. Accuracy, and the measuring range of the equipments were presented in Table 1.

Table 1. Accuracy of the equipments.

Parameter	Interval	Tolerance
Air velocity	0 m/s – 10 m/s	± 0.04 m/s
Relative Humidity	0 % – 100 %	± 0.1 %
Temperature	- 20°C – 70°C	± 0.4 °C

The subject wore casual clothes, which is approximately 1 clo for winter conditions. Level of metabolic activity was taken 1 met for a sedentary person (ISO 9920). The subject stayed 15 min in the car. Experimental setup is illustrated in Figure 1.

Figure 1. Experimental setup inside the cabin, **1-**Temperature, Rh probe, **2-**Air velocity, **3-**Data logger.

To determine the effects of air velocity inside the passenger compartment, subject sat 15 minutes inside the car sedentary and measurements were taken both from inside and outside simultaneously. The differences of both temperature and humidity between air velocity values were presented via multiple analyses of variance (MANOVA).

RESULTS

Air velocity

The measured air velocity values for the velocity levels from the vent outlets were presented in Table 2.

Table 2. Air velocity values.

Symbol	Air velocity (m/s)
V_1	0.78
V_2	1.65
V_3	2.66

Vent outlet temperatures

The measured air temperature values in the car at the outlet of the vents for the heating period were presented in Figure 2.

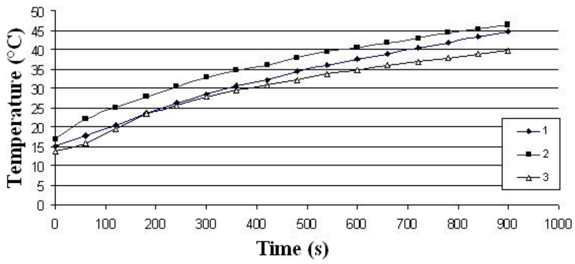

Figure 2. Measured air temperature values at the vent outlet for the heating period.

As seen on from the Figure 2 outlet air temperature for the third air velocity level is lower than that of other velocity levels. The capacity of the heater is same for all air velocity levels, therefore outlet air temperature values are lower for the high air velocity levels.

Vents and indoor air temperature differences

The measured air temperature difference values between vent outlet and the indoor for the heating period were presented in Figure 3.

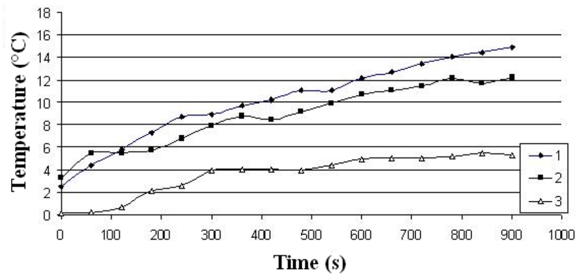

Figure 3. Air temperature difference values between vent outlet and the indoor for the heating period.

In the Figure 3 temperature difference between vent outlet and the indoor air temperature were calculated during the heating period. With the increasing air velocity level, indoor air was also heated. Hence the third air velocity level has the lowest outlet temperature and the highest indoor temperature, lower air temperature differences were obtained than that of for the other air velocity levels.

Effect of air velocity

Mean (and standard error) plots of temperature for air velocity values at 10°C outside temperature are given in Figure 4.

Mean (and standard error) plots of relative humidity for air velocity values at 10°C outside temperature are given in Figure 5.

From the multiple analysis of variance (MANOVA), the effects of air velocity and time factors on temperature

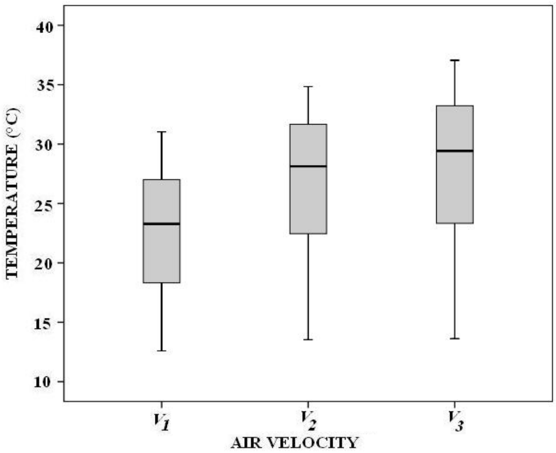

Figure 4. Mean temperatures for air velocity values at 10°C outside temperature.

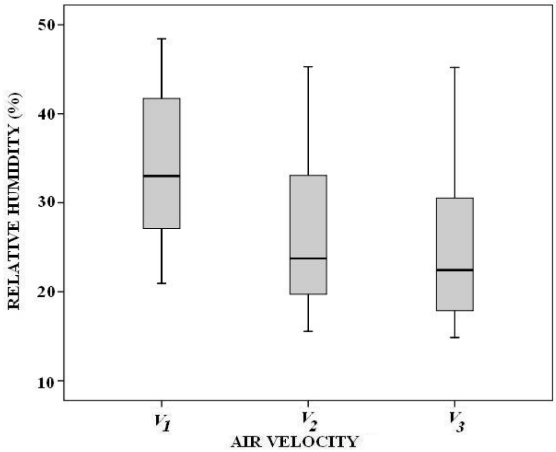

Figure 5. Mean humidity values for air velocity values at 10°C outside temperature.

were found significant ($F_{VELOCITY}$ =190.164, p < 0.05) and (F_{TIME} =161.828, p < 0.05). On the other hand, the effect of the interaction of air velocity and time factors on temperature was not found significant ($F_{VELOCITYxTIME}$ =1.145, p >0.05).

Multiple analysis of variance (MANOVA) results for the relative humidity showed that the effects of air velocity and time on humidity were found significant ($F_{VELOCITY}$ =208.813, p < 0.05), (F_{TIME} =138.797, p < 0.05), but the interaction of air velocity and time factors were not found significant ($F_{VELOCITYxTIME}$ =1.411, p >0.05).

As seen from the Figure 4 and Figure 5, temperature and the humidity values differ with V_1 , V_2 and V_3 air velocity values.

The test statistics for air velocity values after multiple analysis of variance (MANOVA) are presented in Table 3.

From the partial eta squared values of the multiple analysis of variance (MANOVA) results which were presented in Table 4, both air velocity and time factors were found significant on temperature and humidity parameter at the same level. On the other hand, interaction of air velocity and time factors was found less effective on temperature and humidity.

Table 3. MANOVA test statistics for air velocity at 10°C outside temperature.

	Air-Velocity	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
Temp. (°C)	V_1	22.62	.20	22.23	23.02
	V_2	26.79	.20	26.40	27.18
	V_3	27.74	.20	27.35	28.13
Rel. Hum. (%)	V_1	34.06	.32	33.42	34.71
	V_2	26.66	.32	26.01	27.30
	V_3	25.42	.32	24.78	26.06

Table 4. Partial eta squared results at 10°C outside temperature.

Source	Dependent Variable	Partial Eta Squared
Air-Velocity	Temp.	0.80
	Rel. Hum.	0.81
Time	Temp.	0.96
	Rel. Hum.	0.95
Air-Velocity x Time	Temp.	0.26
	Rel. Hum.	0.31

In Table 5, the results of Student-Newman Keul's Test were presented of temperature for air velocity values at 10°C outside temperature.

In Table 6, the results of Student-Newman Keul's Test were presented of relative humidity for air velocity values at 10°C outside temperature.

From the Tables 5 and 6, it can be seen that there are three subgroups occurred both in temperature and humidity parameters, because V_1, V_2 and V_3 values are different from each other.

Table 5. Student-Newman Keul's Test of temperature for air velocity values at 10°C outside temperature.

Air-Velocity	Subset		
	1	2	3
V_1	22.62		
V_2		26.79	
V_3			27.74

Table 6. Student-Newman Keul's of relative humidity for air velocity values at 10°C outside temperature.

Air-Velocity	Subset		
	1	2	3
V_3	25.42		
V_2		26.66	
V_1			34.06

The relations between time and temperature, and humidity with time and temperature were obtained from the linear regression analysis. From the Equation (1), relation between time (*t*) and temperature (*T*) is presented for the first air velocity value (R^2=0.933).

$$T=14.713+1.055t \tag{1}$$

In Equation (2), relative humidity (*Rh*) is obtained in terms of time and temperature for the first air velocity value, (R^2=0.952).

$$Rh= 69.282-0.0073t-1.533T \tag{2}$$

For the second air velocity value, the relationship between time and temperature is presented in Equation (3), (R^2=0.952).

$$T=17.507+1.237t \tag{3}$$

The relative humidity value for the second air velocity value is presented in Equation (4) in terms of time and temperature, (R^2=0.957).

$$Rh=73.76+0.54t-1.911T \tag{4}$$

In Equation (5), the variation between temperature and time is presented for the third air velocity value, (R^2=0.897).

$$T=17.981+1.302t \tag{5}$$

The relative humidity value for the third air velocity value is presented in Equation (6) in terms of time and temperature, (R^2=0.914).

$$Rh=59.839-0.314t-1.146T \tag{6}$$

CONCLUSION

The driver vigilance and the concentration are vital for driving safety. The ambient conditions inside an automobile directly affect both the driver and also the passengers. Thermal comfort studies for automobile compartments have been always a concern for the HVAC designers, and the assessment of temperature and humidity is no more a luxury, on the other hand a necessary for modern cars.

In this study, affects of air velocity and time on ambient conditions inside an automobile during the heating period were found. Relationships between time, temperature and relative humidity were calculated.
From this study, the following conclusions were drawn:

(1) The effect of air velocity on temperature is similar to relative humidity for heating period.

(2) The effect of time on temperature is similar to relative humidity for heating period.

(3) With increasing air velocity values, inside temperature also increases during the heating periods.

(4) For the third air velocity level lower air temperature differences between vent outlet and the indoor air temperature were obtained than that of for the other air velocity levels during the heating period.

(5) Low air velocity values have more relative humidity values during the heating period.

(6) From this study it is understood that temperature and humidity inside a car varies directly from air velocity values.

(7) Equations for predicting the temperature and relative humidity values respect to time and air velocity levels were obtained.

(8) The obtained results from this study will lead further studies in automobile thermal comfort studies and with this research; CFD studies and thermal comfort models with regard to thermophysical interactions between subjects and the ambient can be validated for transient conditions.

(9) There are many studies for building HVAC systems but the investigations for automobile HVAC systems are restricted. Results from this study will be useful for automobile manufacturers for designing and improving HVAC systems.

(10) We recommend that more experiment time with more cars, in a climatic chamber or wind tunnel at determined conditions will be better for thermal comfort researches inside a car.

ACKNOWLEDGEMENTS

The authors would like to acknowledge to the Scientific and Technological Research Council of Turkey (TUBITAK) for supporting this research under the project number of 105M262 and also to FIAT-TOFAS for providing the test car.

REFERENCES

Akyol, Ş.M., Kılıç, M., Dynamic Simulation of HVAC System Thermal Loads in an Automobile Compartment., *Int. J. of Vehicle Design*, Vol.52, Nos.1/2/3/4, pp,177-198, 2010.

Ambs, R., Improved Passenger Thermal Comfort Prediction in the Preprototype Phase by Transient Interior CFD Analysis Including Mannequins, *SAE World Congress Detroit*, Michigan, 2002.

Aroussi, a. and Aghil, S., Characterisation of the flow Field in a Passenger Car Model, *Optical Diagnostics in Engineering*, Vol. 4(1), 1-15, 2000.

Bhatti M. S., Riding in comfort: Part 1. *ASHRAE J.*. September, 51-57, 1999a.

Bhatti M. S., Riding in comfort: Part 2. *ASHRAE J.*. August, 44-52, 1999b.

Cascetta F., Musto, M., Assessment of thermal comfort in a car cabin with sky-roof, *Journal of Automobile Engineering*, 264, 2007.

Cisternino M., Thermal climate in cabs and measurement problems, Proceedings of CABLI Seminar on Assessment of Thermal Climate in Operator's Cabs, Florence *(Uppsala: JTI – Swedish Institute of Agriculture and Environmental Engineering)*, pp. 16–23, 1999.

Daanen H. A. M., Vliert E. v. d. and Huang X., Driving Performance in Cold, Warm and Thermoneutral Environments, *Applied Ergonomics*. 34, 597-602, 2003.

Guan Y., Hosni M.H., Jones B.W. and Gielda, T.P., Investigation of human thermal comfort under highly transient conditions for automotive applications—Part 1: experimental design and human subject testing implementation, *ASHRAE Trans.* 109, 885–897, 2003a.

Guan Y., Hosni M.H., Jones B.W. and Gielda, T.P., Investigation of human thermal comfort under highly transient conditions for automotive applications—Part 2: thermal sensation modeling, *ASHRAE Trans.* 109, 898–907, 2003b.

Guan Y., Hosni M.H., Jones B.W. and Gielda, T.P., 2003c. Literature review of the advances in thermal comfort modeling. *ASHRAE Trans.* 109, 908–916.

Hodder S.G. and Parsons K., The effects of solar radiation on thermal comfort, *International Journal of Biometeorology*, Vol. 51, 233-250, 2007.

ISO 9920 Ergonomics: Estimation of the Thermal Characteristics of a Clothing Ensemble, *International Standards Organisation*, Geneva, 1993.

Jones B.W., Capabilities and limitations of thermal models for use in thermal comfort models, *Energy and Buildings*, 34, 653–659, 2002.

Kaynakli O., Unver U. and Kilic M., Simulation of thermal comfort heating and cooling periods in an automobile compartment, *Proceedings of the Automotive Technologies Congress*, 24–26 June, Bursa, Turkey, pp. 127–135 (in Turkish), 2002.

Kaynakli O. and Kilic M., An investigation of thermal comfort inside an automobile during the heating period. Applied Ergonomics, 36, 301–312, 2005.

Kılıç M. and Sevilgen G., Evaluation of heat transfer characteristics in an automobile cabin with a virtual manikin during heating period, *Numerical Heat Transfer, Part A: Applications*, 56, 6, 515- 539, 2009.

Korukçu Ö. and Kılıç M., The usage of IR-thermography for the temperature measurements inside an automobile cabin, *Int. Comm. in Heat and Mass Transfer*, Vol.36, No.8, pp.872-877, 2009.

Mezrhab A. and Bouzidi M., Computation of thermal comfort inside a passenger compartment, *Applied Thermal Engineering*, Vol. 26, 1697-1704, 2005.

Nasr K. J., Defrosting of automotive wind shields: progress and challenges, *International Journal of Vehicle Design*, 24, 243-258, 2000.

Quanten S., Brecht A. V. and Berckmans D., Comparison of thermal comfort performance of two different types of road vehicle climate control systems, *Ergonomics*, 50, 3, 364-378, 2007.

Walgama C., Fackrell S., Karimi M., Fartaj A. and Rankin G. W., Passenger thermal comfort in vehicles- a review, *Proceedings of IMechE.* 220, Part D: J. Automobile Engineering, 2006.

Yamashita K., Kuroda T., Tochihara Y., Shibukawa T., Kondo Y. and Nagayama H., Evaluation of summertime thermal comfort in automobiles, *Environmental Ergonomics*, Vol. 3, 299-303, 2005.

Zimny K., Hermann Z., Doemoek S. and Ellinger M., Comparison between measured and computer simulated t_{eq}, Proceedings of CABLI Seminar on assessment of Thermal Climate in operator's Cabs, Florence, 71-82, 1999.

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