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THE EFFECT OF DIFFERENT INDOOR AIR VELOCITIES AND TEMPERATURES ON THERMAL COMFORT

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Abstract: Nowadays, an objective of different systems and technologies widely used in the HVAC systems is to provide acceptable quality of clean indoor air and comfort. The main reason of using mechanical ventilation in office buildings is to supply comfortable and healthy living environments for occupants, while maintaining minimum energy consumption. Electricity, which is the most expensive energy resource, is used in HVAC systems. Saving energy without changing the thermal comfort level would provide vast amount of profit considering operation costs. There are many measures which can be taken in this regard. In this study, experiments were hold in a climate chamber in the Department of Mechanical Engineering Heat Technology Laboratory in Uludag University, neck skin temperatures were measured and thermal sensations were questioned of subjects under different climate conditions. To evaluate the thermal comfort or discomfort "Predicted Mean Vote (PMV) index was used. After comparing the graphics obtained using the experiment results with the PMV values, optimum HVAC system operation conditions that yield profit without compromising thermal comfort are determined. In the conclusion optimum operation conditions for HVAC systems are suggested.
Keywords: Air conditioning, Thermal comfort, PMV.

FARKLI İÇ HAVA HIZLARININ VE SICAKLIKLARININ ISIL KONFOR ÜZERİNE ETKİSİ

Özet: Günümüzde değişik sistem ve teknolojilerle yaygın olarak kullanılan iklimlendirme sistemlerinin amacı; kabul edilebilir kalitede konforlu ve temiz iç ortam havası hazırlamaktır. Mekanik olarak iklimlendirilmiş hacimlerde temel amaç, minimum enerji tüketimi elde etmekle birlikte, bu hacimleri kullanan insanlar için, sağlıklı ve konforlu yaşam alanları sağlamaktır. Klima sistemlerinde en pahalı enerji biçimi olan elektrik enerjisi kullanılmaktadır. Bu enerjiden konfordan fedakarlık etmeden gerçekleştirilebilecek tasarruf, işletme maliyetlerinde önemli karlılıklar sağlayacaktır. Bu çerçevede alınabilecek pek çok önlem bulunmaktadır. Bu çalışmada, Uludağ Üniversitesi Makine Mühendisliği Bölümünde Isı Tekniği Laboratuarında bulunan iklimlendirme odasında deneyler yapılmış olup farklı iklimlendirme koşullarında deneklerin ense deri yüzey sıcaklıkları ölçülmüş ve deneklerin ısıl duyumları sorgulanmıştır. Isıl konforun tespiti için "Tahmini Ortalama Oy (*PMV*)" indisi kullanılmıştır. Yaptığımız deneyler sonucu ortaya çıkan grafikleri ve PMV değerlerini birlikte değerlendirerek konfordan fedakarlık etmeden tasarruf gerçekleştirebilecek iklimlendirme sistemlerinin optimum çalışma şartları belirlenmeye çalışılmış ve sonuç bölümünde iklimlendirme sistemlerinin optimum çalışma şartları için önerilerde bulunulmuştur.
Anahtar kelimeler: İklimlendirme, Isıl konfor, PMV.

INTRODUCTION

In this section the literature review performed within the scope of our study is summarized. In the literature there are various studies on this issue. The studies in the literature about thermal comfort are summarized. Partial and whole body thermal sensation and comfort were investigated for uniform and non-uniform conditions by Arens et al. (2006a and 2006b, respectively). Arens et al. (2006a) exposed the subjects to uniform environments and collected the subject's local and whole body thermal sensation and comfort. In the latter study, Arens et al. (2006b) exposed the subjects to sequences of partial body cooling and warming over a period of 3 hours and collected the subject's skin temperatures, core temperature, thermal sensation and comfort responses for 19 local body parts and for the whole body. For thermal comfort and indoor air quality, international standards such as ASHRAE standard 55-2004, and ASHRAE Standard 62.1-2004 have been presented. According to the current standards, thermal comfort is defined as "that condition of mind which expresses satisfaction with the thermal environment" which is assessed by subjective evaluation, and acceptable indoor air quality is defined as "air in which there is no known contaminant at harmful concentrations as determined by cognisant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction". For thermal comfort, acceptable intervals have been given in International Standarts such as ISO 7730.

The climate chamber experiments to investigate thermal comfort at high humidity were performed by Fountain et al. (1999). Havenith et al. (2002) discussed the representation and measurement of personal factors such as clothing parameters and metabolic heat production rate in thermal comfort assessment. Olesen and Parsons (2002) described existing ISO standards and current activity associated with thermal comfort including draught, vertical air temperature difference, floor temperature and radiant asymmetry, which cause mostly local thermal discomfort. Todde (2000) dealt with experimental investigation on human reaction to local air movements, and provided the evidence of how the exposure duration to air movements plays a fundamental role on air flow sensitivity.

In our study it is tried to determine the optimum HVAC system operation conditions that save energy without compromising thermal comfort. In this study, for a person, the impacts of local air velocity and temperature on the changes of the skin temperature in time have been experimentally investigated. In the performed experiments, the deviations of the skin surface temperatures of dry subjects entering the climate chamber were measured and examined. The subjects were investigated about their predicted mean vote (PMV) indices to obtain the deviation of the PMV index depending on the air velocity and temperature for dry skin conditions. The results have been examined and compared.

EXPERIMENTAL METHODOLOGY

The experiments were carried out in a prefabricated climate chamber (3.7x2.4x1.9 m^3) in which the air temperature, velocity and relative humidity could be controlled. The test person was seated on a chair in the climate room; his back was facing towards the air-conditioning system. The positions of the subjects, the experimental apparatus, and measurement points are presented in Fig. 1. In the climate chamber, subjects were exposed to various combinations of air velocity, air temperature and relative humidity for 120 min. A computer was provided for the subjects and they were allowed to watch films and/or surf on the internet. The rationale behind the selection of these environmental conditions for the experimental analyses was that they may occur in the mechanically ventilated buildings and are within or close to the comfort limits that are recommended in current standards.

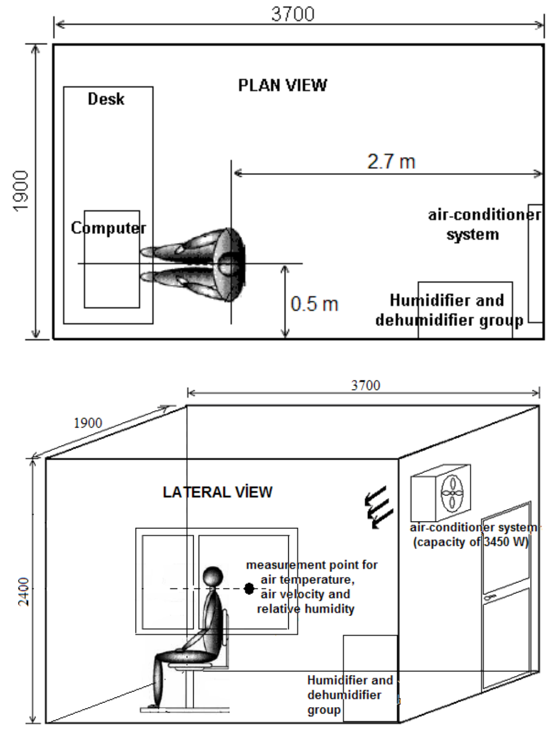

Figure 1. Experimental design: lateral and plan view.

Each of two investigated thermal comfort parameters (air temperature and air velocity) was used as a variable while the other was kept constant in the climate chamber. Constant parameters were selected for maintaining thermal comfort. Based on the observation that individuals often enter the air-conditioned room perspiring in summer conditions, dry conditions were examined. The subjects participated in tests of 120 min each, where they were exposed to one constant condition. The impact of thermal comfort parameters on the skin surface temperature and the PMV index were studied at various combinations of air temperature, air velocity, relative humidity and skin conditions, and these combinations are shown in Table 1 according to study weeks.

Experimental study had continued for 4 weeks. In the first week, relative humidity and air velocity were adjusted to be constant at 50%rh and 0.2 m/s, respectively and the exposures ranged from 20 ^{o}C to 26 ^{o}C with 2 ^{o}C intervals for air temperature. In the second week, air temperature and relative humidity were held constant in the climate chamber at 24 ^{o} C and 50%rh, respectively, and air velocity was changed from 0.2 m/s to 0.6 m/s with 0.2 m/s intervals. In the third week, air velocity and relative humidity were held constant in the climate chamber at 50%rh and 0.4 m/s, respectively, and the air temperature exposures ranged from 26 ^{o}C to 28 ^{o} C, In the forth week, air velocity and relative humidity were held constant in the climate chamber at 50%rh and 0.6 m/s, respectively, and the exposures ranged from 26 ^{o}C to 28 ^{o}C.

Table 1. Combinations of investigated parameters according to study weeks.

Week	Skin condition	Constant	Parameter	Number of Subjects
1	Dry	0.2 m/s, %50rh	20 ^{o}C	25
			22 ^{o}C	25
			24 ^{o}C	25
			26 ^{o}C	25
2	Dry	24 ^{o}C, %50rh	0.2 m/s	25
			0.4 m/s	25
			0.6 m/s	25
3	Dry	0.4 m/s, %50rh	26 ^{o}C	25
			28 ^{o}C	25
4	Dry	0.6 m/s, %50rh	26 ^{o}C	25
			28 ^{o}C	25

The subjects were also asked to evaluate their thermal environments according to the PMV index. During the experiment, subjects were asked about their impressions of their thermal sensation to constant indoor conditions at 10 min, 60 min and 120 min of the experiment and the average value of the three responses were calculated for each experiment.

Experiments were carried out in climate chambers at a university laboratory in summer months of 2009. The subjects were twenty-five healthy male university students. All subjects gave their informed consent prior to the experiments. Only subjects in good health and with almost the same physique and body shape were allowed to participate to the experiments. The anthropometric data for the subjects are listed in Table 2. All subjects were requested to wear the same type of clothing ensemble (briefs, short sleeve shirt, long trousers, and socks) made of cotton. The clothing insulation value of the ensemble was not measured, but was estimated to be approximately 0.5 clo.

Table 2. Anthropometric data for the subjects.

Sex	*Number of subjects*	*Age in years*	*Height in metres*	*Weight Kg*	*Du Bois area* m^2
Male	25	22.9 ± 2.09	1.78 ± 0.07	76.99 ± 8.98	1.94 ± 0.14

The air temperature and humidity in the climate chamber were monitored continuously by a temperature and humidity transmitter and noted manually by the experimenter every 5 minutes. Relative humidity were held constant in the climate chamber at 50%rh via dehumidifier and humidifier .The transmitter measures relative humidity by means of a sensor in the range 0 to 100% with an accuracy of ±2rh in the 0 – 9.9%rh, ±1rh in the 10 – 90%rh range and ±2rh in the 90.1 – 100%rh range and temperature in the range -20 ^{o} C to +70 ^{o} C with an accuracy of ±0.5 ^{o} C in the -20 ^{o} C – 10.1 ^{o} C range and ±0.4 ^{o} C in the -10 ^{o} C – +50 ^{o} C range and ±0.5 ^{o} C in the +50.1 ^{o} C – +70 ^{o} C range. The air velocity was measured continuously in the back side of the subjects and registered manually by the experimenter every 5 minutes. The range of air velocity sensor is 0 m/s to 20 m/s with an accuracy of ±0.03 m/s in the 0 m/s – 2 m/s range and ±0.2 m/s in the 2 m/s – 20 m/s range. The local variations in air temperature, air velocity and relative humidity inside the chamber were negligible. Air and mean radiant temperatures were almost equal.

RESULTS AND DISCUSSION

In this study, three of the parameters affecting thermal comfort (relative humidity, clothing parameter and metabolic heat production rate) were kept constant, while the effects of changes in the other two parameters (air velocity and air temperature) on the thermal comfort were investigated. Furthermore, all subjects were questioned about their PMV indices for all the different thermal room conditions tested. The measurement results are shown in the following figures and tables. PMV is an index that predicts the mean value of the votes of a large group of people on a 7-point thermal sensation scale: 0 neutral, ±1 slightly warm/cool, ±2 warm/cool, ±3 hot/cold. Table 3 shows the mean PMV values obtained from the experimental subjects in the experiments. Examining the values in this table, we can see that the thermal sensation approaches to warm via increase in temperature. This table also shows that increase in air velocities moves the thermal sensation to cool. The effects of air velocities on the thermal sensation have revealed interesting results. Changing indoor air temperature from 24 ^{o} C to 26 ^{o} C and increasing air speed to 0.4 m / s from the value of 0.2 m / s value appear to cause the same thermal sensation. We also see from this table that at 28 ^{o} C air temperature, increasing air speed to 0.6 m / s from 0.4 m / s appear to cause almost the same thermal sensation. The neck skin surface temperature variations in time are shown in the following figures for different indoor air temperatures depending for air velocity value of 0.2 m/s, 0.4 m/s, 0.6m/s. In Table 3, obtained experimental data has been compared with values that were calculated from the equality in ISO 7730, and as a result, it has been seen that the majority of experimental data is consistent with values obtained from this empirical equality.

Figure 2 shows the neck skin surface temperature variations in time for different indoor air temperatures and for air velocity value of 0.2 m / s. For 20 ^{o} C air temperature; the initial temperature of the neck is nearly 31 ^{o}C, it monotonously decreases about 4 ^{o}C in 2 hours.

For 22 ^{o}C air temperature; it monotonously decreases about 1 ^{o}C in 2 hours. For 24 ^{o}C air temperature; in the first hour it approximately decreases 1^{o} C, and then it increases about 0.7 ^{o}C in the second hour. For 26 ^{o}C air temperature; in the first hour it monotonously decreases about 1 ^{o} C, and then it increases about 0.7^{o} C in the second hour. The observed increase in skin temperature after a period of time is caused by the heat balance mechanisms in the body that increase the body temperature.

Figure 3 shows the neck skin surface temperature variations in time for different indoor air temperatures for air velocity value of 0.4 m / s. For 24 ^{o} C air temperature; in the first 80 minutes, the neck skin surface temperature is monotonously decreasing about 2 ^{o}C; in the last 40 minutes it is constant. For 26 ^{o}C air temperature; it is decreasing about 1 ^{o} C in 2 hours. For 28 ^{o} C air temperature; in the first hour it is decreasing approximately 0.1 ^{o}C from 32 ^{o}C, it is increasing about 0.1 ^{o}C in second hour.

Figure 4 shows the neck skin surface temperature variations in time for different indoor air temperatures depending for air velocity value of 0.6 m / s. For 24 ^{o}C air temperature; First 80 minutes; it is constantly decreasing about 1 ^{o} C, last 40 minutes it is increasing about 0.5 ^{o}C. For 26 ^{o}C air temperature; First 1 hour it is decreasing approximately 0.8 ^{o}C, then it is increasing about 0.2 ^{o}C in second hour. For 28 ^{o}C air temperature; First 1 hour it is decreasing approximately 0.2 ^{o}C, then it is increasing about 0.2 ^{o} C in second hour. These increases demonstrate the reactions of the body heat balance mechanisms.

Table 3. The mean PMV values responses of the subjects.

Air velocity	*Temperature*	*Relative humidity*	*PMV(Experimental)*	*PMV(ISO 7730)*
0.2 m/s	20 ^{o}C	50%	-1.75	
	22 ^{o}C	50%	-1.33	
	24 ^{o}C	**50%**	**-0.5**	-1.11
	26 ^{o}C	50%	0.75	-0.31
0.4 m/s	24 ^{o}C	50%	-0.75	-1.55
	26 ^{o}C	**50%**	**-0.55**	-0.66
	28 ^{o}C	50%	-0.55	0.23
0.6 m/s	24 ^{o}C	50%	-1.25	-1.8
	26 ^{o}C	50%	-0.92	-0.87
	28 ^{o}C	50%	-0.15	0.1

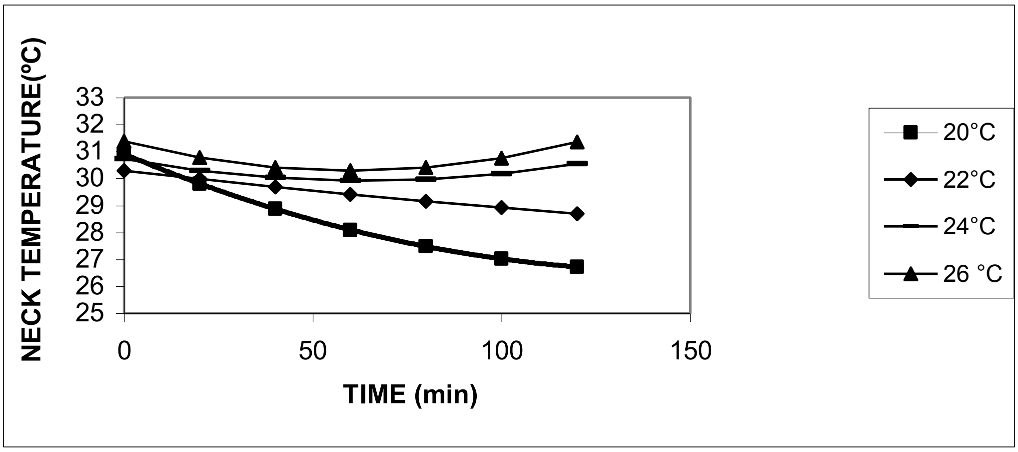

Figure 2. The neck skin surface temperature variations in time for different indoor air temperatures for air velocity value of 0.2 m/s.

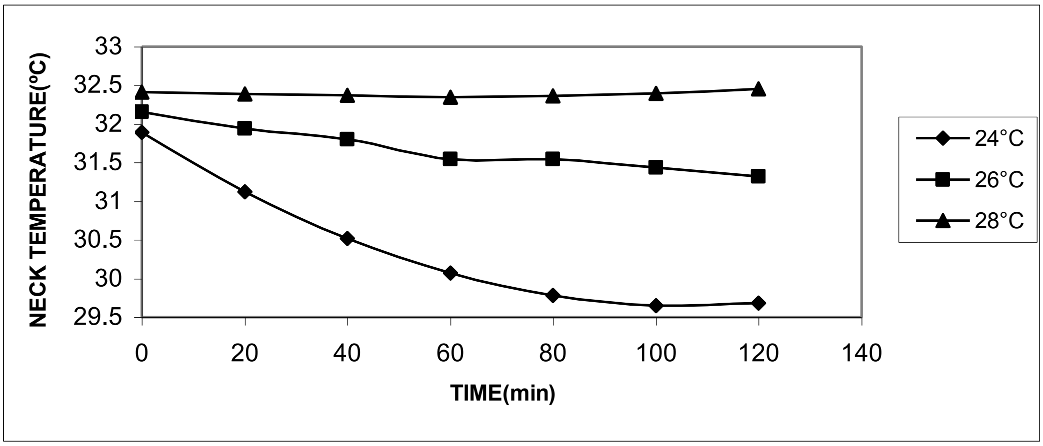

Figure 3. The neck skin surface temperature variations in time for different indoor air temperatures for air velocity value of 0.4 m/s.

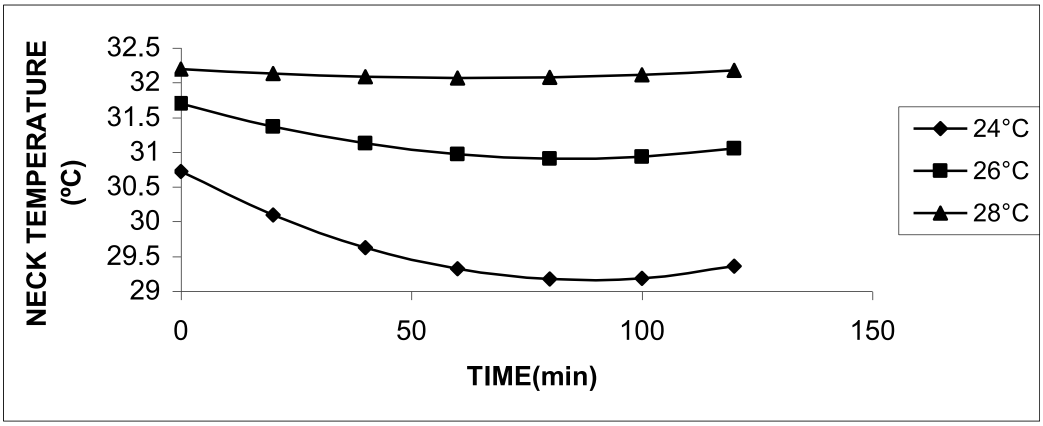

Figure 4. The neck skin surface temperature variations in time for different indoor air temperatures for air velocity value of 0.6 m/s.

CONCLUSION

Figure 2 shows that at 0.2 m / s air velocity, 20 ^{o}C is a low indoor air temperature in summer. Neck temperature decreased 4 ^{o}C in 2 hours for 20 ^{o}C indoor air temperature. Table 3 shows that the negative maximum value of the mean PMV value is -1.75 at this temperature. 4 degrees of reduction can adversely affect human health and can cause headache and neck pain. Considering that these results are obtained when the air-conditioner is operated at 20 ^{o}C and the first level of fan speed, it is obvious that at the second and third speed levels the results will have more negative consequences in terms of human health. Therefore air conditioning in summer at 20 ^{o} C for indoor air temperature is not suitable for human health. Ambient temperature of 22 ^{o} C in a continuous decrease in surface temperature in the neck is, Therefore it is caused thermal discomfort can be seen from PMV indices. There is no significant difference between the PMV index values at air temperature values of 24 ^{o}C and 26 ^{o}C at the second and third speed levels. At air velocity 0.2 m / s, when the indoor ambient temperature gets above 26 ^{o} C, the thermal discomfort starts to be observed.

Fig.3. shows the neck skin surface temperature variations at 0.4 m / s air velocity and 24 ^{o}C indoor ambient temperature and Figure 2 shows those at 0.2 m / s air velocity and 22 ^{o}C indoor ambient temperature. The neck temperatures for these two different air conditioning settings get closer to each other in 2 hours, and the PMV values are close to each other in these two different settings. Operation of an air conditioner under 22^{o}C temperature of cooling air and 0.2 m/s air velocity or under 24 ^{o} C and 0.4 m/s air velocity has the same thermal comfort level on a person. Hence increasing the air velocity by 0.2 m/s can be preferred to decreasing the air temperature by 2 ^{o} C considering economic benefits. This result is essential since it proposes an easy way to reduce the energy consumption in air conditioning systems.

PMV index changes and the temperature of neck changes were examined of air velocity on thermal comfort sensation that is very effective. Fig.2. shows the neck skin surface temperature variations at 0.2 m / s air velocity and 24 ^{o}C indoor ambient temperature and Figure 3 shows those at 0.4 m / s air velocity and 26 ^{o}C indoor ambient temperature. The neck temperatures for these two different air conditioning settings get closer to each other in 2 hours. Decreased indoor air temperature together with increased air velocity provide the same perception of thermal comfort. 24 ^{o}C and 0.2 m/s, 26 ^{o} C and 0.4 m/s, 28 ^{o}C and 0.6 m/s indoor environment conditions bring about that were observed near the thermal sensation. Therefore, in the design of energy efficient buildings, optimal selection of the set values of air conditioning inside the building will reduce the energy consumption significantly. Although 28 ^{o} C is a high temperature for indoor air temperature, during night, when the outdoor temperature is in the vicinity of 28 ^{o} C, it has been observed that thermal comfort can be obtained via natural circulations. This result is important in reducing energy consumption in buildings and can be used in building air conditioning control. As a result of this study, following conclusions were obtained:

- There is a relationship between skin surface temperature and PMV values. Sudden decrease in skin surface temperature causes thermal discomfort.

- Same perception of thermal comfort was obtained for indoor conditions of 24 ^{o} C, 0.2 m/s and 26 ^{o} C, 0.4 m/s. Therefore, as optimal selection of indoor set values, the set values of 26 ^{o} C, 0.4 m/s can be treated as appropriate values instead of 24 ^{o} C, 0.2 m/s from economical point of view.

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