Parametric Analysis of Environmental and Physiological Parameters on Comfort Air-Conditioning

Mohammad Faizan

Abstract — Human thermal comfort is governed by six basic environmental and physiological parameters viz. air temperature, mean radiant temperature, air velocity, air humidity, thermal insulation of clothing and activity level of occupants. Thermal comfort can be achieved by many different combinations of these basic variables. The relative effect of these variables on thermal comfort is of great importance. It is impossible to consider the effect of any of these factors independently on thermal comfort as the effect of each of them and the necessary requirement depends on the level and condition of other factors. In order to investigate the relative effect of environmental and physiological parameters a human thermoregulatory model proposed by Fanger was employed as a tool. A detailed analysis was done by considering four different values of clothing insulation and two activity levels over varying environmental conditions. It was deduced that relative humidity made no insignificant effect on thermal comfort in the comfort zone. It was also found that under extreme hot and cold discomfort conditions, a small change in the climatic conditions made large effect on the thermal sensation.

Index Terms—Air conditioning, Clothing, Environment control, Heat transfer, Model, Thermal comfort, Thermal sensation

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1. INTRODUCTION

THE term comfort air conditioning is referred to the process of controlling the environment in view of the human occupants. According to the ASHRAE standards, thermal comfort for a person is defined as "that condition of mind which expresses satisfaction with the thermal environment". A comfortable, pleasant and healthy environment is essential for good living and efficient working of human being. Whenever artificial climate is created for human occupants, the aim is that the thermal environment be adopted so that each individual is in thermal comfort. If a group of people is subjected to the same climate, it will not be possible due to biological variance to satisfy everyone at the same time. Effort is then made to provide and environment in which the highest possible percentage of the group is in thermal comfort.

Thermal environment is a combined effect of the basic parameters viz. air temperature, mean radiant temperature, air velocity, air humidity, thermal insulation of clothing and activity level of occupants. The first four parameters are known as the physical parameters while the last two are called the personal parameters. It is not possible to consider the effect of any of the parameters independently, as the thermal comfort is the combined effect of all variables. This fact constituted the idea of deriving the general comfort equation which combines the important governing parameters. As thermal comfort is the primary aim of most heating and air conditioning systems, considerable research is done over the years with the purpose of investigating comfort conditions. Thermal psychological models of the human body have great importance with the concept of local sensation and thermal comfort [12], [13]. The thermal sensation and comfort are mainly based on the local skin and core temperatures [14], [15].

A number of studies have been carried out as field experiments, where the surrounding variables have been measured under practical condition and at the same time people have been asked to vote on their thermal sensation on suitable psycho-physical scale [11]. Subsequently, results were treated statistically and most often the optimum ambient temperature was determined for the actual group. Thermal comfort studies are also carried out theoretically, by modeling the process mathematically.

To evaluate the thermal comfort and evaluate the acceptability of indoor environment, two nodes thermal regulation model was used by Azer [4] as a tool in assessing and identifying limits of acceptability of hot industrial environment. Lines of constant core temperature were plotted for one rest and three different industrial environments with constant clothing, activity and air movement. Thermal sensation neutrality with different activities was plotted on psychometric chart for constant clothing resistance and relative air velocity. Two additional categories were added by Azer et.al [3] to the thermal

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Dr. Mohammad Faizan is Asstt. Prof. of Mechanical Engineering at Taif University Taif, KSA. He obtained his Masters degree in Engineering from Youngstown State University, Youngstown Ohio USA and Ph.D. degree from University of Akron, Akron Ohio USA. His areas of research are Human thermal comfort design, heat and mass transfer in material processing, lead-free solders and computational fluid dynamics. He can be reached at: mofaizan@hotmail.com

sensation scale namely, very hot and very cold. Two new parameters namely, sweat wittedness factor and vasoconstriction factor were plotted and correlated with warm and cold sensation respectively. The results were plotted and correlated with the net number of *mets* and the predicted thermal sensation was compared with the experimental results of other researchers. The variation of core temperature and thermal sensation were plotted for different environmental conditions.

The effect of garment design on thermal comfort under hot and humid condition was studied by Hasebe et al. [5]. Subjects were exposed to three different air velocities with three different types of clothing ensembles in a controlled climate chamber. Mean radiant temperature was equal to the air temperature and clo value was the same for all ensembles. Thermal sensation, mean skin temperature and evaporative heat loss were investigated.

A simplified model was proposed by Burrati et al. [17] aiming to extend results in a wider range of clothing thermal insulation (0.25 - 1.65 clo). This model was an improvement in the Rohles model developed in the seventies [18] which found a correlation between PMV, air temperature and relative humidity, for sedentary activity and clothing thermal insulation equal to 0.6 clo.

A more advance model was developed by Huizenga et al. [12] known as the UC Berkeley Thermo-physiological Comfort model (BTCM). The model included several improvements over the Stolwijk physiological model [16] from which it was derived. The BTCM model had 16 body segments whose areas correspond to a widely used electrical manikin. Each of these segments was simulated as four body layers (core, muscle, fat, and skin tissues) and a clothing layer. A separate series of nodes represented the transport of heat by blood flow between segments, including the effect of countercurrent heat exchange between paired arteries and veins in the limbs.

A comprehensive review of vehicular thermal comfort models was done by Alahmer et.al. [19]. The study classified the in-cabin modeling into two classes viz. human physiological and psychological perspectives in addition to the compartment zone and the human thermal manikin modeling. The effect of body posture and activity on thermal insulation of clothing was studied by Oleson et al. [7] to assign thermal insulation value to individual garments. The required clothing insulation as an analytical index of cold stress was studied and put forth by Holmer [8]. The index was presented to evaluate the thermal stress of cold environments in terms of minimal required clothing insulation (Ireq) for the maintenance of an adequate heat balance. The minimal required clothing insulation was derived from a heat exchanger analysis based on heat transfer equations and physiological criteria available in the literature. The index provided an integrated measure of the combined effect of climate parameters and activity level and served as a guideline for the appropriate choice of an adequate insulation of clothing. The effect of air velocity on thermal comfort at moderate activity levels was studied by Jones et.al [6]. The experimental data was compared with thermal models and the results showed that the level of comfort that can be attained when exerting at 2.3 met activity levels are as high at elevated air velocity, than they are with relatively still air. The study also indicated that females are more sensitive to temperature than are males at the same activity level.

In relation to the velocity of ambient air, of the important environmental parameters, study of ceiling fans as extenders of the summer comfort envelope, was done by Roles et.al [9]. The findings of the research showed that 75% comfort level is experienced at 29^{o}C with a ceiling fan and also at 26^{o}C at still air. The research concluded that the energy demand with a fan is equal to a difference of 3.3^{o}C. With this approach, the use of ceiling fan will reduce the energy demand.

The asymmetric thermal radiation effect on the human physiological and psychological responses has been studied by Harikoshi [20]. Difference between right and left area operative temperature against the difference between right face and mean skin temperature were plotted. Moreover, area mean radiant and area operative temperature with thermal sensation vote were also plotted.

2. MATHEMATICAL MODEL

To develop a mathematical model of human thermoregulatory mechanism, the human body was represented by two concentric cylinders. The inner cylinder represented the body core with a uniform temperature of 37^{o}C (98.6^{o}F) while the outer layer represented the clothing. The primary heat source in the body was metabolic heat. In addition to the conductance though skin and evaporation through sweat, the core also exchanged heat with the environment through respiration.

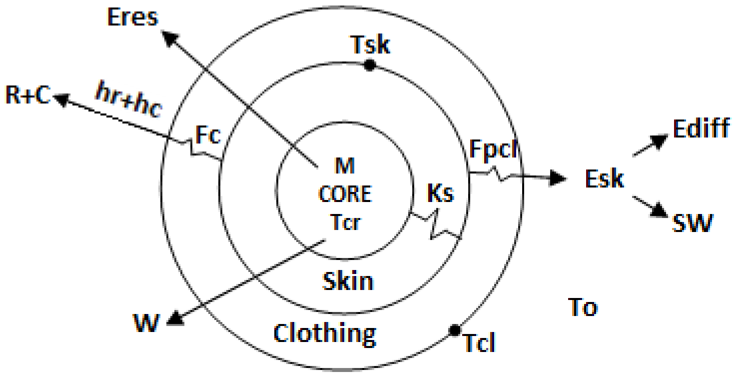


Fig. 1: Various modes of heat flow for mathematical model of human thermoregulatory system

2.1 Heat balance equations

The heat exchange between human body and its surroundings may be described by the following equations.

$$M_{cr}.C_{cr}\frac{dT_{cr}}{dt} = (M+W) - E_{res} - K_s(T_{cr}-T_{sk}) \qquad (1)$$

$$M_{sk}.C_{sk}\frac{dT_{sk}}{dt} = K_s(T_{cr}-T_{sk}) \pm (R+C) - E_{sk} \qquad (2)$$

Where the symbols have their usual meanings as given in the nomenclature.

2.1.1.Sensible and latent respiration heat loss (Eres)

The sensible and latent respiratory energy exchange with the environment (Eres) is a combination of latent respiration heat loss (EresL) and dry respiration heat loss (EresD) and can be evaluated as follows [1].

$$E_{res} = E_{resL} + E_{resD} \tag{3}$$

The two terms in equation (3) can further be written as [1].

$$E_{resL} = 0.0023M(44 - (RH)P_{as}) \tag{4}$$

$$E_{resD} = 0.0014M(34 - T_a) \tag{5}$$

2.1.2. Dry heat exchange (R+C)

The dry heat flow by conduction through the clothing and by radiation and convection to or from the ambient can be calculated from the following equation found in literature [2].

$$(R + C) = h.f_{cl}\ F_c(T_{sk} - T_o) \tag{6}$$

Where h is the combined convective and radiative heat exchange coefficient, Fc is thermal efficiency of clothing and fcl is the ratio of the surface are of clothed body to that of the nude body.

2.1.3. Skin evaporative heat loss (Esk)

The evaporative heat loss from the skin (Esk) is governed by water vapor diffusion through the skin (Ediff), sweat secretion from the body core and the skin (SW) and maximum evaporative heat loss (Emax). Water vapor diffusion through the skin can be calculated as follows [1].

$$E_{diff} = 0.408(P_s - (RH)P_{as}) \tag{7}$$

Where RH is the relative humidity ratio, Ps is the saturated water vapor pressure at skin temperature and Pas is saturated vapor pressure at ambient air temperature.

The thermoregulatory sweat control (SW) is measured as sweat wittedness factor [3] as follows.

$$SW = \emptyset \frac{[260(T_{cr} - 36.9) + 26(T_{sk} - 33.8)]^{\frac{(T_{sk} - 33.8)}{8.5}}}{1 + 0.05(33.37 - T_{sk})^{0.24}} \tag{8}$$

Where, ∅ is the suppression factor due to skin wettedness. All bracketed terms in equation (8) must be positive, negative values are assigned a zero value.

The maximum evaporative heat loss (Emax) from the skin surface to the ambient occurs when the skin surface is 100% wet due to regulatory sweating and can be estimated from the following equation [2].

$$E_{max} = 2.2F_{pcl}\, h_c[P_s - (RH)P_{as}] \tag{9}$$

Finally, the total evaporative heat loss from the skin (Esk) can be estimated as follows:

$$E = SW + (1 - WSW)E_{diff} \qquad \text{if SW} \le \text{E}_{\text{max}} \tag{10}$$

$$E_{sk} = E_{max} \qquad \text{if SW} > \text{E}_{\text{max}} \tag{11}$$

Where WSW = SW/Emax

2.1.4. Skin blood flow and skin conductance (Ks)

The skin conductance represents an overall contribution of thermal conductance and peripheral blood flow. Its value is not directly measurable but can be calculated indirectly from the energy balance equation. The following expression can be used to calculate skin conductance [3].

$$K_s = \frac{5.3 + 6.75 + 42.45(T_{cr} - 36.98) + 8.15(T_{cr} - 35.15)^{0.8}(T_{sk} - 33.8)}{1 + 0.4(32.1 - T_{sk})} \tag{12}$$

2.1.5. Thermal Sensation (TS)

As a measure for the thermal sensation the commonly used seven point psycho-physical ASHRAE scale [1] was modified by adding two additional categories [3]. The final scale is shown as under.

Very Cold	-4
Cold	-3
Cool	-2
Slightly Cool	-1
Neutral	0
Slightly Warm	1
Warm	2
Hot	3
Very Hot	4

To calculate the thermal sensation for different activities and environmental conditions, it is related best with vasoconstriction factor (εvc) for cold thermal sensation and with wettedness factor (εwsw) for warm sensation [3]. The actual skin conductance and actual wettedness can be determined by solving thermoregulatory model using a suitable numerical scheme like RK4. Using above equations, the sweat wettedness and vasoconstriction factor can be related to thermal sensation as follows.

If Ks ≥ Kso, the thermal sensation is in hot side and can be calculated as:

$$TS^{+} = (5.0 - 6.56(RH - 0.5)\varepsilon_{wsw} \tag{13}$$

If Ks < Kso, the thermal sensation is in cold side and can be calculated as:

$$TS^{-} = -1.46\ )\varepsilon_{vc} + 3.75\ \varepsilon_{vc}^{2} - 6.19\ \varepsilon_{vc}^{3} \qquad (14)$$

3. RESULTS AND DISCUSSION

The present work was related to the study of variation of thermal sensation with change in environmental conditions clothing and activity level. These parameters were studied through a numerical model of human temperature regulation system. The thermoregulatory model was solved using Runge-Kutta 4 numerical scheme. Although thermal sensation is a combined effect of all parameters, it is necessary to know the effect of individual parameters. In this view, three activity levels were chosen viz. light activity (M=60 W/m²) medium activity (M=110 W/m²) and high activity (M=160 W/m²).

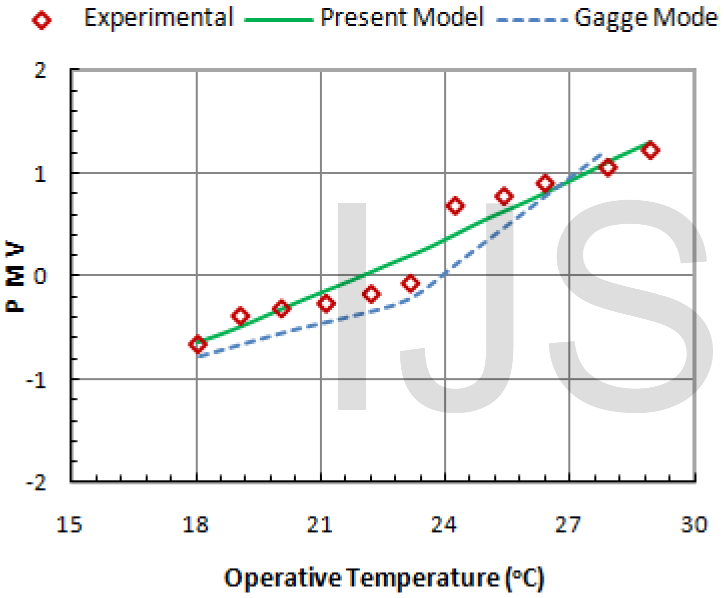


Fig. 2: Comparison of model results with experimental data

Plots of variation of air velocity, relative humidity and operative temperature were drawn for four different clothing. The clothing were chosen as nude (Icl=0.0), light clothing (Icl=0.5), medium clothing (Icl=1.0) and heavy clothing (Icl=1.5).

The numerical results from the present model were compared with the field study data by Brager [10] as shown in Fig. 2. In this study survey was conducted in ten San Francisco area buildings at moderate activity during and winter seasons. Results were compared with the Gagge's PMV and the comfort equation of Fanger. Results from the present model showed a good agreement with the measured field data.

3.1. Effect of Relative Air Velocity

Effect of relative air velocity can be seen in Fig. 3 for three activity levels and for different clothing insulation values. The air velocity is responsible for convective heat transfer from body.

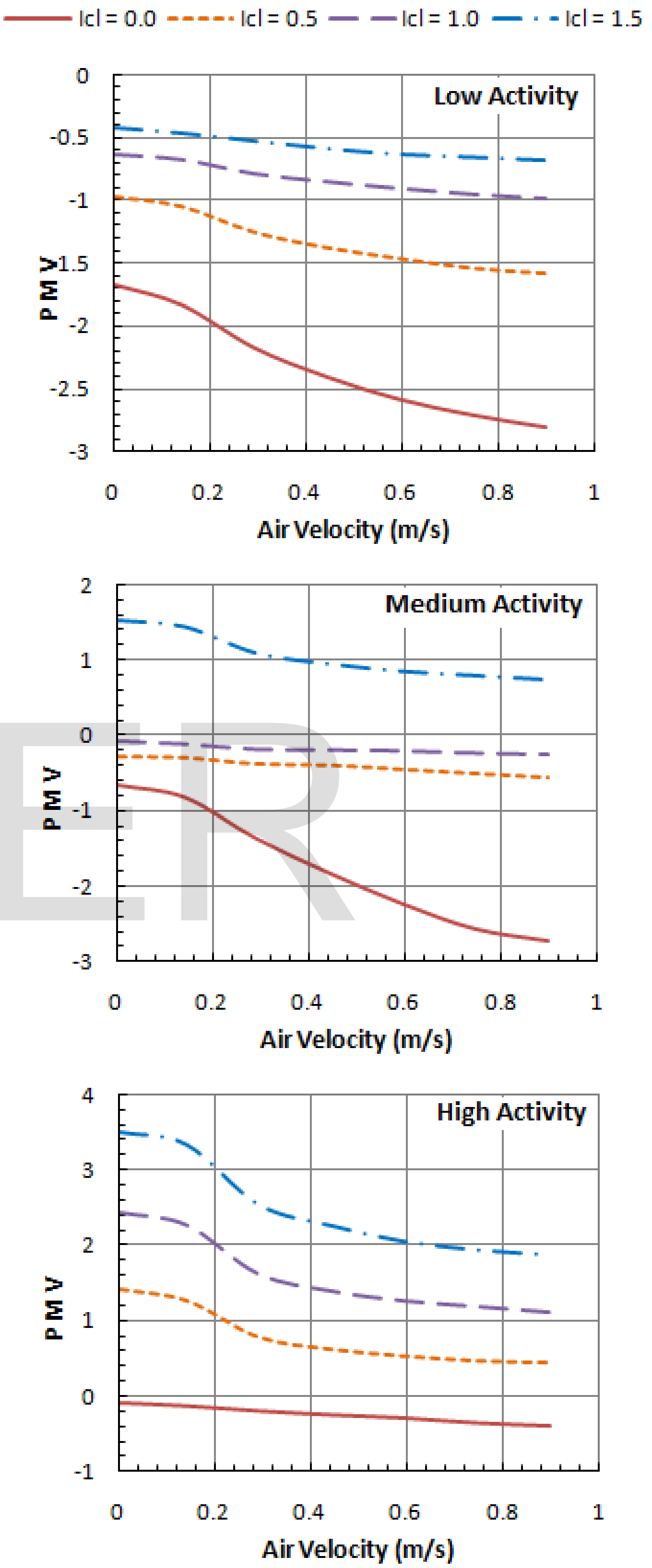
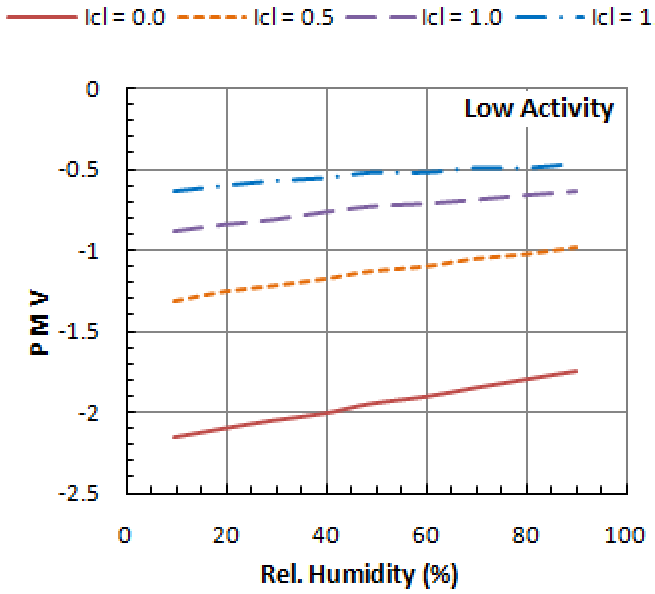


Fig. 3: Effect of Air Velocity on thermal sensation at various clothing insulations for Low, Medium and High activity at RH = 40% and T_o = 20°C

The results showed that increase in air velocity shifted the thermal sensation towards the cold side. Moreover, the effect of velocity was most significant when the subject was nude. The reason was obvious that for a nude body, almost whole of the body came in contact with the surrounding air, consequently, the evaporative heat transfer was high and a slight change in velocity lead to a high change in thermal sensation. As the clothing value increased the effect of velocity change decreased due to increased thermal insulation of body by clothing. It was interesting to note that at medium activity level, for bare body the thermal sensation was around zero, the change in air velocity did not make much difference. This is true for other parameters also when the conditions are met for thermal neutrality.

3.2. Effect of Relative Humidity

Relative humidity in the environment also plays an important role in determining thermal sensation for human subject. Effect of relative humidity at three activity levels and various clothing insulation is shown in Fig 4. It was observed that at low velocity level and less clothing, the relative humidity did not play and significant role in determining the thermal sensation. This is particularly true when the environmental conditions are such that the subject feels comfortable, however, in the hot discomfort high humidity would make it more discomfortable. In fact humidity limits are specified not for thermal comfort but for the probable impact on indoor air quality.



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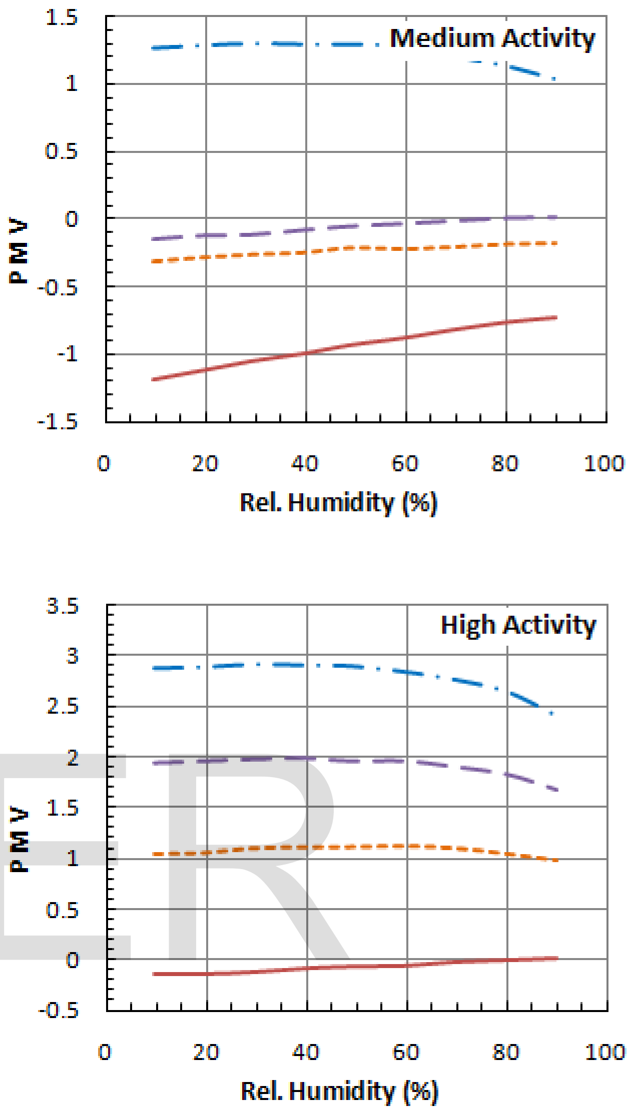

Fig. 4: Effect of relative humidity on thermal sensation at various clothing insulations for Low, Medium and High activity at V = 0.2 m/s, and T_o = 20°C

3.3. Effect of Operative Temperature

The effect of operative temperature on thermal sensation at various clothing and activity level is shown in Fig 5. It is evident from the plots that operative is thermal sensation is a direct function of operative temperature and is greatly affected with its change. An increase in operative temperature always shifted the thermal sensation towards hotter side. It was interesting to note that when conditions are met for thermal neutrality (thermal comfort), the curves tend to flatten around the thermal neutrality (PMV = 0.0). This is true for cold thermal sensation only and is attributed to the fact when the conditions for thermal comfort are met, the occupants were found to be less sensitive to any small change in the environmental conditions.

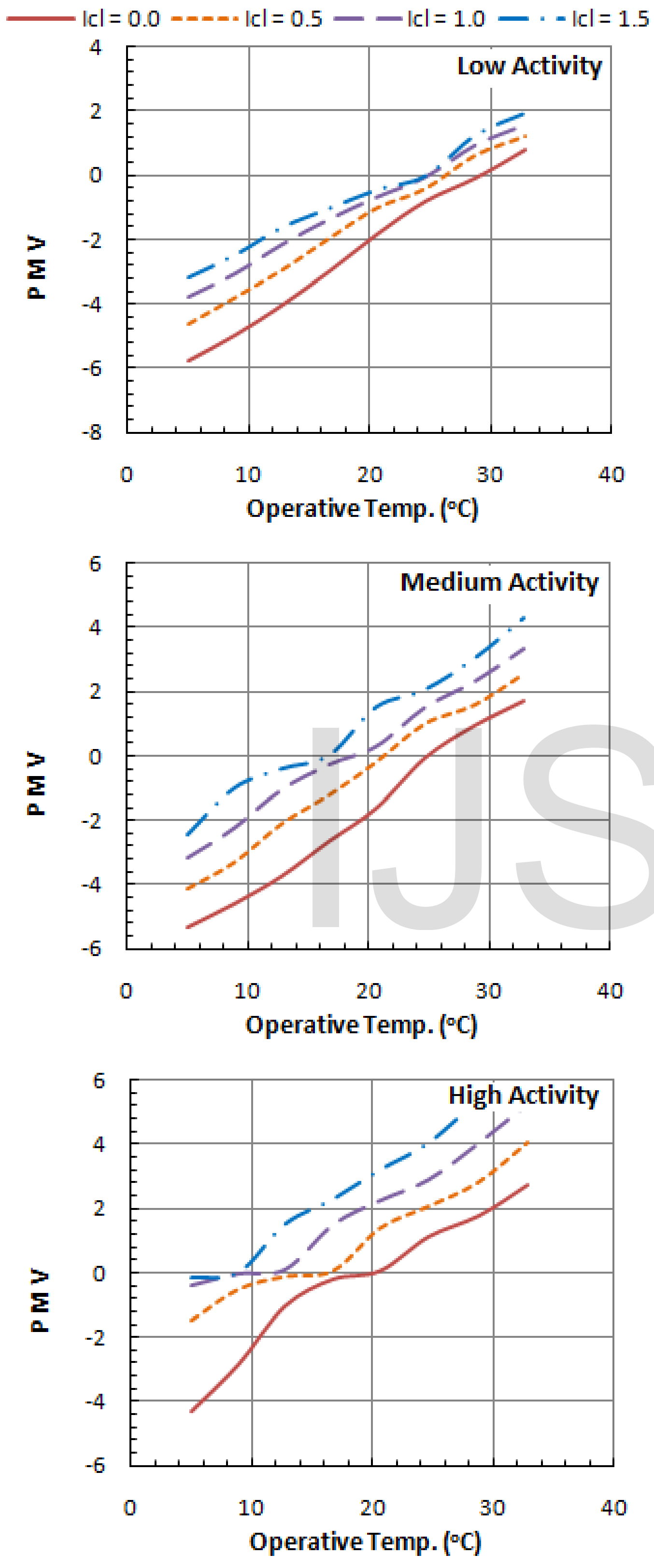

Fig. 5: Effect of operative temp. on thermal sensation at various clothing insulations for Low, Medium and High activity at RH=40%, V=0.2 m/s

4. CONCLUSIONS

The present study aimed at the investigation of the effect of environmental and physiological parameters on thermal comfort of human body. It was observed that relative air velocity and operative temperature had a significant effect on thermal sensation and shifted the value towards cold side. However, relative humidity had little effect on thermal sensation as the humidity control is a requirement for indoor air quality. Relative air velocity had the most significant effect on thermal sensation when the subject had no clothing. As a general observation it was also concluded that when the human body was in thermal comfort, any small change in environmental parameters did not make significant effect on thermal sensation, this is particularly true for cold side. In the extreme discomfort condition, any small change in environmental parameters greatly affected thermal sensation.

NOMENCLATURE

C_{cr}	Avg. specific heat of body core (W hr/kg^{o}C)
C_{sk}	Specific heat of skin (W hr/kg^{o}C)
E_{res}	Sensible and latent respiratory energy exchange with the environment (W/m^{2})
E_{sk}	Total evap. energy loss from skin (W/m^{2})
E_{max}	Maximum evaporative heat loss (W/m^{2})
F_{c}	Thermal efficiency of clothing
F_{cl}	Clothing area factor
h	Combined radiative and convective heat exchange coefficient (W/m^{2o}C)
K_{s}	Overall skin conductance (W/m^{2o}C)
M	Metabolic rate (W/m^{2})
M_{cr}	Core mass/unit body surface area (kg/m^{2})
M_{sk}	Skin mass/unit body surface area (kg/m^{2})
P_{as}	Sat. vapor pressure at air temp. (mmHg)
P_{s}	Sat. vapor pressure at skin temp. (mmHg)
(R+C)	Dry energy exchange by radiation and convection (W/m^{2})
RH	Relative humidity ration
S_{w}	Heat loss by sweat evaporation (W/m^{2})
T_{a}	Ambient air temperature (^{o}C)
T_{cr}	Core Temperature (^{o}C)
T_{o}	Operative temperature (^{o}C)
TS	Thermal sensation
T_{sk}	Skin temperature (^{o}C)
W	External mechanical work (w/m^{2})

Greek Symbols

ε_{vc}	Vasoconstriction factor
ε_{wsw}	Wettedness factor

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