Proceedings of the
International Conference on Mechanical Engineering and Renewable Energy 2017
(ICMERE2017) 18 – 20 December, 2017, Chittagong, Bangladesh

ICMERE2017-PI-397

Study of Natural Convection from human body in different postures

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Abstract: *The aim of this paper is to determine the heat transfer from human body at different postures via natural convection. This field of study is crucial for design of ventilation systems, air-conditioning, thermal cooling of offices and homesteads, designing thermal barrier suits for astronauts or any other fields of application where human body is the prime concern. For this experiment we consider a 2-Dimensional human model analysis. Three different postures namely standing, sitting and supine are considered. For the standing condition, the Human is considered standing vertically with arms hanging down, For the supine condition the model is considered to have it's back contacted with the ground with head a bit raised from the floor. The sitting position resembles a human sitting on a chair with upright backbone as viewed from the side. Temperature all across the human skin is considered to be constant. The results are obtained by using finite volume method in Ansys Fluent. Nusselt Number and Heat Transfer coefficient is obtained for surrounding Air and Skin surface of the human model. Comparative analysis between skin surface nusselt number for different human postures and nusselt number at warm air has been drawn to attention. The Skin Surface Nusselt Number obtained has then been verified against previous experiments.*

Keywords: *Natural Convection, Heat Transfer, Human Model, Computational Fluid Dynamics (CFD)*

Introduction

Natural Convection is a process in which heat is transferred via density variation in the fluid caused by thermal heating. For instance, if a heated object is placed within a room having air temperature cooler than the surface temperature of the object, then the air film which is in immediate contact with the surface of the heated body gains energy from the heated surface of the hot body. The density of the air film drops upon gaining heat energy from the heated object and henceforth moves upward due to buoyancy driven force. Cold air from the surrounding area having a higher density rushes into the vacant layer and the same process repeats. This paper is aimed to find the Natural Heat Transfer Coefficient of the human body under different postures and compare the obtained result using dimensionless numbers (like Nusselt number) with results obtained in those of other experiments.

The simulation based experiment might be subjected to some variations in results when compared to similar experiments. Thus, the obtained Heat Transfer Coefficient might vary. Gravity plays a dominating role in Heat Transfer via Natural convection. Gravitational force acts along different paths for different body posture. Moreover, sources of disturbances such as clothings and complicated body shapes causes alterations in the obtained results. For simplification we considered that the entire surface area takes part in the heat transfer process though the ones in contact with ground do not take part in heat transfer via natural convection, but for simplification we have considered the surface ratio to be 1. The basic origin of heat in a human body are these metabolic activities. When proteins and nucleic acids are broken down by cellular respiration and anabolism, it releases energy for physical activities as well as heat for keeping the core temperature of the human body at a particular level to keep the organ activity at a biologically optimal level for proper functionality.

The core temperature of the human body is 36.8°C to 37.2°C. And the ectodermic skin temperature is maintained at 33.7°C by the skin blood flow. So human body has an interior core which acts like a heat generation source where the heat generation depends on the rate of metabolic activities. The body generates heat from about 75 watts during sleep to up to 1000 watts during heavy aerobic exercises. The excess heat generated during this period must be conveyed to the external environment to maintain the core temperature around at 37.0 ± 0.5 °C. When calculating the heat transfer coefficient value just considering the metabolic rate for different circumstance by mathematical approach, we must have to be conscious about the fraction of metabolic rate. So, the calculated value will be different for different conditions. When setting appropriate system for analysis in CFD this fraction under different circumstance with separate conditions will definitely have to be considered for completing the analysis with a constructive approach."MET" or Metabolic Equivalents shall be used as a comparative standard while validating our results using Nusselt Number.

Governing Equations

The four basic modes of Heat Transfer from a human body are Convection, Radiation, Respiration and Transpiration. Conduction takes place only when the body is in contact with another surface. For process simplification Human body is sometimes considered a collection of six cylinders or spheres. Steady state heat transfer is considered and by applying the equations to a human body the natural convection coefficient is determined.

The Generalized Governing equation in our case is a Substantial derivative given by equation (1)

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + V \cdot \Delta \quad \text{.................................(1)}$$

Where $\frac{D}{Dt}$ is the Substantial Derivative, the time rate of change following a moving fluid element. $\frac{\partial}{\partial t}$ is the Local derivative, the time rate of change at a fixed point. And $(V \cdot \Delta)$ is the convective derivative, the rate of change due to the movement of the fluid element from one point to another in the flow field. But the governing equation for natural convection for a stationary frame are a special case of this generalized equation which is given by equation (2)

$$\frac{D\rho}{Dt} + \rho V \cdot \Delta = 0 \quad \text{...}(2)$$

For 2D Case and Incompressible flow, we resort to the Navier-Stokes Equations for the Continuity, Momentum and Energy Equations which are given by equation (3),(4) and (5) respectively:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad \text{..(3)}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial v}{\partial y} = v\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + g\beta(T - T_\infty) - \frac{1}{\rho_\infty}\frac{\partial}{\partial x}(p - p_\infty) \quad \text{.(4)}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \quad \text{..............................(5)}$$

Where, the thermal expansion coefficient and is given by $\beta = -(1/p)(\partial\rho/\partial T)_p$

The prime factor for natural convection is the temperature gradient which causes a change in the density of the fluid. The density variation and buoyancy forces cause movement of the fluids.

For validation of the obtained result, dimensionless numbers are used. The equations for Grasshof, Prandtl and Nusselt number are given in the following equations-

$$Gr_x = \frac{g\beta(T_W - T_\infty)x^3}{v^2} \quad \text{...............................(6)}$$

$$Pr = \frac{v}{\alpha} \quad \text{......................................(7)}$$

$$Nu_L = \frac{\square L}{k} \quad \text{..(8)}$$

Nusselt number is also expressed in terms of Grashof and Prandtl number using the following equations:

$Ra = Gr.Pr$ ....(9)

Here Grashof number is calculated to be ($<10^8$) and hence the system will be laminar in nature.

For Laminar Flow, $10^{-1} < Ra_L < 10^{12}$ the equation for the nusselt number-

$$Nu^{-1/2} = .825 + \frac{.387Ra^{1/6}}{[1 + (.492/Pr)^{9/16}]^{8/27}} \quad \text{......(10)}$$

Surface Nusselt Number,

$$Nu = \frac{q \times x}{K \times (T_S - T_\infty)} \quad \text{............(11)}$$

The value of the Nusselt Number obtained from this simulation is the surface Nusselt number at any defined surface. Richardson's number is also an important parameter to determine cases of pure natural convection and forced convection. The equation for Richardson's number is as follows:

$$Ri = \frac{g\beta(T_{\square ot} - T_{ref})L}{v^2} \quad \text{............................(12)}$$

Here the velocity has a minimal value and the value of Richardson's number obtained is greater than 10. Hence Forced convection will be negligible and the case will be purely Natural Convection based.

Geometry

The Human Manikin is assumed to be in a square shaped room with each side being 3.05 m (10 feet). For the standing posture a symmetric sketch is obtained. As for the Supine and Sitting conditions, the asymmetric regions have been properly demarcated with appropriate dimensions. All the limbs of the body are modelled considering a human of 1.6 m (5 Feet) height having an average health.

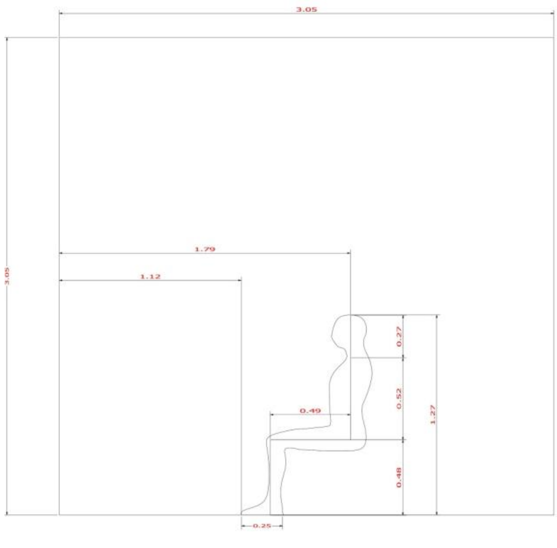


Fig 1(a): Geometry of Sitting Posture

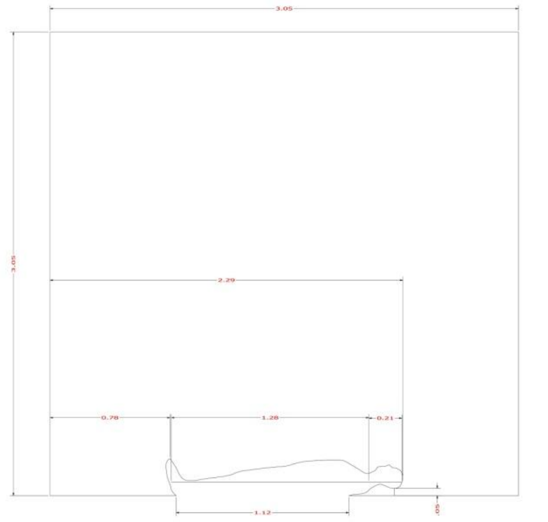


Fig 1(b): Geometry of Supine Posture

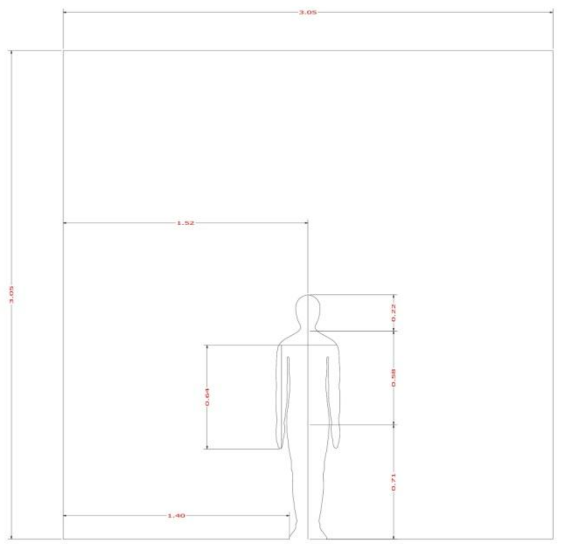


Fig 1(c): Geometry of Standing Posture

The model in standing posture is assumed such that the Vertical symmetry line of the room passes exactly axial center of the human model. The soles are in total contact with the floor. All the limbs are modelled to near perfection considering an ideal human body.

Solution Procedure

The human shapes were generated by Autodesk Inventor software, where the measurement of each of the limbs are drawn to near perfection from existing models. Then the model was imported to Design Modeler module in Ansys where the Mesh has been generated with refined edges and the individual mesh size limited to 5 mm. Then boundary conditions (such as surface temperatures, air density, gravity, insulations), the initial results were obtained from the software in the Fluent module. The software uses boundary layer approximations to solve problems. Different Body parts have different MET rates, that's why the values of heat transfer coefficient varies at different segments and for simplification we just made an average of the obtained heat transfer coefficient.

Boussinesq Approximations

In Boussinesq approximations the density variations are neglected. The effect of pressure is neglected and the temperature effect is used to estimate the the density differences in the fluid which is given by the following equation:

$\rho_\infty - \rho = \rho\beta(T - T_\infty)$ ……………………….(13)

In natural convection the surrounding pressure is mostly hydrostatic pressure and the velocity is very low. Heat transfer mostly occurs in a very thin layer of fluid that is very close to the body surface. So the gradients in the tangent direction of the surface are smaller than the ones in the normal direction. In boundary layer approximations. The flow terms except the vertical ones are neglected in the momentum and heat equations.

Results and Discussions

The human models are considered to be 5 feet in height enclosed in a room of (3.05x3.05) meter. The Surface temperature of the Human body remains constant at 310 kelvin. The upper and the lower wall are considered to be insulated and the input parameter for such a case has been defined by setting the Heat Flux to zero. The side walls are maintained at a constant temperature of 298 kelvin. The skin conduction coefficient, specific heat capacity and average density are set to .209W/mk, 3470 J/KgK and 1000 Kg/m^3

The heat transfer is considered to be steady and ther other fluid characteristics in natural convection are assumed constant. The domains have been prepared in such a way that in the standing and sitting posture, only the soles are considered in contact with the ground. As for the Supine posture it is considered that the entire back side is in contact with the ground surface except the posterior part of the head which resembles a human lying on the floor with the head slightly raised by pillow as in sleeping.

The results were obtained for 100 iterations and the solution. The static temperature profiles have been generated by segmenting it to 100 levels where the minimum temperature in the domain is obtained at 298 K (Lateral Walls) and a maximum of 310 K (Human body). For the supine and standing posture the thermal profile is almost symmetric and as for the sitting posture, the temperature curve gets a bit hued more to the right side due to additional non-symmetry. Although Human body loses heat to the surrounding atmosphere in several processes, Radiation being one of them, the heat lost through radiation is of a minimal magnitude compared to the convective heat loss.

For study of pure convective heat lost, the loss incurred by Radiation has also been discarded. Since the fluid velocity associated with natural convection is relatively low. So Reynold's Number (which indicates the nature of flow either Laminar, Transient or Turbulent) will be less than 2300 under the scope of which the flow will be laminar.

Then the Temperature Graphs were plotted against the horizontal distance which was later used to calculate the value of Heat transfer Coefficient, Rayleigh Number and Nusselt number. For this consideration, we took temperature along 3 different lines for each posture. The Bottom Edge which is .01 m Above the floor level as marked Green, the Mid Plane line, which passes exactly through the midway between the total height of the enclosure (ie 1.5 m appx) is marked Red. The Top Edge Line is marked Yellow which has been marked at a height of 3 m from the ground level. The reason the Top and the bottom line were not taken along the Floor and Ceiling length is because the top and bottom are set to be insulated in the boundary condition. For that we would not get any value in the temperature graph.

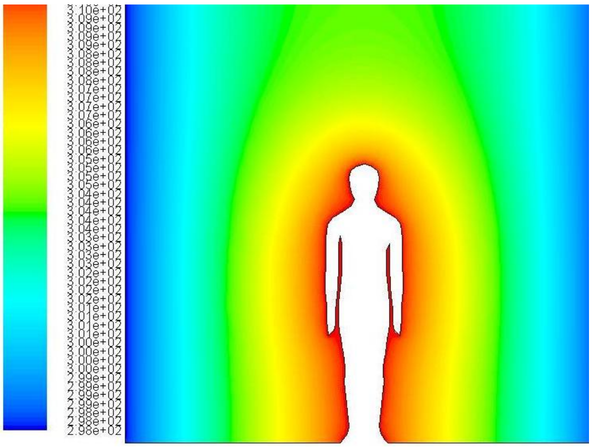


Fig 2(a): Chromatic Thermal Profile (Standing)

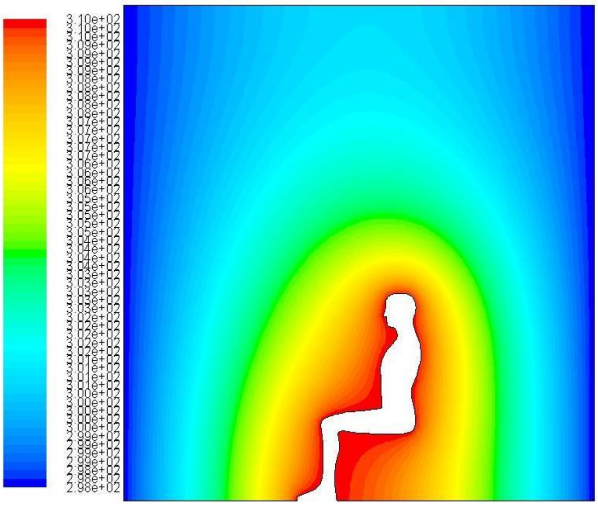


Fig2(b): Chromatic Thermal Profile (Sitting)

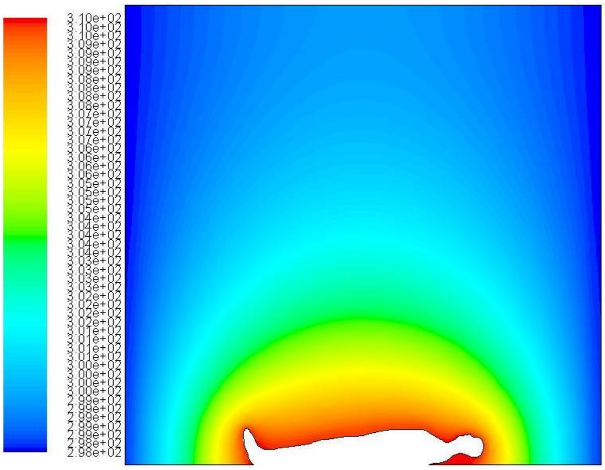


Fig2(c): Chromatic Thermal Profile (Supine)

Then the Temperature Graphs were plotted against the horizontal distance which was later used to calculate the value of Heat transfer Coefficient, Rayleigh Number and Nusselt number. For this consideration, we took temperature along 3 different lines for each posture. The Bottom Edge which is .01 m Above the floor level as marked Green, the Mid Plane line, which passes exactly through the midway between the total height of the enclosure (ie 1.5 m appx) is marked Red. The Top Edge Line is marked Yellow which has been marked at a height of 3 m from the ground level. The reason the Top and the bottom line were not taken along the Floor and Ceiling length is because the top and bottom are set to be insulated in the boundary condition. For that we would not get any value in the temperature graph.

The temperature curve obtained from this section was later on used to calculate the temperature gradient which plays a vital role in determination of the Rayleigh number. As for the asymmetry of the sitting and lying condition, the temperature curve obtained will have some noticeable effect on the heat transfer which will be shown in the coming sections. As in case of calculations of Rayleigh number, the gradient temperature changes the entire value obtained as Rayleigh number is a function of temperature gradient.

For the experimental purpose, Ansys CFD-Post was used to generate the temperature curve along 3 different lines namely the top, bottom and the midline along the reference enclosure. As temperature gradient is different for the same posture depending upon which line we decide to consider, the obtained Rayleigh number will also vary depending on which line we consider for the temperature gradient. For our calculation purpose, we shall be using the mid-line temperature curve obtained for our calculation of Rayleigh number in the upcoming sections.

The suitable series lines for plotting temperature against the horizontal position for each of the postures are shown as below:

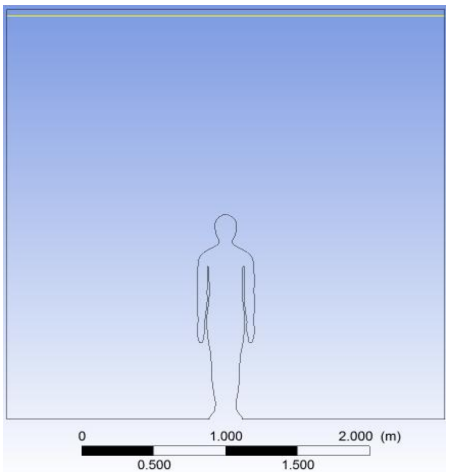


Fig 3(a): Top Considered Line (Yellow)

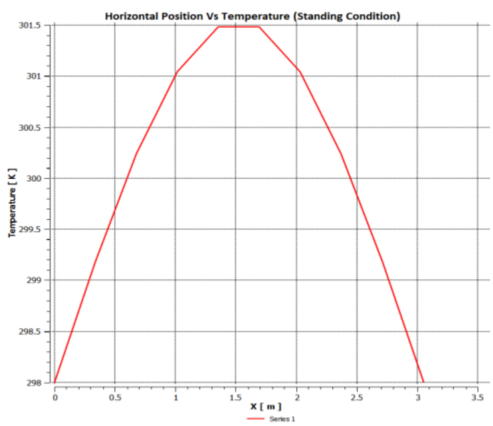


Fig 3(b): Temperature Curve along the Top Line (Yellow)

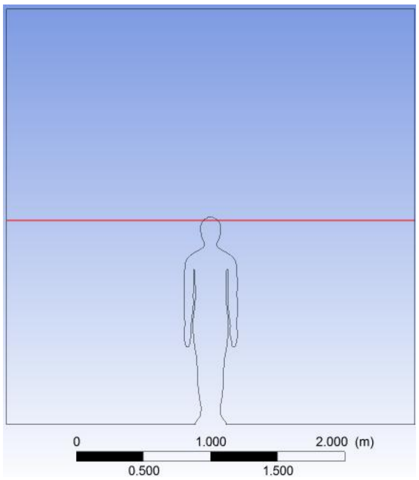


Fig 4(a): Mid Considered Line (Red)

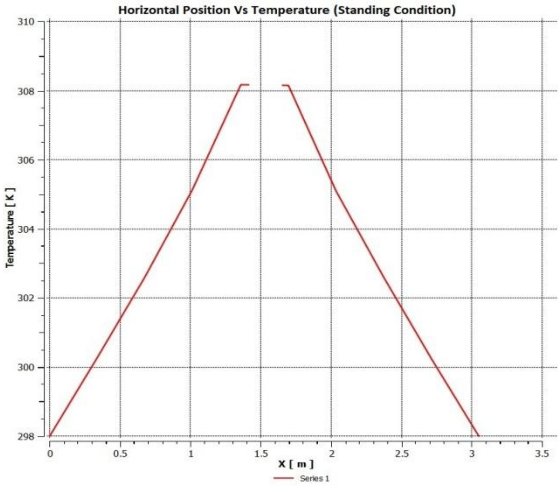


Fig 4(b): Temperature Curve along the Midline (Red)

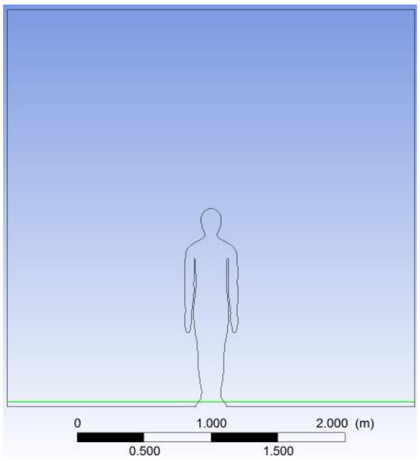


Fig 5(a): Bottom Considered Line (Green)

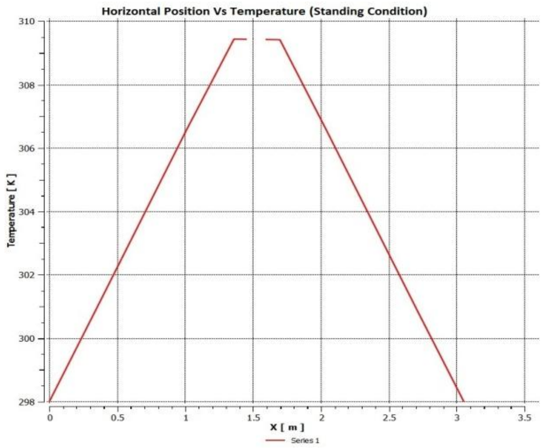


Fig 5(b): Temperature Curve along the Bottom Line (Green)

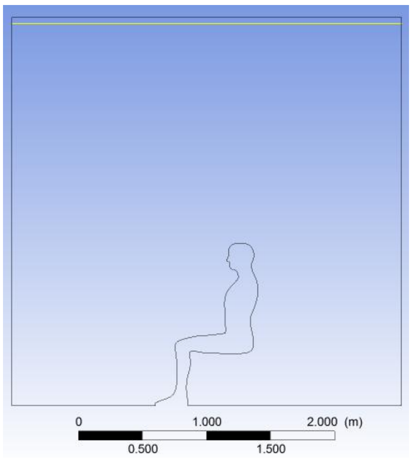


Fig 6(a): Top Considered Line (Yellow)

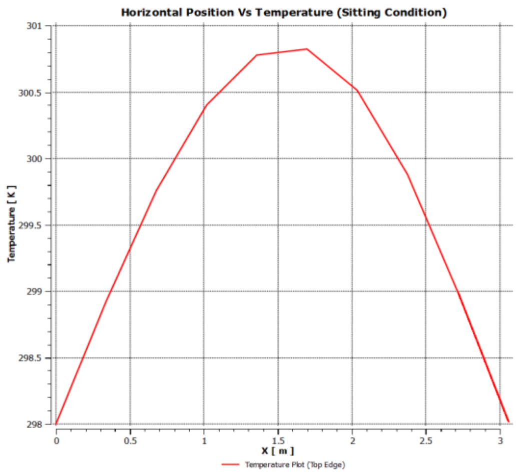


Fig 6(b): Temperature Curve along the Top Line (Yellow)

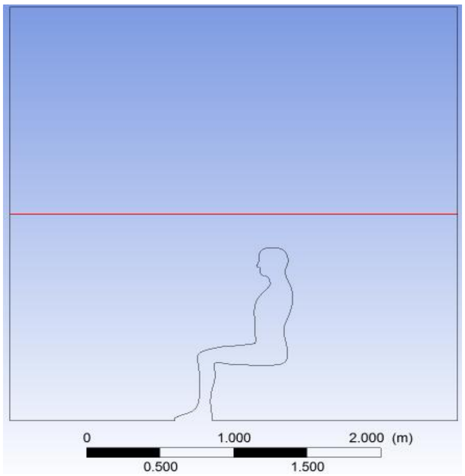


Fig 7(a): Mid Considered Line (Red)

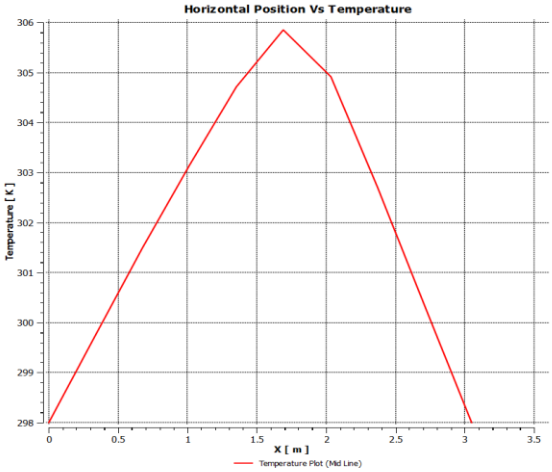


Fig 7(b): Temperature Curve along the Mid Line (Red)

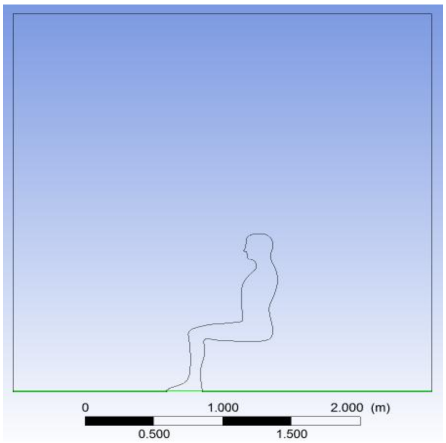


Fig 8(a): Bottom Considered Line (Green)

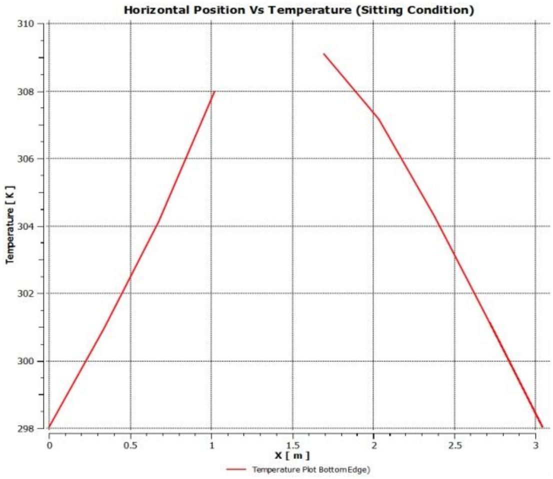


Fig 8(b): Temperature Curve along the Bottom Line (Green)

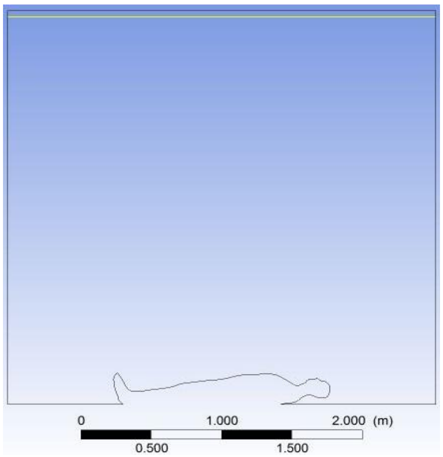


Fig 9(a): Top Considered Line (Yellow)

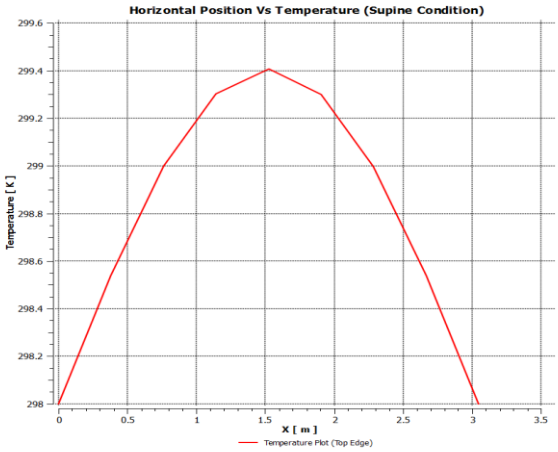


Fig 9(b): Temperature Curve along the Top Line (Yellow)

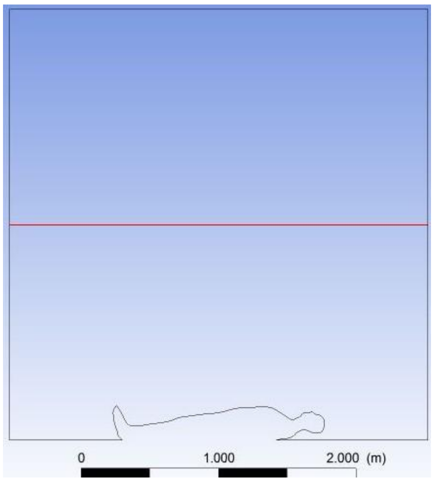


Fig 10(a): Mid Considered Line (Red)

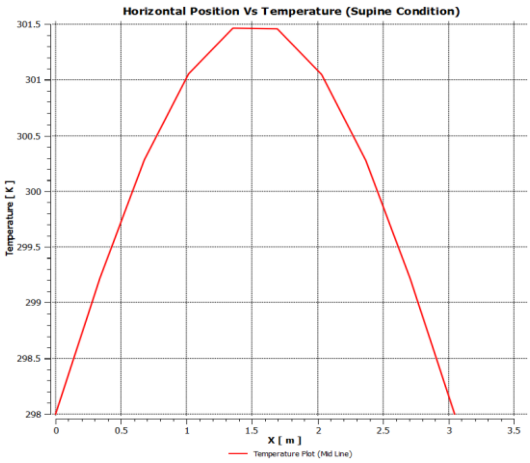


Fig 10(b): Temperature Curve along the Mid Line (Red)

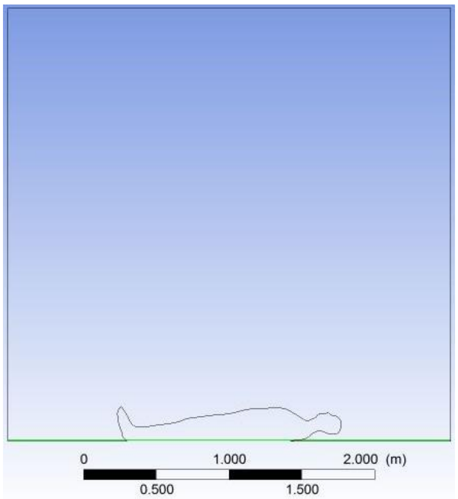


Fig 11(a): Bottom Considered Line (Green)

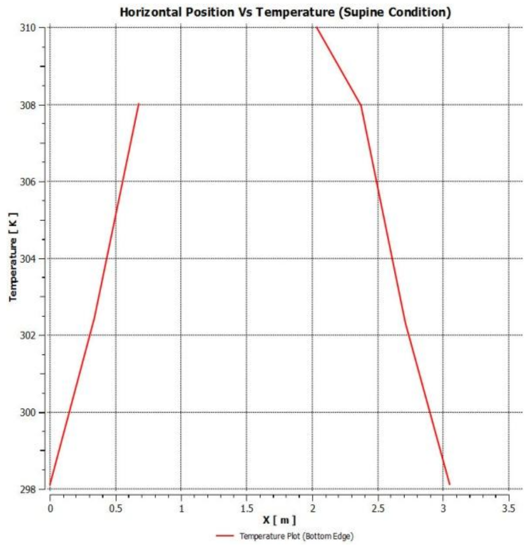


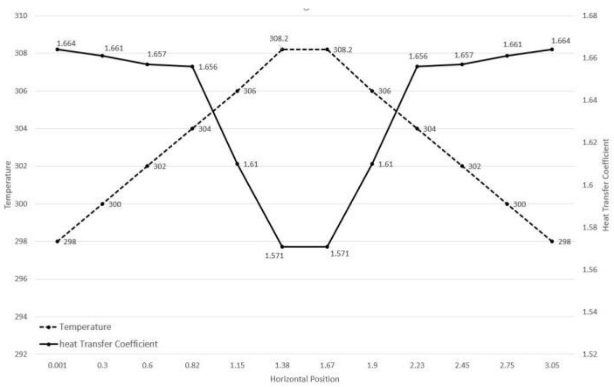
Fig 11(b): Temperature Curve along the Bottom Line (Green)

It is observed from the temperature curve that there are gaps in some of the obtained temperature curves. In case of Supine condition when the bottom line is considered, the void is created to the fact that entire posterior part of the human model in contact with the ground so there is no free air in which the temperature value could be extracted. Similarly in case of sitting posture, the feet of the model is considered to be in total contact with the floor.

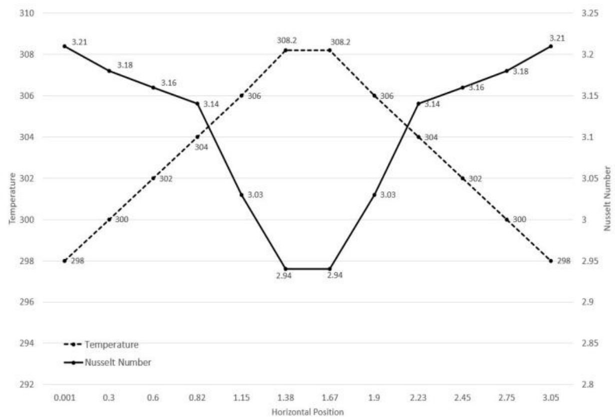
These are basically the reasons why there's a depreciation in the continuity of some of the obtained temperature curves.

Determination of Nusselt Number in Air

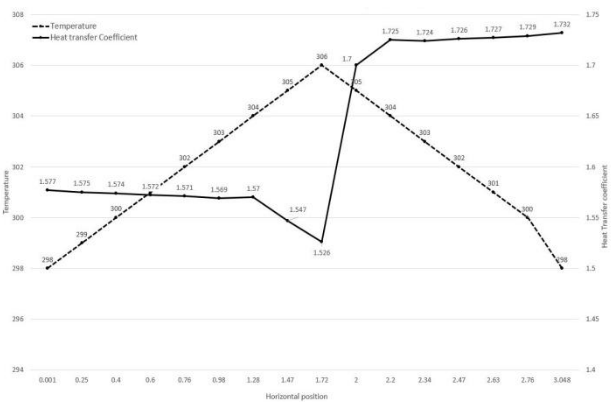
For calculation of Rayleigh Number, the film temperature was taken to be complete integers along the Midline (Red) as shown in the Figures above for each of the postures. With a .025 m characteristic length, the temperature gradient changed with the change of the boundary layer of each of the temperature zones. Corresponding to the Film temperatures the values needed for calculation of the Rayleigh Number,such as the thermal expansion coefficient, thermal diffusivity, kinematic viscosity etc were determined from the Air-Standard table values. This was then used to determine the values of Nusselt Number and the Heat Transfer coefficient from CFD-post using user defined formulas. For Rayleigh number ranging $10^3 < Ra < 10^5$ The obtained Results are illustrated in the preceding page.



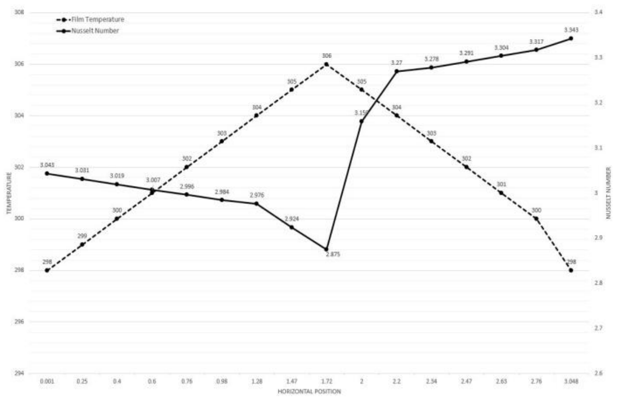
Graph 1(a): Change of Heat Transfer Coefficient with change of Temperature (Standing Condition)



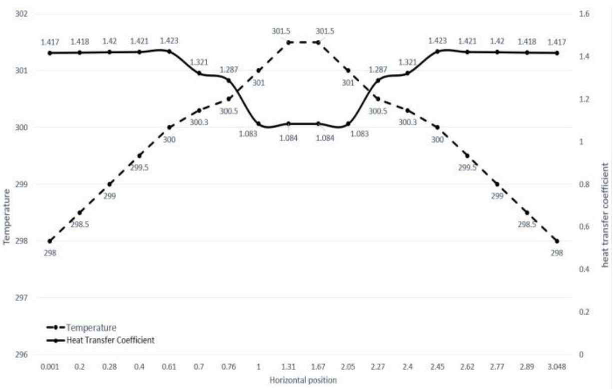
Graph 2(a): Change of Nusselt Number with change of Temperature (Standing Condition)



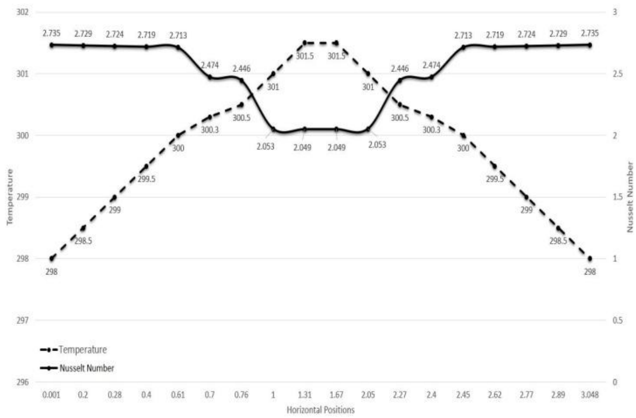
Graph 1(b): Change of Heat Transfer Coefficient with change of Temperature (Sitting Condition)



Graph 2(b): Change of Nusselt Number with change of Temperature (Sitting Condition)



Graph 3(a): Change of Heat Transfer Coefficient with change of Temperature (Supine Condition)



Graph 3(b): Change of Nusselt Number with change of Temperature (Supine Condition)

Posture	Average 'Nu'	Average 'hc'
Standing	3.11	1.62
Sitting	3.11	1.63
Supine	2.56	1.39

From the tabulated data it is evident along the midline the Heat Transfer coefficient is maximum for Sitting and Standing condition, which have near identical value along the line of interest. Minimum Heat Transfer Coefficient is observed for Supine Condition as the body is comparatively at a lower altitude from the Midline compared to that of the other two postures

Determination of the Surface Nusselt Number along Human Skin

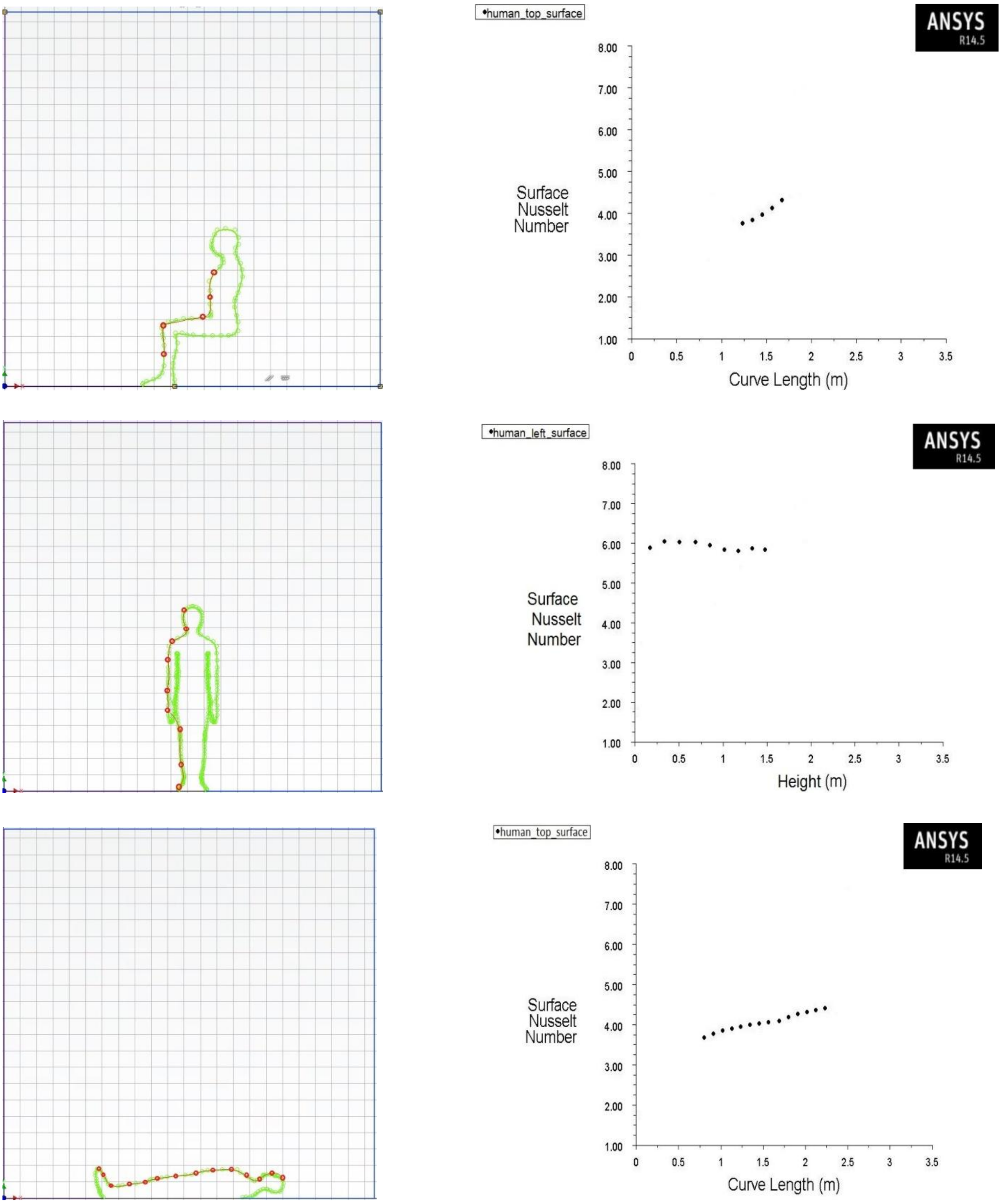


Fig: Surface Nusselt Number Plotted at the edge of Human Skin (Points of interest Marked in left diagrams)

Surface Nusselt number was extracted from Ansys CFD post using user defined functions. The values were obtained along edge of skin-air boundary where the skin was assumed the heated solid surface from where heat was transferred to the adjacent air via natural convection. The values were obtained along the Red Curve marked in all geometries of all the three postures. The specific point on the red curves for which the value of Nusselt number was calculated has been marked with Red Dots in the figure. The variation in nusselt number at different point of the human body is due to the different rates of heat generation of different body parts at different postures. The values of those heat generation rates were incorporated in our user defined function which gave the proper nusselt numbers at those specific points of interest. The following table gives the average value for each of the postures-

Sl. No	Condition	Skin Surface Nusselt Number Average Value by **Ansys CFD-POST**
1	Standing	5.925
2	Sitting	4.280
3	Lying	4.166

A Standard Table is shown here which provides the average Rated value of Natural convective heat transfer coefficients (hc) for a nude thermal manikin standing and sitting in still air (velocity < 0.1 m/s), Obtained at a fixed skin-to-air temperature gradient of 12K. For different segments of the body parts the avg. value of convective heat transfer skin surface coefficient is different. Here we are handling just with the average value showing here. From the table it is observed that the average value of "hc" under seated condition is 3.3 W/m² per K. This is the standard value with which our value, obtained by experimental analysis have to be compared. And moreover the "hc" value under Standing Condition is absolutely 3.4 W/m² per K , which indicates the average value of different portions of human thermal manikin. This value will also have to be compared with our CFD aided value.

Following this, the heat transfer coefficient was determined from the obtained nusselt number values. In order to check the authenticity of the obtained values, the experimental values were compared to the Standard Table Values as well as the pure MET calculations for each of the body postures. The deviations obtained were comparatively low.

The following table gives the comparison between the values obtained from Ansys to that of Standard table values and calculations from pure MET-

Condition	**Manikin (hc) Standard Table Values**	**Pure MET (hc)**	**ANSYS Experiment Average (hc) from Nu**
Standing	**3.4**	**3.450**	**3.466**
Sitting	**3.3**	**3.220**	**3.327**
Lying	**2.9**	**2.592**	**2.740**

Deviations of our experimental values from these Standard values are as follows:

Deviation of Experimental values	
ANSYS Experiment vs Nude Thermal Manikin	**ANSYS Experiment vs pure MET calculation**
1.904 %	**0.46 %**
.8 %	**3.2 %**
5.5 %	**5.4 %**

Kurazumi et al and Oguru et al derived formulas for determining the coefficient of heat transfer for supine, sitting and standing posture. These formulas are empirically derived from experimental observations and are as follows:

$\square_{standing} = 1.21(T_{skin} - T_{\infty})^{0.43}$ …………………(14)

$\square_{sitting} = 0.78(T_{skin} - T_{\infty})^{0.56}$ …………………(15)

$\square_{supine} = 1.183(T_{skin} - T_{\infty})^{0.347}$ …………………..(16)

Conditions	**$\square_c$from empirical Formulas**	**$\square_c$from Ansys Experiment**	**Deviation**
Standing	3.522	3.466	1.59%
Sitting	3.131	3.327	5.9%
Lying	2.801	2.740	2.17%

While comparing the heat transfer coefficients extracted from Ansys to that of calculated from equation (14), (15) and (16) the maximum deviation is observed for the lying condition when the extracted data are compared to that of Nude thermal Manikin $\square_{\square}$ and pure MET $\square_{\square}$. The other postures have a significantly lower deviation (<5%).

When calculating the "hc" value just considering the metabolic rate for different circumstance by mathematical approach ,we must have to be conscious about the fraction of metabolic rate. So the calculated value will be different for different conditions. When setting appropriate system for analysis in CFD this fraction under different circumstance with separate conditions will definitely have to be considered for completing the analysis with a constructive approach.

Conclusion

The aim of this research is determining the coefficient of natural convection heat transfer of human body. Human body is simulated as a sample and then in three different

segments (standing , sitting and supine) exposed to the natural convection. The considered segments are in a situation which some parts of the body are in contact with the ground and the other surfaces of the body are exposed to the surrounding air. Future scope of studies

include adding forced convection, vents and fans to improve the rate of heat dissipation from human body for comfort improvement study. Changing the parametric conditions it is possible to calculate the values under turbulent and transient zones under natural and forced convections which will create a diversity in this research. Moreover the minor limitations relating to the research can also be enhanced to get more accurate results if more boundary conditions and involved physics are added to the simulation process.

References

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Nomenclature

g	gravitational acceleration, m/s^2
T	local temperature, k
T_∞	free stream temperature, k
ρ_∞	free stream density, kg/m^3
p	local pressure, Pa
u	velocity along x-axis, m/s
p_∞	free stream pressure, Pa
v	velocity along x-axis, m/s
□	convective coefficient, $W/(m^2K)$
α	thermal diffusivity, m^2/s
k	coefficient of thermal conductivity, $W/(m.K)$
β	thermal expansion coefficient, K^{-1}
L	characteristic length, L
q	heat transfer rate, W
ρ	Local density, kg/m^3