A DISSERTATION REPORT

ON

EXPERIMENTAL ANALYSIS OF THERMOREGULATORY MECHANISM OF HUMAN BODY

Submitted in partial fulfilment of requirements for the award of degree of

MASTER OF TECHNOLOGY

In

MECHANICAL ENGINEERING

(With Specialisation in Thermal Engineering)

by

LOVLEET KUMAR

En. No: 17541007

Under the guidance of

Dr. SUDHAKAR SUBUDHI

Associate Professor, MIED

DEPARTMENT OF MECHANICAL AND INDUSTRIAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY, ROORKEE

ROORKEE-247667 (INDIA)

INDIAN INSTITUTE OF TECHNOLOGY ROORKEE, ROORKEE

CANDIDATE'S DECLARATION

I hereby certify that the work carried out in this dissertation entitled **"EXPERIMENTAL ANALYSIS OF THERMOREGULATORY MECHANISM OF HUMAN BODY"**, is presented in partial fulfilment of the requirements for award of the degree of "Master of Technology" in Mechanical Engineering with specialisation in Thermal Engineering, submitted to the department of Mechanical and Industrial Engineering at the Indian Institute of Technology Roorkee, Roorkee, is an authentic record of my own work carried out under the supervision of Dr. Sudhakar Subudhi, Associate Professor, MIED,IIT Roorkee.

I have not submitted the record embodied in this dissertation report for the award of any other degree or diploma in any institute.

Date: Nov 2019

Place: Roorkee **LOVLEET KUMAR**

CERTIFICATION

This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief.

(Dr.Sudhakar Subudhi)

Associate Professor

MIED

IITR

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LOVLEET KUMAR

ENROLLMENT NO: 17541007

ABSTRACT

Traditional methods of human thermal comfort analysis are based on the first law of thermodynamics. These methods use an energy balance of the human body to determine heat transfer between the body and its environment. By contrast, the second law of thermodynamics introduces the useful concept of exergy. It enables the determination of the exergy consumption within the human body dependent on human and environmental factors. Human body exergy consumption varies with the combination of environmental (room) conditions. This process is related to human thermal comfort in connection with temperature, heat, and mass transfer. A thermodynamic analysis of human heat and mass transfer based on the 2nd law of thermodynamics in presented. It is shown that the human body's exergy consumption in relation to selected human parameters exhibits a minimal value at certain combinations of environmental parameters. The expected thermal sensation also shows that there is a correlation between exergy consumption and thermal sensation. Thus, our analysis represents an improvement in human thermal modelling and gives more information about the environmental impact on expected human thermal sensation. Exergy is only conserved, or in balance, for a reversible process, but is partly consumed in an irreversible process. For a real process the exergy input always exceeds the exergy output; this imbalance is due to irreversibilities and represents exergy destruction or exergy consumption.

In the present work, thermal variations was observed on 16 bodies part of human body and each part was carefully monitored on the basis of their thermal nature. A new thermal comfort questionnaire has been designed for gathering thermal sensation votes and Predicted mean vote was made based on the questionnaire taken from the subjects.

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CHAPTER 1

INTRODUCTION

Humans are warm-blooded, we keep our body at 37 °C regardless of external conduction. This is real challenge as our environment changes all the time depending on the weather, our clothes if we are inside by the fire or outside having a snowball fight. Our body work well it's quite similar to the heating system in a house there has a thermostat that measures the temperature if the house gets cold and thermostat will tell the radiators to turn on and heat it up if it's too hot, they will be told to switch off. Our body work similarly in just the same way here in your brain is a special area called the hypothalamus it measure the temperature of the blood flowing though it and collect information from temperature sensors around the body it then decides if the temperature is too hot or too cold and will try and bring it back to 37 °C if you are too hot the hypothalamus can then send signals out to the body via the nervous system that can cause various effects it can send a signal to your skin and cause sweat glands to secrete the sweat onto the surface of the skin the sweat itself is not cold but it works because it takes heat away from your body in order to evaporate it another way of loosing heat is vasodilation . The blood vessel nearest the surface of the skin open wide and allow blood flow through them the heat is radiated from the blood into the air and the blood cools down if you get too cold you can do the opposite with these blood vessels and close them off keeping the blood away from the surface of the skin this is called vasoconstriction you can also start to shiver this is when your muscles contract in order to make heat another effect you may have noticed when you are cold if you look more closely at these simples what you realize is that each of the little bump has a hair sticking out of it these hairs are stood up on end to trap a layer of around the skin air is a fantastic insulator of heat and this will keep you nice and cozy .

1.1 Thermal comfort

Thermal comfort is defined as **"that condition of mind which expresses satisfaction with the thermal environment"**. This condition is also sometimes called as "neutral condition", though in a strict sense, they are not necessarily same. A living human body may be likened to a heat engine in which the chemical energy contained in the food it consumes is continuously converted into work and heat. The process of conversion of chemical energy contained in food into heat and work is called as **"metabolism"**. The rate at which the chemical energy is converted into heat and work is called as **"metabolic rate"**. Knowledge of metabolic rate of the occupants is required as this forms a part of the cooling load of the air-conditioned building. Similar to a heat engine, one can define thermal efficiency of a human being as the ratio of useful work output to the energy input. The thermal efficiency of a human being can vary from 0% to as high as 15-20% for a short duration. By the manner in which the work is defined, for most of the light activities the useful work output of human beings is zero, indicating a thermal efficiency of 0%. Irrespective of the work output, a human body continuously generates heat at a rate varying from about 100 W (e.g. for a sedentary person) to as high as 2000 W (e.g. a person doing strenuous exercise). Continuous heat generation is essential, as the temperature of the human body has to be maintained within a narrow range of temperature, irrespective of the external surroundings.

A human body is very sensitive to temperature. The body temperature must be maintained within a narrow range to avoid discomfort, and within a somewhat wider range, to avoid danger from heat or cold stress[3]. Studies show that at neutral condition, the temperatures should be:

Skin temperature, $t_{skin} \approx 33.7°C$ Core temperature, $t_{core} \approx 36.8°C$.

At other temperatures, the body will feel discomfort or it may even become lethal. It is observed that when the core temperature is between 35 to 39°C, the body experiences only a mild discomfort.. When the temperature is lower than 35°C or higher than 39°C, then people suffer major loss in efficiency. It becomes lethal when the temperature falls below 31°C or rises above 43°C [4]. This is shown in Fig

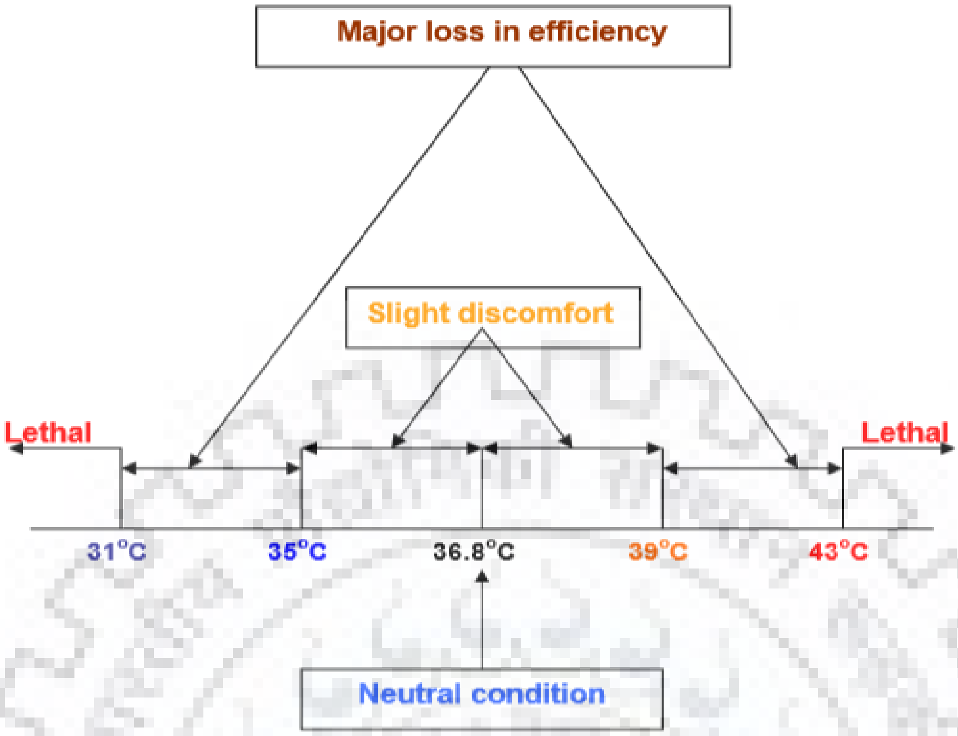

Fig 1: Affect of the variation of core temperature on a human being

1.2 Heat balance equation for a human being :-

The temperature of human body depends upon the energy balance between itself and the surrounding thermal environment. Taking the human body as the control volume, one can write the thermal energy (heat) balance equation for the human body as[4]:

$$Q_{gen} = Q_{sk} + Q_{res} + Q_{st}$$

where :-

Q_{gen} = Rate at which heat is generated inside the body

Q_{sk} = Total heat transfer rate from the skin

Q_{res} = Heat transfer rate due to respiration, and

Q_{st} = Rate at which heat is stored inside the body

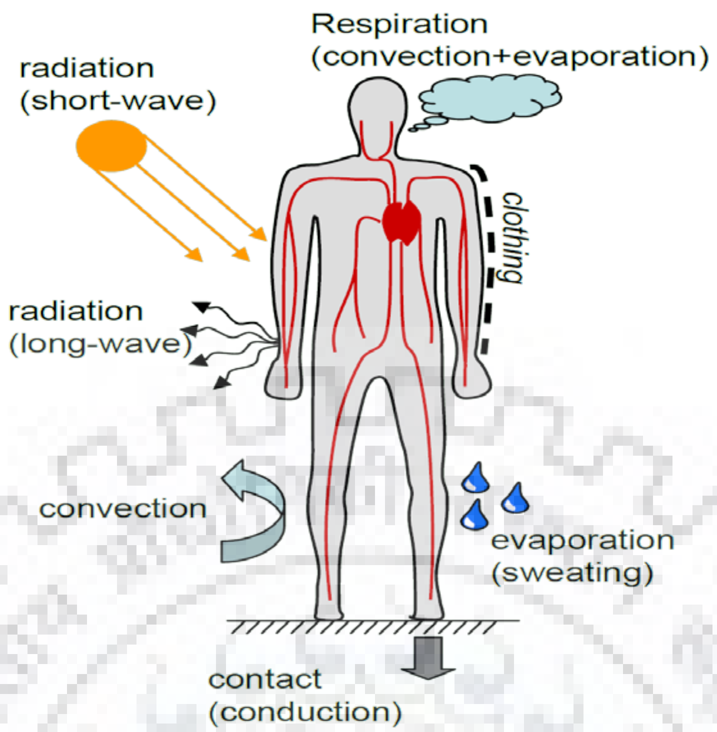

Fig 2 : Heat transfer from the human body [27]

The heat generation rate Qgen is given by:

$$\mathbf{Q_{gen} = M\,(1-\eta) \approx M}$$

Where

M = Metabolic rate, and

η = Thermal efficiency ≈ 0 for most of the activities

The metabolic rate depends on the activity. It is normally measured in the unit **"met"**. A met is defined as the metabolic rate per unit area of a sedentary person and is found to be equal to about 58.2 W/m^2. This is also known as "basal metabolic rate". The following table shows typical metabolic rates for different activities:

Activity	Specifications	Metabolic rate
Resting	Sleeping	0.7 met
	Reclining	0.8 met
	Seated, quite	1.0 met
	Standing, relaxed	1.2 met
Walking	0.89 m/s	2.0 met
	1.79 m/s	3.8 met
Office activity	Typing	1.1 met
Driving	Car	1.0 to 2.0 met
	Heavy vehicles	3.2 met
Domestic activities	Cooking	1.6 to 2.0 met
	Washing dishes	1.6 met
	House cleaning	2.0 to 3.4 met
Dancing	-	2.4 to 4.4 met
Teaching	-	1.6 met
Games and sports	Tennis, singles	3.6 to 4.0 met
	Gymnastics	4.0 met
	Basket ball	5.0 to 7.6 met
	Wrestling	7.0 to 8.7 met

Table 1:- Metabolic rate for different activities

The metabolic rate can be correlated to the rate of respiratory oxygen consumption and carbon dioxide production. Based on this empirical equation have been developed which relate metabolic rate to O_2 consumption and CO_2 production.

Since the metabolic rate is specified per unit area of the human body (naked body), it is essential to estimate this area to calculate the total metabolic rate. Even though the metabolic rate and heat dissipation are not uniform throughout the body, for calculation purposes they are assumed to be uniform.

The human body is considered to be a cylinder with uniform heat generation and dissipation. The surface area over which the heat dissipation takes place is given by an empirical equation, called as Du Bois Equation. This equation expresses the surface area as a function of the mass and height of the human being.

Du Bois Equation :-

$$\mathbf{A_{Du} = 0.202\, m^{0.425}\, h^{0.725}}$$

where

A_{Du} = Surface area of the naked body, m^2

m = Mass of the human being, kg

h = Height of the human being, m

Since the area given by Du Bois equation refers to a naked body, a correction factor must be applied to take the clothing into account. This correction factor, defined as the “ratio of surface area with clothes to surface area without clothes” has been determined for different types of clothing. These values are available in ASHRAE handbooks. Thus, from the metabolic rate and the surface area, one can calculate the amount of heat generation, Qgen. The total heat transfer rate from the skin Qsk is given by:

$$Q_{sk} = \pm\, Q_{conv} \pm Q_{rad} + Q_{evp}$$

Where

Q_{conv} = Heat transfer rate due to convection (sensible heat)

Q_{rad} = Heat transfer rate due to radiation (sensible heat), and

Q_{evp} = Heat transfer rate due to evaporation (latent heat)

The convective and radiative heat transfers can be positive or negative, i.e., a body may lose or gain heat by convection and radiation, while the evaporation heat transfer is always positive, i.e., a body always looses heat by evaporation. Using the principles of heat and mass transfer, expressions have been derived for estimating the convective, radiative and evaporative heat transfer rates from a human body. As it can be expected, these heat transfer rates depend on several factors that influence each of the heat transfer mechanism.

According to Belding and Hatch, the convective, radiative and evaporative heat transfer rates from the naked body of an average adult, Qc, Qr and Qe, respectively, are given by:

$$Q_c = 14.8\, V^{0.5} (T_b - T)$$

$$Q_r = 11.603\, (T_b - T_s)$$

$$Q_e = 181.76\, V^{0.4} (P_{s,b} - P_b)$$

In the above equation all the heat transfer rates are in watts, temperatures are in °C and velocity is in m/s, $P_{s,b}$ and P_v are the saturated pressure of water vapour at surface temperature of the body and partial pressure of water vapour in air, respectively, in kPa. From the above equations it is clear that the convective heat transfer from the skin can be increased either by increasing the surrounding air velocity (V) and/or by reducing the surrounding air DBT (t). The radiative heat transfer rate can be increased by reducing the temperature of the surrounding surfaces with which the body exchanges radiation. The evaporative heat transfer rate can be increased by increasing the surrounding air velocity and/or by reducing the moisture content of surrounding air.

The heat transfer rate due to respiration Qres is given by:

$$Q_{res} = C_{res} + E_{res}$$

where

C_{res} = Dry heat loss from respiration (sensible, positive or negative)

E_{res} = Evaporative heat loss from respiration (latent, always positive)

The air inspired by a human being is at ambient conditions, while air expired is considered to be saturated and at a temperature equal to the core temperature. Significant heat transfer can occur due to respiration. Correlations have been obtained for dry and evaporative heat losses due to respiration in terms of metabolic rate, ambient conditions etc.

For comfort, the rate of heat stored in the body Qst should be zero, i.e.,

$Q_{st} = 0$ at neutral condition

However, it is observed that a human body is rarely at steady state, as a result the rate of heat stored in the body is non-zero most of the time. Depending upon the surroundings and factors such as activity level etc., the heat stored is either positive or negative. However, the body cannot sustain long periods of heat storage with a consequent change in body temperatures as discussed before. Since the body temperature depends on the heat balance, which in turn depends on the conditions in the surroundings, it is important that the surrounding conditions should be such that the body is able to maintain the thermal equilibrium with minimum regulatory effort. All living beings have in-built body regulatory processes against cold and heat, which to some extent maintains the body temperatures when the external conditions are not favourable. For example, human beings consist of a thermoregulatory system, which tries to maintain the body temperature by initiating certain body regulatory processes against cold and heat.

1.3 Need of thermal comfort

The complex interaction of air temperature, mean radiant temperature, air velocity and humidity makes up the human thermal environment. To achieve a satisfactory thermal environment it is useful to be able to predict what the effect of a particular combination of thermal conditions will be on human occupants. Modern indoor design methods are based on the heat exchange conditions of the human body. The calculation of heat exchange can be executed with the help of the so-called heat balance equation, as studies have proved that the subjective heat sensation is pleasant if the heat generated within the human body (metabolism) and the heat dissipated in the various ways are in balance. The human thermal regulatory system is truly remarkable. It allows humans to live under environmental temperatures that range from –45 °C in Arctic regions to 50 °C in the Saharan desert, while maintaining the temperature of critical organs within 61°C of 37. 8 °C, without the benefit of heating and cooling systems we now take for granted. Of course, that requires building suitable shelters and wearing appropriate clothing, but it is still quite remarkable. Describing that system in typical engineering terms is challenging because of its complexity and the high degree of variability exhibited by individuals. The purpose of this paper is to describe salient features of the human thermoregulatory system and demonstrate how they can be incorporated into a rational mathematical model. Such models are often used to predict the probability of survival under life-threatening conditions.

1.4 Thermoregulation :-

Thermoregulation is a process that allows your body to maintain its core internal temperature. All thermoregulation mechanisms are designed to return your body to homeostasis. This is a state of equilibrium.

A healthy internal body temperature falls within a narrow window. The average person has a baseline temperature between 98°F (37°C) and 100°F (37.8°C). Your body has some flexibility with temperature. However, if you get to the extremes of body temperature, it can affect your body's ability to function. For example, if your body temperature falls to 95°F (35°C) or lower, you have "hypothermia." This condition can potentially lead to cardiac arrest, brain damage, or even death. If your body temperature rises as high as 107.6°F (42 °C), you can suffer brain damage or even death.

Many factors can affect your body's temperature, such as spending time in cold or hot weather conditions.

- **Hypothermia**, defined as a core temperature of < 35.0 °C, may present with shivering, respiratory depression, cardiac dysrhythmias, impaired mental function, mydriasis, hypotension, and muscle dysfunction, which can progress to cardiac arrest or coma. Management includes warming measures, hydration, and cardiovascular support. Deaths from hypothermia are twice as frequent as deaths from hyperthermia.
- **Hyperthermia**, defined as a core temperature of > 42 °C, may present with sweating, flushing, tachycardia, fatigue, lightheadedness, headache, and paresthesia, progressing to weakness, muscle cramps, oliguria, nausea, agitation, hypotension, syncope, confusion, delirium, seizures, and coma.

Mental status changes and core temperature distinguish potentially fatal heat stroke from heat exhaustion. Management requires the immediate reduction of core temperature.

Avoidance of thermal risk and early recognition of cold or heat stress are the cornerstones of preventive therapy.

1.4.1 How does thermoregulation work?

When your internal temperature changes, sensors in your central nervous system (CNS) send messages to your hypothalamus. In response, it sends signals to various organs and systems in your body. They respond with a variety of mechanisms.

If your body needs to warm up, these mechanisms include:

- **Vasoconstriction:** The blood vessels under your skin become narrower. This decreases blood flow to your skin, retaining heat near the warm inner body.
- **Thermogenesis:** Your body's muscles, organs, and brain produce heat in a variety of ways. For example, muscles can produce heat by shivering.
- **Hormonal thermogenesis:** Your thyroid gland releases hormones to increase your metabolism. This increases the energy your body creates and the amount of heat it produces.

As in other mammals, thermoregulation in humans is an important aspect of homeostasis. In thermoregulation, body heat is generated mostly in the deep organs, especially the liver, brain, and heart, and in contraction of skeletal muscles. Humans have been able to adapt to a great diversity of climates, including hot humid and hot arid. High temperatures pose serious stress for the human body, placing it in great danger of injury or even death. For humans, adaptation to varying climatic conditions includes both physiological mechanisms resulting from evolution and behavioral mechanisms resulting from conscious cultural adaptations.

There are four avenues of heat loss:

- **Metabolism :-** The metabolic heat production is treated as a sum of the basal value, and the additional heat production from local autonomic thermoregulation, shivering and/or exercising[4]. The extra heat production from the changes in the basal metabolism is the difference between the actual basal rate and the basal rate corresponding to neutral thermal conditions.
- **Blood flow:-** The blood flow controlled by vaso constriction and vasodilation, is Important for any dynamic model of human thermal regulation. The human blood circulatory system has three main components: the central blood pool ,counter current heat exchanges ,and path ways to individual tissue nodes [4]. The Stolwijk model

assumes the arterial blood temperature to be the same throughout the body ,so that the heat exchanges between local tissues and blood at this core temperature. The arteries in the multi-branched model are divided into 128 vessels, starting from the central vessels to major peripheral arteries, supplying the extremities. Blood flows out through the central artery, and returns through the central vein. Counter current heat exchanges between the artery and vein, and between the blood vessels and the contacting tissue.

- **Convection:-** Convection usually occurs when the skin surface transfers heat to the surrounding air. There are two mechanisms for the air movements near the body surface: natural convection (due to density differences and temperature gradients); and forced con- vection (due to external forces by wind from the environment)[3]. The theoretical analysis is conducted to quantify the convection mixed by the natural and forced convection .
- **Radiation:-** Radiation is the loss of heat in the form of infrared waves, by short-wave (solar) radiation and long-wave (terrestrial) radiation[3]. Solar radiation(~0.3– 4 mm) is received in the form of visible light and solar infrared radiation. Terrestrial radiation (~4–100 mm) is emitted as a function of temperature and emissivity. The human energy balance is affected by the absorbed radiant energy ,and the radiation which is emitted or reflected by the human body. Three methods are used to estimate the total absorbed radiation by a human a theoretical estimation model based on noon-site radiation measurements; horizontal measurements by a planar netradiometer ; and a simple to construct cylindrical the rmometer. In the mathematical modeling, radiation by long-wave radiation can be calculated using a linearized model based on mean radiant temperature and the view factors specified for each body segment[5]. Short-wave radiation from the sun, heat lamps or other sources can be calculated based on a complex model, such as Solar Cal.
- **Evaporation:-** The water lost by evaporation occurs, when the heat loss by convection and radiation alone are unable to maintain the heat balance at hot environments or during strenuous physical activities. The evaporative heat losses occur by several mechanisms: by diffusion of water through the skin; by sweat secretion; and by evaporation of water. Sweat loss is affected by the physical and physiological conditions near or at the skin surface, such as environmental conditions, clothing properties, metabolic heat production, and hydration status. Both the rational

model and the empirical model are used to predict the sweating rate. The moisture transport between the skin and the environment is modelled, considering the sweating water absorbed/desorbed by clothing as changing the weight of the garment.

- **Respiration:-** Respiration is one of the important ways for heat exchange with the environment, distributed over body part of the pul- monary tract for the lung, face and neck[5]. The latent heat exchange is calculated by the pulmonary ventilation, the humidity difference between the expired and inspired air, and partial vapor pressure of the ambient air. The dry heat loss of re- spiration can be expressed by the temperature difference between the expired and inspired air, the pulmonary ventilation rate, and partial vapour pressure of the ambient air.

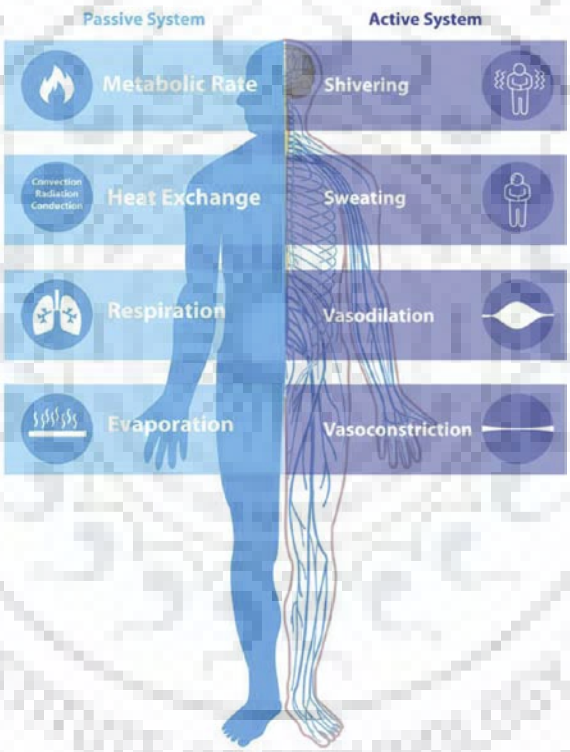

Fig 3:- Shematic diagram for human body thermoregulation by active and passive systems.

The core temperature of a human is regulated and stabilized primarily by the hypothalamus, a region of the brain linking the endocrine system to the nervous system, and more specifically by the anterior hypothalamic nucleus and the adjacent preoptic area regions of the hypothalamus. As core temperature varies from the set point, endocrine production initiates control mechanisms to increase or decrease energy production/dissipation as needed to return the temperature toward the set point

1.5 Factors affecting thermal comfort:

Thermal comfort is affected by several factors. These are:

- **Physiological factors** such as age, activity, sex and health. These factors influence the metabolic rate. It is observed that of these factors, the most important is activity. Other factors are found to have negligible effect on thermal comfort.
- **Insulating factor due to clothing.** The type of clothing has strong influence on the rate of heat transfer from the human body. The unit for measuring the resistance offered by clothes is called as “clo”. 1 clo is equal to a resistance of about 0.155 m^2. K/W. Typical clo values for different types of clothing have been estimated and are available in the form of tables. For example, a typical business suit has a clo value of 1.0, while a pair of shorts has a clo value of about 0.05.
- **Environmental factors**. Important factors are the dry bulb temperature, relative humidity, air motion and surrounding surface temperature. Of these the dry bulb temperature affects heat transfer by convection and evaporation, the relative humidity affects heat loss by evaporation, air velocity influences both convective and evaporative heat transfer and the surrounding surface temperature affects the radiative heat transfer.

Apart from the above, other factors such as drafts, asymmetrical cooling or heating, cold or hot floors etc. also affect the thermal comfort. The objective of a comfort air conditioning system is to control the environmental factors so that comfort conditions prevail in the occupied space. It has no control on the physiological and insulating factors. However, wearing suitable clothing may help in reducing the cost of the air conditioning system.

1.6 Indices for thermal comfort:

It is seen that important factors which affect thermal comfort are the activity, clothing, air DBT, RH, air velocity and surrounding temperature. It should be noted that since so many factors are involved, many combinations of the above conditions provide comfort. Hence to evaluate the effectiveness of the conditioned space, several comfort indices have been suggested. These indices can be divided into direct and derived indices. The direct indices are the dry bulb temperature, humidity ratio, air velocity and the mean radiant temperature (Tmrt).

The mean radiant temperature Tmrt affects the radiative heat transfer and is defined (in K) as:

$$\mathbf{T_{mrt}^4 = T_g^4 + CV^{1/2}(T_g - Ta)}$$

where:

Tg = Globe temperature measured at steady state by a thermocouple placed at the center of a black painted, hollow cylinder (6” dia) kept in the conditioned space, K. The reading of thermocouple results from a balance of convective and radiative heat exchanges between the surroundings and the globe.

T_a = Ambient DBT, K

V = Air velocity in m/s, and

C = A constant, 0.247×10^9

The derived indices combine two or more direct indices into a single factor. Important derived indices are the effective temperature, operative temperature, heat stress index, Predicted Mean Vote (PMV), Percent of People Dissatisfied (PPD) etc.

- **Effective temperature (ET):** This factor combines the effects of dry bulb temperature and air humidity into a single factor. It is defined as the temperature of the environment at 50% RH which results in the same total loss from the skin as in the actual environment. Since this value depends on other factors such as activity, clothing, air velocity and Tmrt, a Standard Effective Temperature (SET) is defined for the following conditions:

  Clothing = 0.6 clo

  Activity = 1.0 met

  Air velocity = 0.1 m/s

  Tmrt = DBT (in K)

- **Operative temperature (Top):** This factor is a weighted average of air DBT and Tmrt into a single factor. It is given by:

$$T_{op} = \frac{h_r T_{mrt} + h_c T_{amb}}{h_r + h_c} \approx \frac{T_{mrt} + T_{amb}}{2}$$

where hr and hc are the radiative and convective heat transfer coefficients and Tamb is the DBT of air.

The recommended comfort conditions for different seasons and clothing suitable at 50 % RH, air velocity of 0.15 m/s and an activity level of ≤ 1.2 met.

Season	Clothing	I_{cl}	$T_{op,opt}$	T_{op} range for 90% acceptance
Winter	Heavy slacks, long sleeve shirt and sweater	0.9 clo	22°C	20 to 23.5 °C
Summer	Light slacks and short sleeve shirt	0.5 clo	24.5°C	23 to 26°C
	Minimal (shorts)	0.05 clo	27°C	26 to 29 °C

Table 2. Optimum and recommended operative temperatures for comfort

Use of suitable clothing and maintaining suitable air velocities in the conditioned space can lead to reduced cost of air conditioning. For example, in summer the clothing should be minimal at a socially acceptable level, so that the occupied space can be maintained at higher temperatures. Similarly, by increasing air velocity without causing draft, one can maintain the occupied space at a higher temperature in summer. Similarly, the inside temperatures can be higher for places closer to the equator (1°C rise in ET is allowed for each 5° reduction in latitude). Of course, the above recommendations are for normal activities. The required conditions change if the activity levels are different. For example, when the activity level is high (e.g. in gymnasium), then the required indoor temperatures will be lower. These special considerations must be kept in mind while fixing the inside design conditions.

1.7 Predicted Mean Vote (PMV) :-

Based on the studies of Fanger and subsequent sampling studies, ASHRAE has defined a thermal sensation scale, which considers the air temperature, humidity, sex of the occupants and length of exposure. The scale is based on empirical equations relating the above comfort factors. The scale varies from +3 (hot) to –3 (cold) with 0 being the neutral condition. Then a Predicted Mean Vote (PMV) that predicts the mean response of a large number of occupants is defined based on the thermal sensation scale.

The PMV is defined by Fanger as:

$$\mathbf{PMV=[0.303\exp(-0.036M) + 0.028]\ L}$$

where M is the metabolic rate and L is the thermal load on the body that is the difference between the internal heat generation and heat loss to the actual environment of a person experiencing thermal comfort. The thermal load has to be obtained by solving the heat balance equation for the human body.

1.7.1 The PMV-model :-

The PMV-model by Fanger is a predictive model for general, or whole-body, thermal comfort. The model was derived during the second half of the 1960's from laboratory studies and climate chamber research. With his work, Fanger wanted to present a method for use by heating and air-conditioning engineers to predict, for any type of activity and clothing, all those combinations of the thermal factors in the environment for which the largest possible percentage of a given group of people experience thermal comfort26. The PMV-model is often referred to as a static or constancy model due to its construct. The human body produces heat, exchanges heat with the environment, and loses heat by diffusion and evaporation of body fluids. The body's temperature control system tries to maintain an average core body temperature of approximately 37°C even when thermal disturbances occur. According to Fanger2, the human body should meet a number of conditions. These requirements for steady-state thermal comfort are:

(i) The body is in heat balance,

(ii) Mean skin temperature and sweat rate, influencing the heat balance, are within certain limits

(iii) No local discomfort exists.

Fanger defined PMV as the index that predicts, or represents, the mean thermal sensation vote on a standard scale for a large group of persons for any given combination of the thermal environmental variables, activity and clothing levels. The PMV-model includes all the major variables influencing thermal sensation and quantifies the absolute and relative impact of six factors of which air temperature, mean radiant temperature, air velocity and relative humidity are measured, and activity level and clothing insulation are estimated with the use of tables. However, the PMV-model is not as static as is often suggested, as one can use different parameters as input for the model, i.e., different values of activity level and clothing insulation.

The PMV-model is based on Fanger's comfort equation. The satisfaction of this equation is a condition for optimal thermal comfort of a large group of people. PMV predicts the mean thermal sensation vote for a large group of persons and indicates the deviation from presumed optimal thermal comfort or thermoneutrality. Results of the model are expressed on the 7-point ASHRAE scale of thermal sensation.

CHAPTER 2
LITERATURE REVIEW

- **Fanger's PMV method**

Several methods are used for the estimation of thermal sensation and comfort. The widely used international standards ISO 7730 (2005) and ASHRAE 55 (2004) use Fanger's PMV (Predicted Mean Vote) method (Fanger 1970). Fanger's PMV method, developed in 1970, is based on a heat balance model, also referred to as a "static" or "constancy" model. While assuming that the effects of the surrounding environment are explained only by the physics of heat and mass exchanges between the body and the environment, heat balance models view the human being as a passive recipient of thermal stimuli. The PMV method combines four physical variables (air temperature, air velocity, mean radiant temperature, and relative humidity), and two personal variables (clothing insulation and activity level) into an index that can be used to predict the average thermal sensation of a large group of people in a space. The PMV index predicts the mean response of a large group of people .

- **Zhang's thermal sensation**

Zhang (2003) has developed a thermal sensation model to predict local and overall sensations, and local and overall comfort in non-uniform transient thermal environments. The local thermal sensation is represented by a logistic function of local skin temperature. The overall thermal sensation and comfort are calculated as a function of the local skin temperatures and the core temperature, and their change over time. According to Fiala (2003) the relationship between the skin temperature and thermal sensation is linear in the region where the mean skin temperature is between 3 °C below and 1 °C above its set point. The set point is defined as the local skin temperature when the thermal sensation of that body part feels neutral (local thermal sensation index = 0). Zhang (2003) proposes that the local thermal sensation local is a logistic function of local skin temperature, presented as the difference between the local skin temperature and its set point.

- **VTT House building simulation environment**

The non-commercial building simulation environment VTT House simulates air infiltration, ventilation and heat transfer processes. The simulation program is designed for simulation experts, because use of the program requires good knowledge of the simulated case, the target of the simulation and the principles of the nodal network creation. VTT House simultaneously calculates both heat transfer and fluid flow processes. The calculation is based on-

i) a free nodal approach with discrete definition of mass balance, momentum, and heat balance equations

ii) true modelling of thermal conduction, convection, and radiation

iii) SIMPLE Algorithm and

iv) a sparse matrix solver (Preconditioned Conjugate Gradient Method).

The nodal network consists of node capacitances and inter-nodal conductances. The transient node temperatures are solved using the finite difference heat balance method . Thermal conduction, convection, and radiation are included in the calculation, and transient phenomena are modelled allowing transient and asymmetrical simulation results.

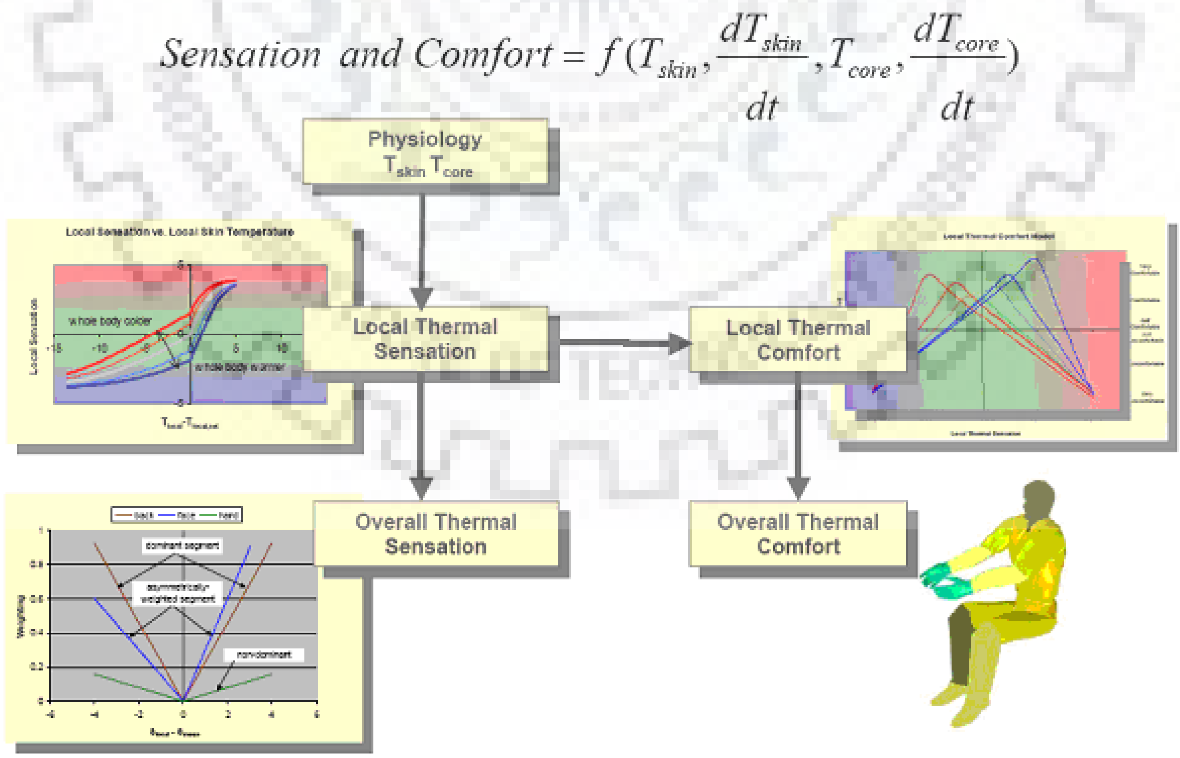

Fig 4: Overall Thermal Comfort

Chapter - 3

EXPERIMENTAL SET-UP

3.1 Climate Simulator

Fig 5: Climate Simulator Lab, IIT Roorkee**.**

3.1.1 Specifications of the Interior

- The interior consists of two chambers, the Test Chamber and the Ante Chamber.
- The Test Chamber size is 3.5 m x 5 m x 3 m (height) and that of the Ante Chamber is 1.5 m x 5 m x 3 m.
- The Ante Chamber is connected with the Test Chamber via a 1 m x 2 m door and with the outside via a 1 m x 2 m door.

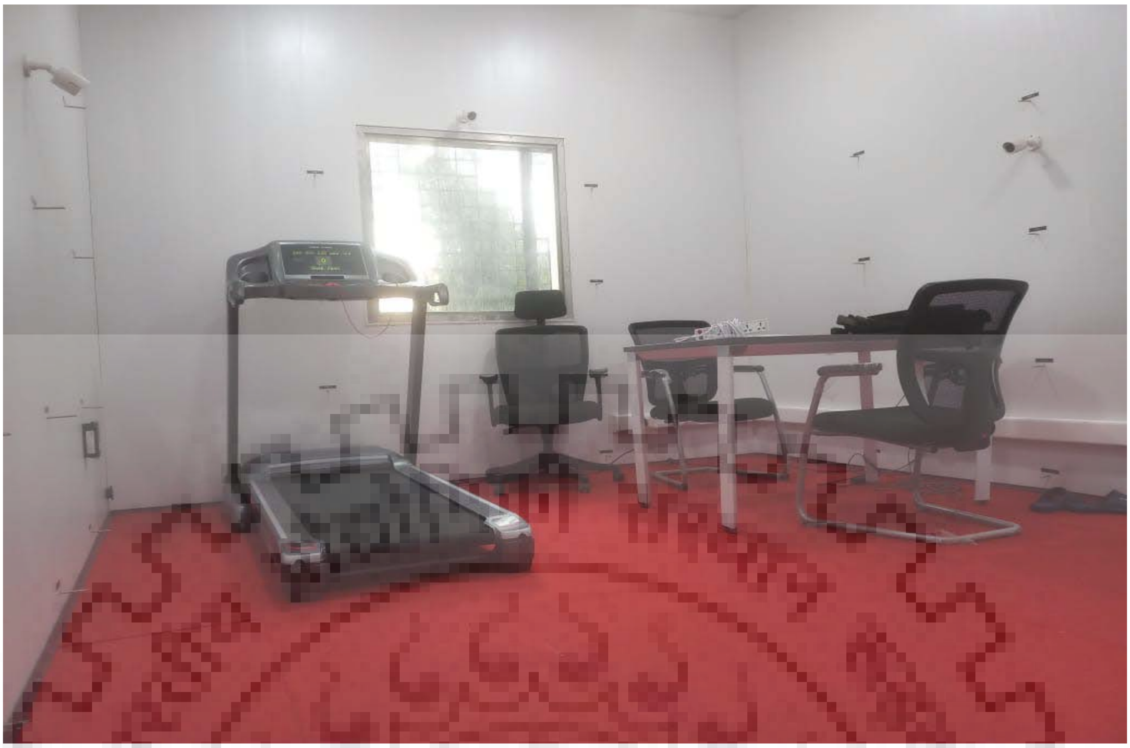

Fig 6: Test Chamber

Fig 7: Ante Chamber

3.1.2 Specifications of the Temperature and Humidity Controller

- Microprocessor based EPLC Programmable cyclic digital temperature, humidity indicator cum controller with 0.1°C / 1% display resolution & 7 Inch ESA HMI with 1 serial port, 1 Ethernet port & 1 USB port.
- Temperature Range for Test Chamber: -20°C to 50°C or more.
- Temperature Range for Ante Chamber: 5°C to 30°C or more.
- Humidity Range for Test Chamber: 20 to 95% RH or better for full scale of temperature range.
- Humidity Range for Ante Chamber: 30 to 60 % RH or better for full scale of temperature range.
- PT-100 Sensor, Class A type for Temperature & 4-20 ma Sensor for Direct RH Sensing.
- Controlling accuracy: ±1°C or better.
- Humidity Controlling Accuracy: ±3% RH or better.
- Temperature deviation high and low alarms.
- CO_2 Control with concentration varying between 0.5 to 5% by volume and better; 2 CO_2 Cylinders & 2 IR Sensor to sense the concentration of CO_2.

3.1.3 Specifications of the Refrigeration System

- Single stage refrigeration system with semi hermetic compressor. (4FE – 35 Y) – 1 Nos. for test chamber or better.
- Single stage refrigeration system with semi hermetic compressor. (4EES – 4 Y) – 1Nos. for Ante Chamber or better
- CFC free refrigerant filled.
- Fin and tube type air-cooled condenser.
- Fin & tube type evaporator provided inside the inner chamber.
- Defrost system: capacity of running for 45 Min in every 5 Hrs time.

Fig 8: Refrigeration system

3.1.4 Specifications of the Power Supply

- Three phase, 440 Volts, 50 Hz; provided with single phase preventer.
- 120 kVA Auto Changeover Genset.

3.2 Instrumentation and Control :-

3.2.1 Measurement of Temperature

Thermocouple

- T-type (Copper/ Constantan) thermocouples were used as temperature sensors in the experiment.
- Each type of fruit, apple and orange, had three thermocouples inserted at three different locations, one attached to its surface, one pierced midway through it, and one up to the centre or core of the fruit.
- One thermocouple was left hanging inside the duct to measure the temperature of the cooling air that flowed through it.

Calibration of the thermocouples

The thermocouples were calibrated with the help of precision constant temperature bath which was able to maintain its temperature within ±0.1°C of the specified value. A graph between thermometer reading and thermocouple reading (in℃) was plotted and the regression line was extracted.

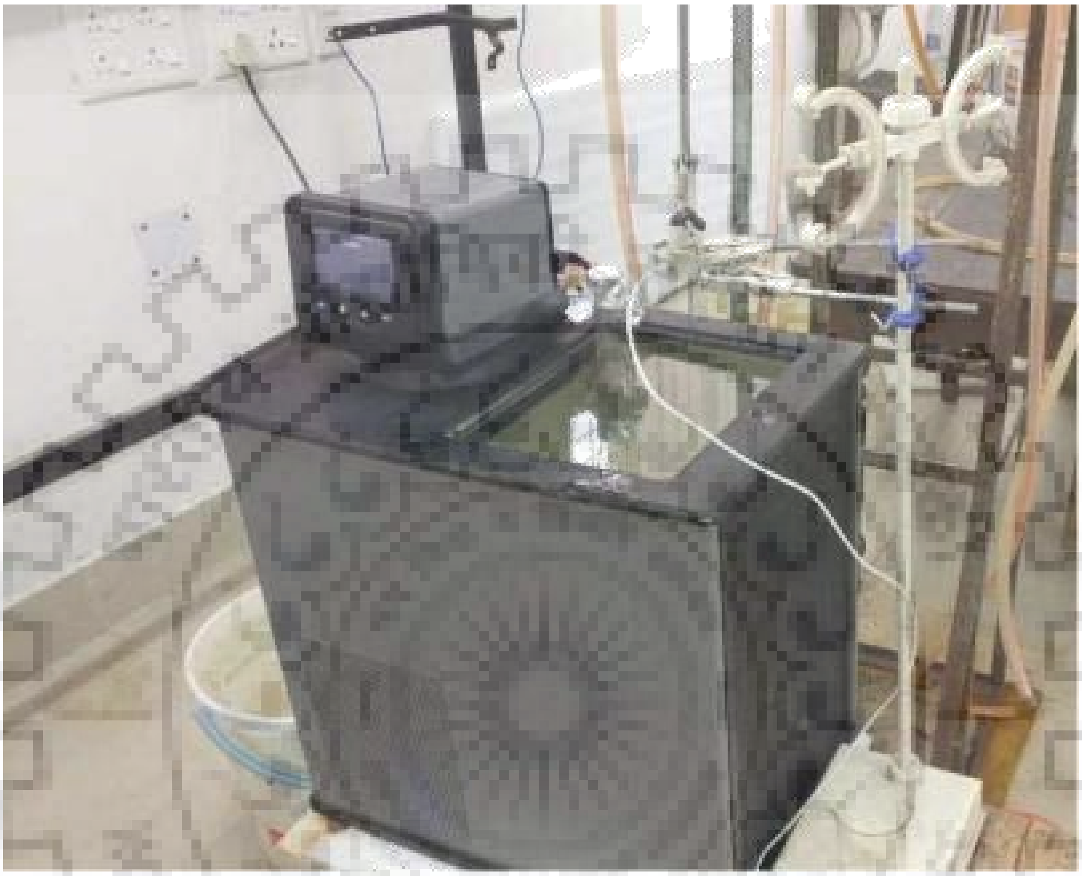

Fig 9: Hot water bath

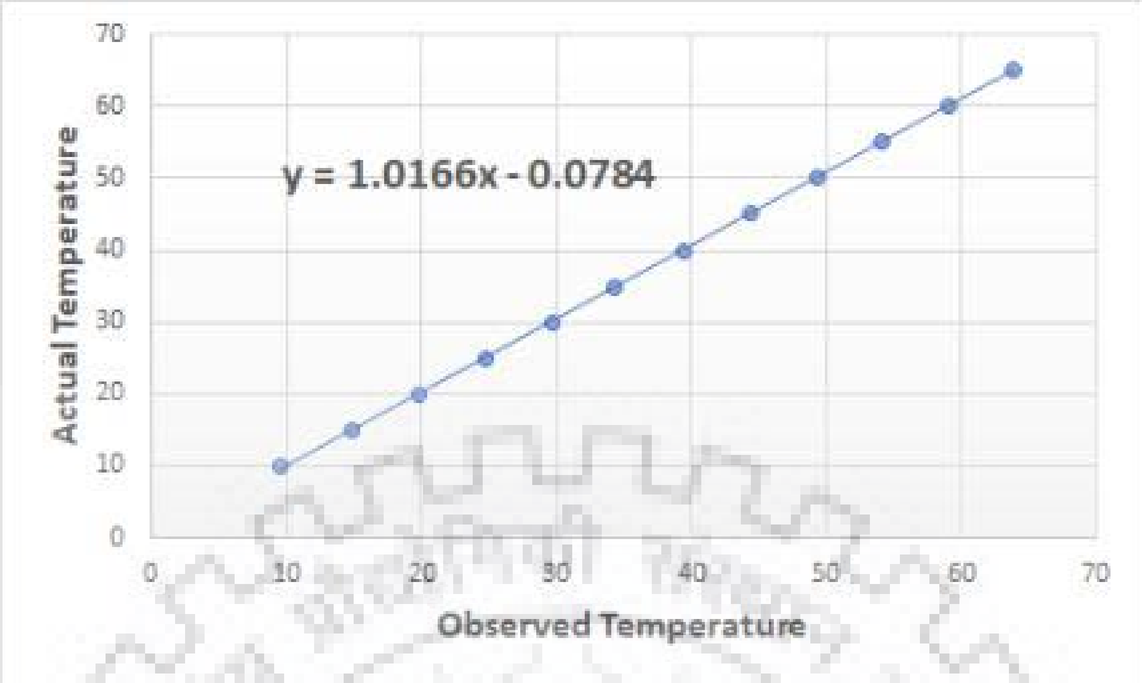

Fig 10: Graph showing relation between Actual and Observed Temperature

Data Acquisition System

- Model 2701 is a 6½-digit high-performance multimeter/data acquisition system.
- It can measure voltage (DC and AC), current (DC and AC), resistance (2- and 4-wire), temperature (thermocouple, thermistor, and 4-wire RTD), frequency and period, and test continuity.
- The Model 2701 has two slots that will accommodate Keithley Model 7700 series switching modules.
- Each channel of a switching module that is closed or scanned is measured by the Model 2701.
- For scanning, each channel can have its own unique setup (i.e., function, range, digits, etc.).

Temperature Measurement Steps

1. Switch on the Keithley DAQ and configure IP address.
2. Connect DAQ to computer using LAN cable and configure IP with same gateway as that of DAQ.
3. Install and Open Keithley configuration and follow steps given below:
    a. Add a new configuration.
    b. Select model Enter IP address of DAQ. Set port as 1394.
    c. Click next and finish the configuration setup.

d. This will finish setup. Now to take reading proceed with following step.
e. Right click on the instrument and click open instrument.

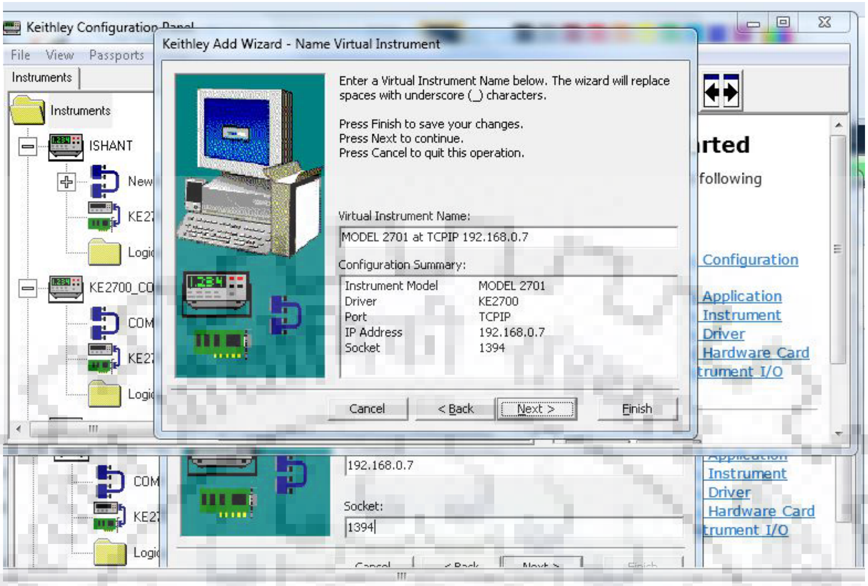

Fig 11: Finishing of configuration set up

But for using this software programming need to be done which was very complex. Because one level of programming was for DAQ reading level 2 programming for formatting reading in proper understandable way.

So we used another tool by Keithley which is '**Kick-start**'.

It provides many feature storing data of multiple channels in proper format and plotting graphs.

Steps to use Kick start are as follows:

1. Open Kick-start software.
2. Enter IP Address 192.168.0.7 and enter port 1394. Click on refresh instrument discovery it will show model 2701 as instrument.
3. Right click on instrument, select add instrument as Model 2701 and click on select test type as Data Logger.
4. Select channel configuration and select add group. Select function as temperature. Select respective channels on which thermocouples are connected. These thermocouples are placed on various positions where temperature is needed to be measured.

5. Select scan list configuration. Select start test as intermediate, subsequent trigger as timer and stop test as no of scans. Here time between scan and no of scan are selected as per accuracy is required.
6. Select START TEST and click on sheet where readings and timings are displayed in proper format.
7. Click on graph and select channel for which graph will be plotted in real time format.

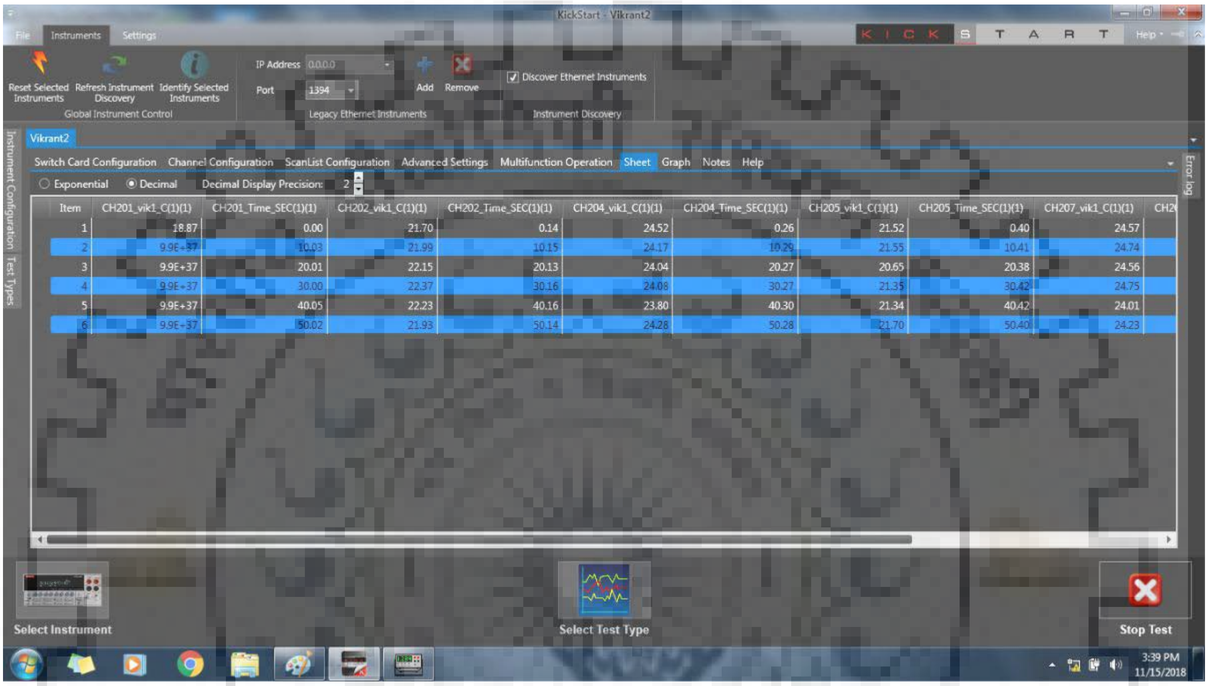

Fig 12: Sheet showing recorded readings

CHAPTER 4

Experimental Procedure

Aim of our experiment is to study both Psychological & Physiological of human body at Hot thermal condition at 34 , 34, 38, 42 °C each at 40% & 80% humidity and cold thermal condition at 3, 5,8, 11°C at 40% humidity .

Whole experiment was carried out on 15 subjects and each subject had to undergo each steps. Different steps are as follows :-

i. First the main chamber temp. and humidity was made to set at which the experiment to be carried out .It takes nearly 3-4 hrs to achieve that thermal conditions.
ii. Subject had to enter Antechamber before going to Main chamber to accommodate the conditions of climate chamber.
iii. Then the thermocouples are connected to16 bodies part of subject for sensing the temperature of specified part through data logger.
iv. Then the Subject had to enter the main chamber and have to sit on the chair for 5 min. in order to stabilize the body with current temp. conditions.
v. Then subject was provided a Thermal Questionnaire sheet for Psychological study to determine the comfort conditions at that time.
vi. Then subject had to walk on a Treadmill for 15 min. and data logger was continuously recorded the temp. variations at each 30 sec interval through thermocouples.
vii. After that the subject was provided the Questionnaire sheet again for determining the comfort conditions immediately after the treadmill.
viii. Hence it will be repeated to each 15 subjects for same procedure.

CHAPTER – 5

RESULTS AND DISCUSSIONS

5.1 Physiological results :-

We have performed the experiments on each 15 subjects first at Hot thermal condition at 34 , 34, 38, 42°C's each at 40% & 80% humidity and then at cold thermal condition at 3, 5, 8, 11°C's at 40% humidity. The temperatures was measured at 16 bodies parts was carefully studied for plotting graphs of different bodies parts between Temperature and Time at each thermal conditions mentioned above.

5.1.1 At Hot conditions :-

Fig 13-20 were plotted taking time (min) as the X co-ordinate and Temperature at Y co-ordinate at 10 bodies part at different temperatures and humidity.

Temp. variations at Different temp. and humidity

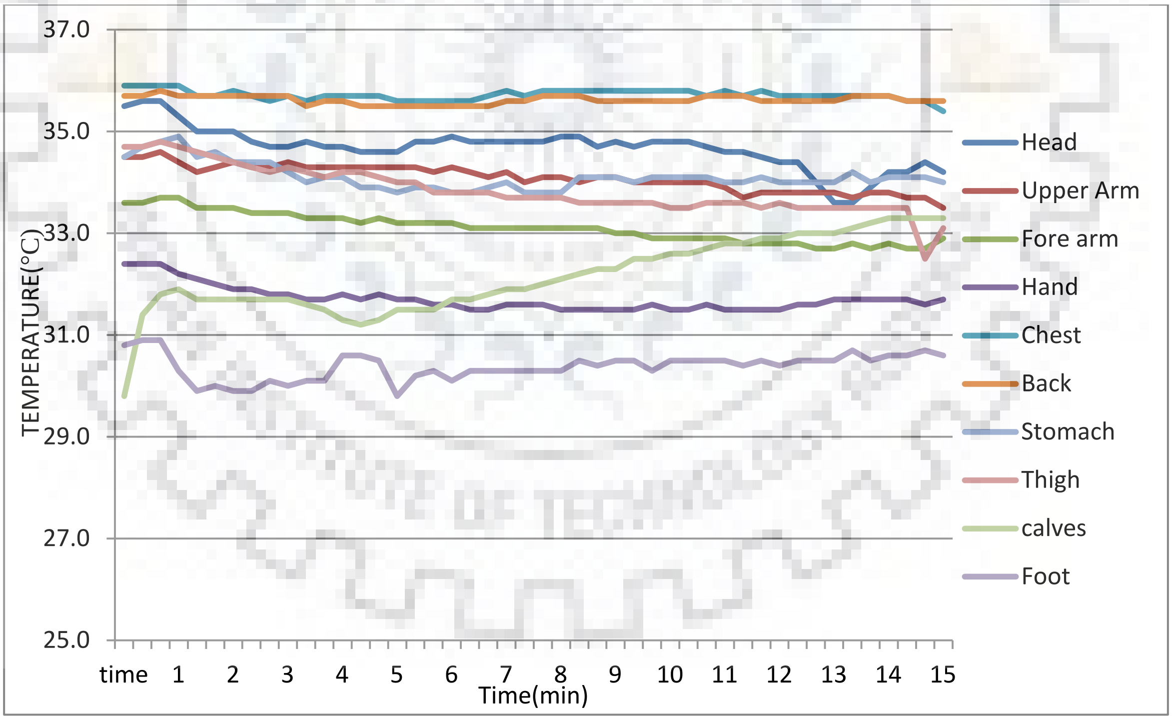

Fig 13: Temperature vs Time(min) at 30°C and 40% humidity

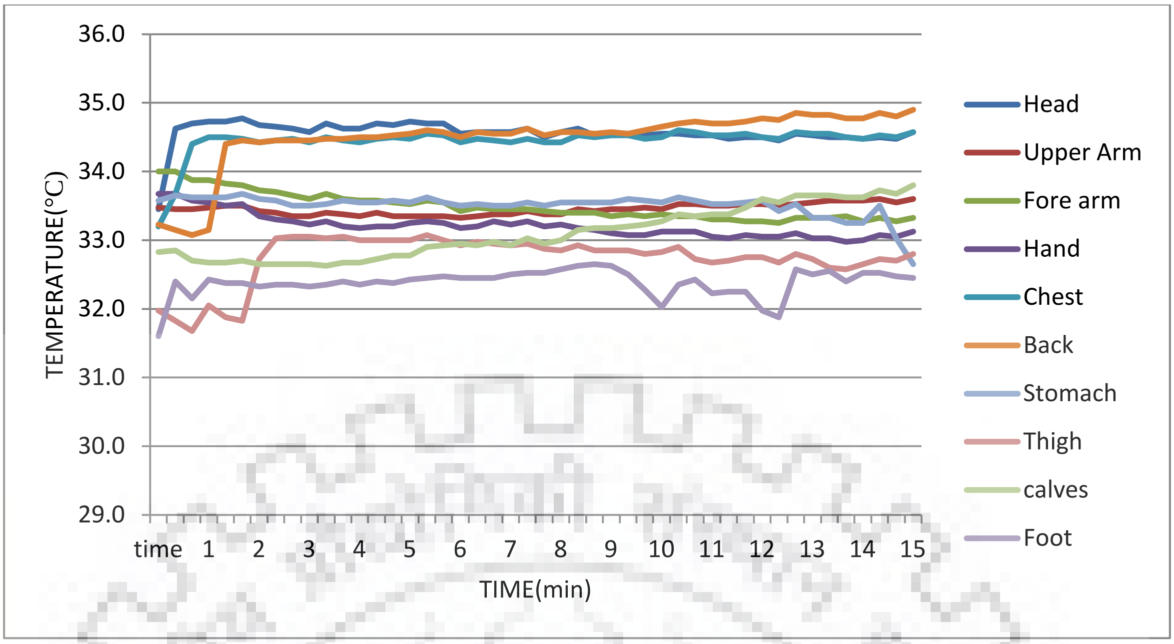

Fig 14: Temperature vs Time(min) at 30°C and 80% humidity

From Fig 13 & 14, it depicts that all body parts vary approximate linearly with time. Out of 10 body parts. foot has a low temperature variation in respect of all body parts and Chest & back have higher temp variations. And as humidity increases, bandwidth of temperature variations reduces and Calves slope also reduces more as compare to others.

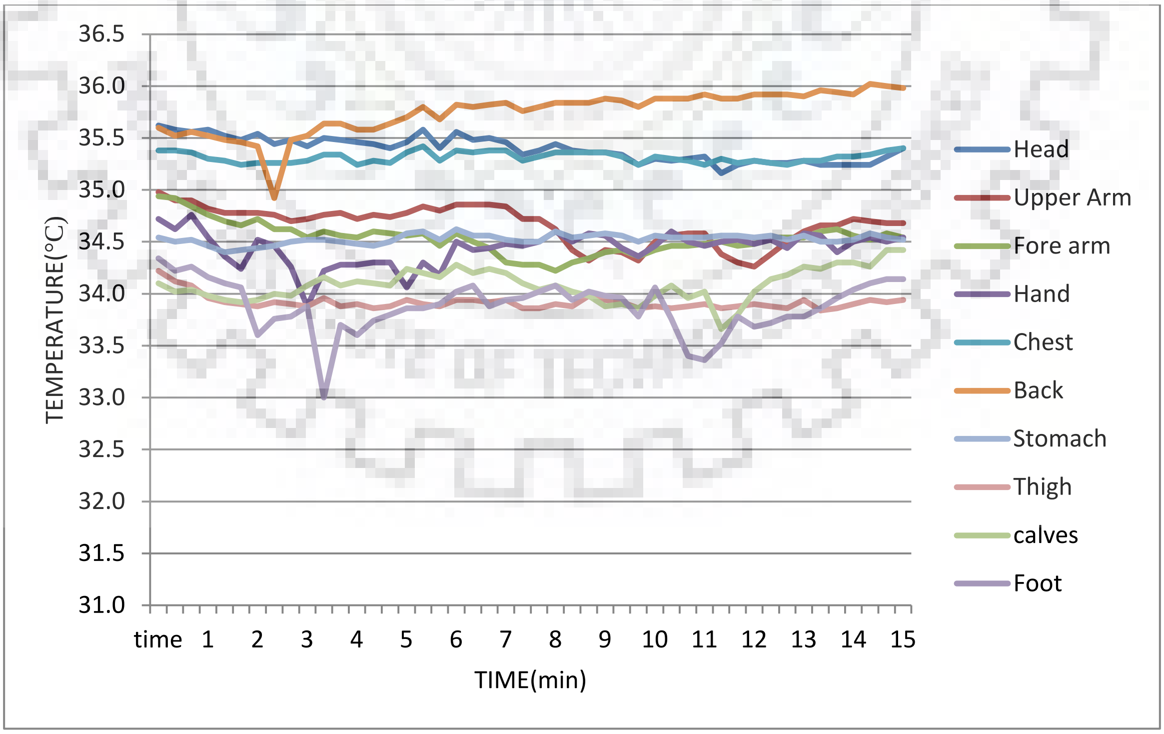

Fig 15: Temperature vs Time(min) at 34°C and 40% humidity

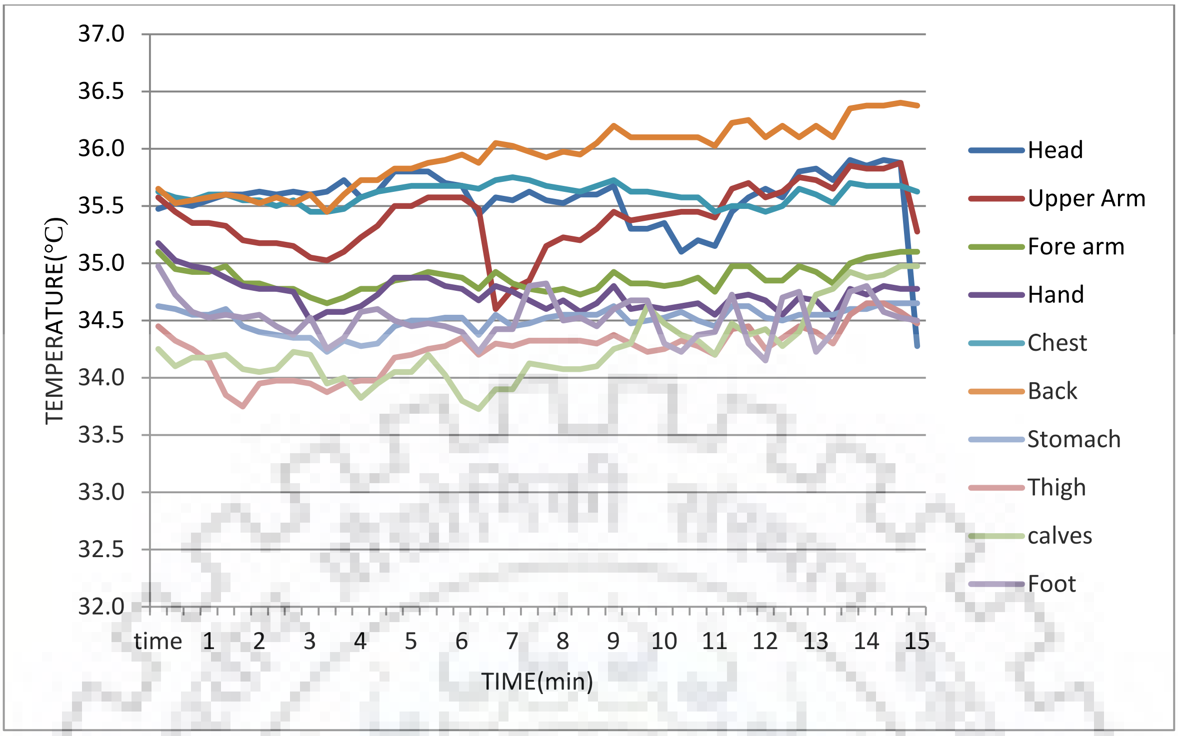

Fig 16: Temperature vs Time(min) at 34°C and 80% humidity

From Fig 15 & 16 , it depicts that all body parts vary approximate linearly with time. Out of 10 body parts, back having a highest temperature variations and calves & thighs lowest.

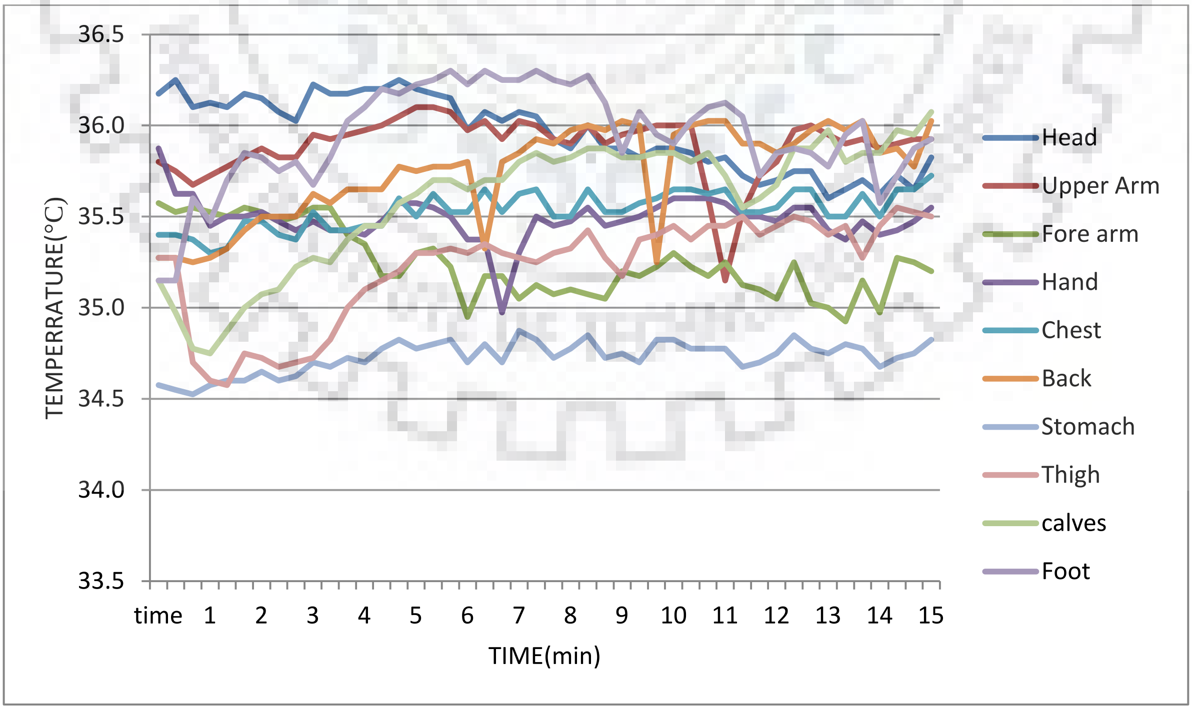

Fig 17: Temperature vs Time(min) at 38°C and 40% humidity

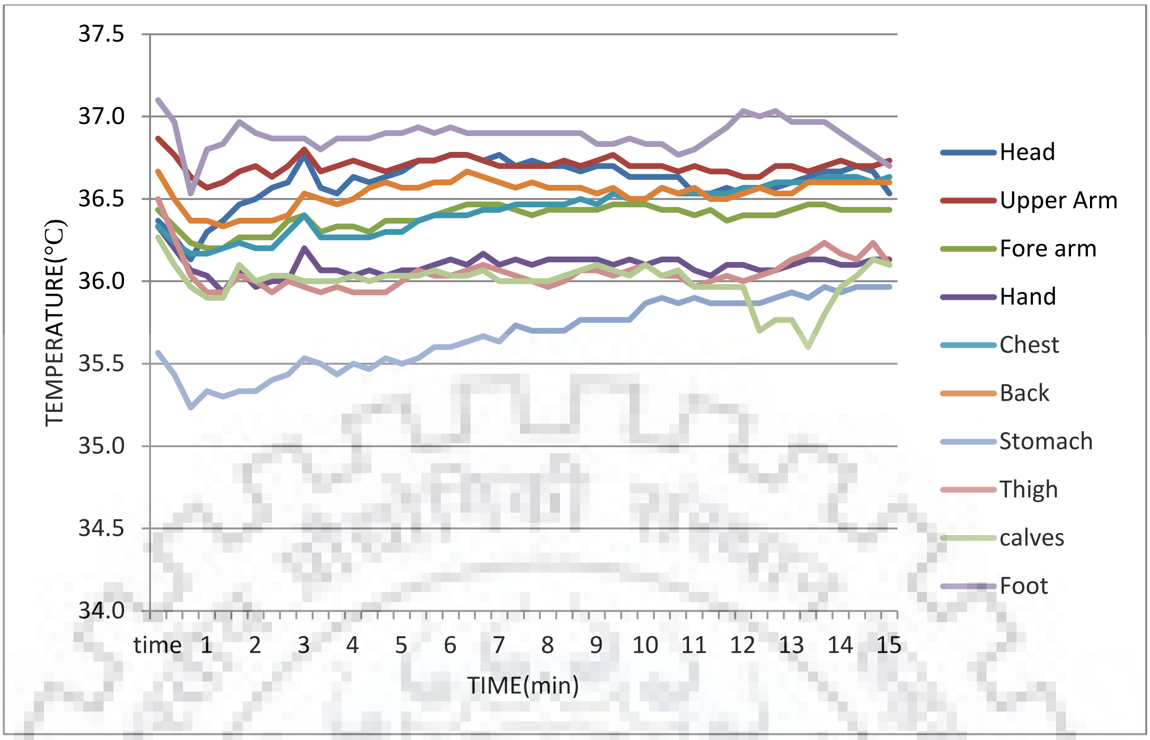

Fig 18: Temperature vs Time(min) at 38°C and 80% humidity

From Fig 17 & 18, it depicts that all body parts vary approximate linearly with time. Head part slope linearly decrease as temperature of chamber increase. With increase in both temperature and humidity, foot & upper arm temperature also increases.

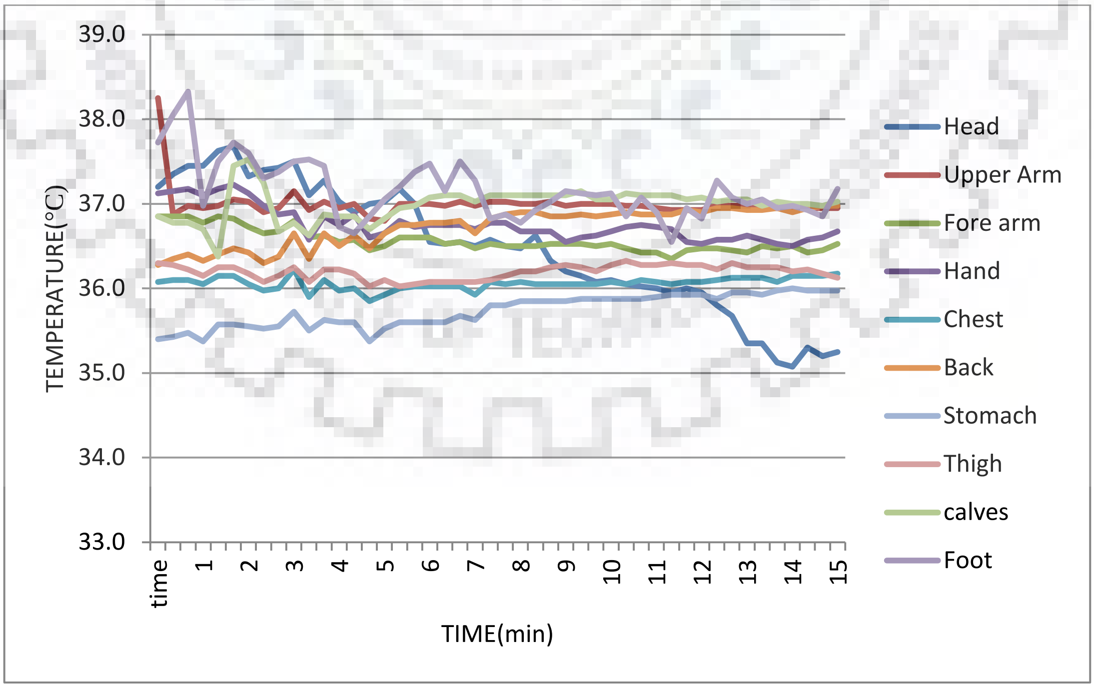

Fig 19: Temperature vs Time(min) at 42°C and 40% humidity

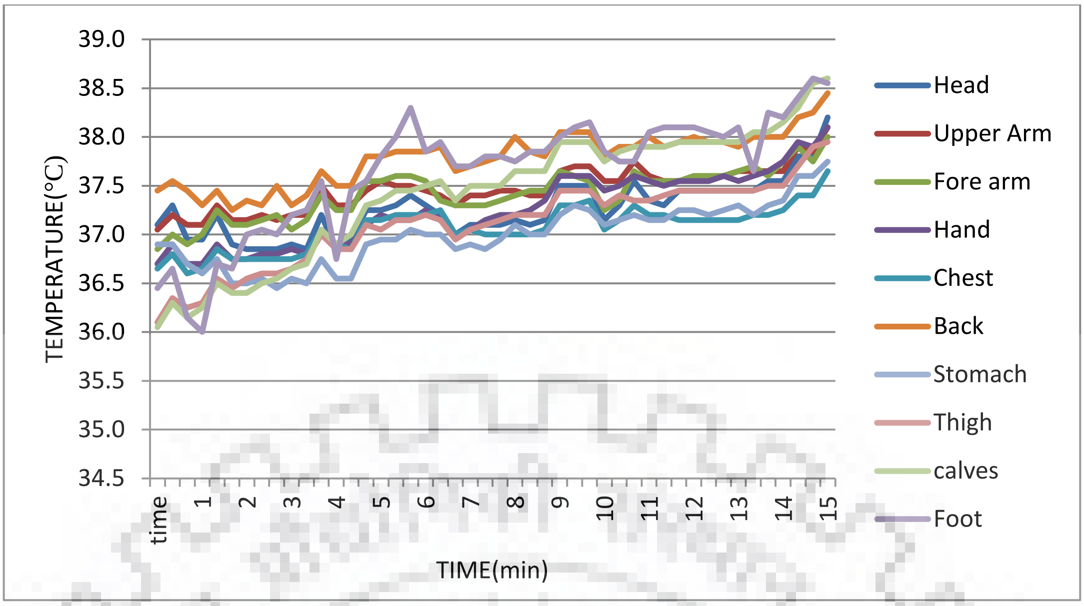

Fig 20: Temperature vs Time(min) at 42°C and 80% humidity

From Fig 19 & 20, it depicts that all body parts approximate linearly increases with time. It was comparatively extreme conditions as compared with others thermal conditions at hot case. Foot & calves temperature and slope increases more as compared to others as temperature and humidity increases. And the bandwidth of temperatures also reduces to narrow range as compared at below temperature and humidity.

5.1.2 At Cold conditions :-

Fig 21–24 were plotted taking time (min) as the X co-ordinate and Temperature at Y co-ordinate at 10 bodies part at different temperatures and humiditiy.

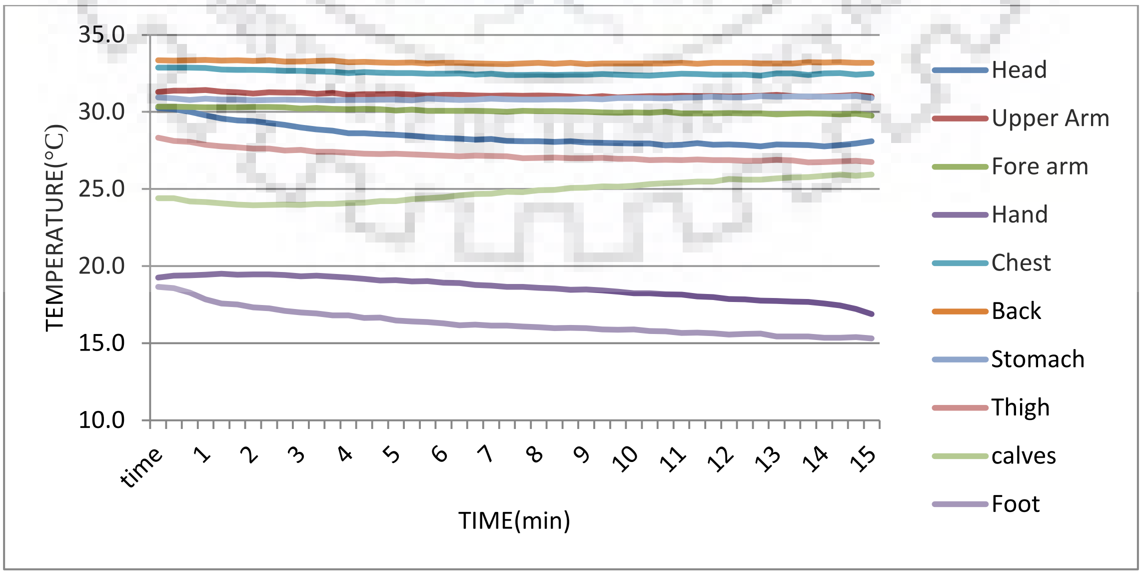

Fig 21: Temperature vs Time(min) at 2°C

From Fig 5.1.2.1, all body parts was almost linearly varies with respect to time. Only calves having little bit increasing nature and hand decreasing nature as compared to others. Foot has got lowest temperature and back at highest.

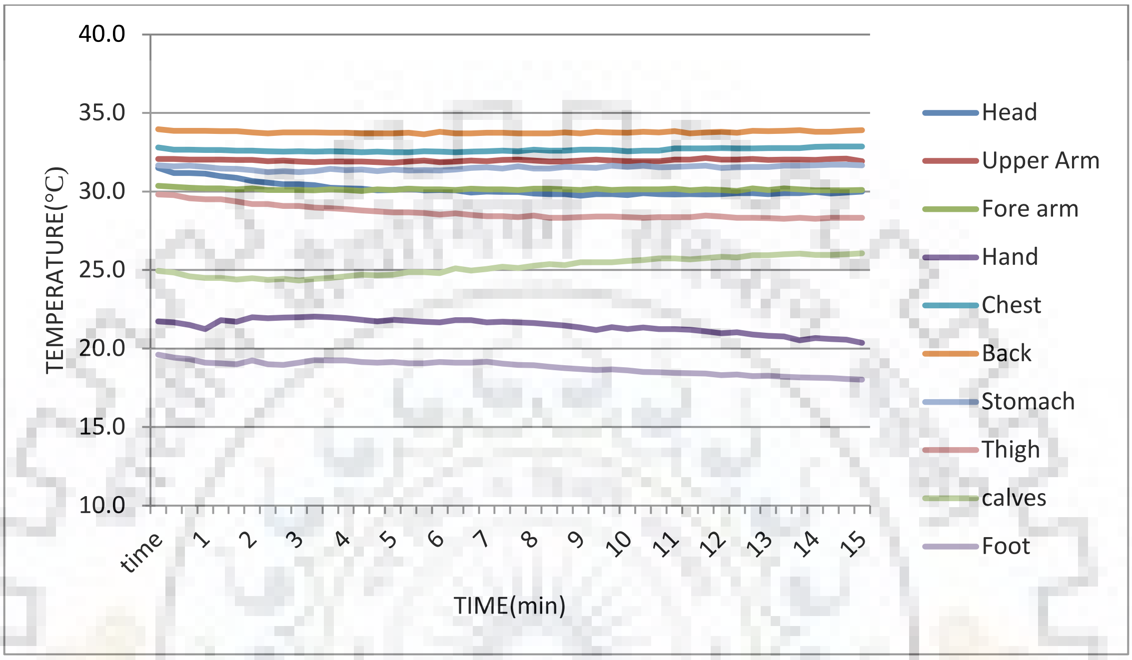

Fig 22: Temperature vs Time (min) at 5°C

From Fig 22, all body parts were almost constantly varies with respect to time.Foot at the lowest temperature and back & chest at highest temperature.

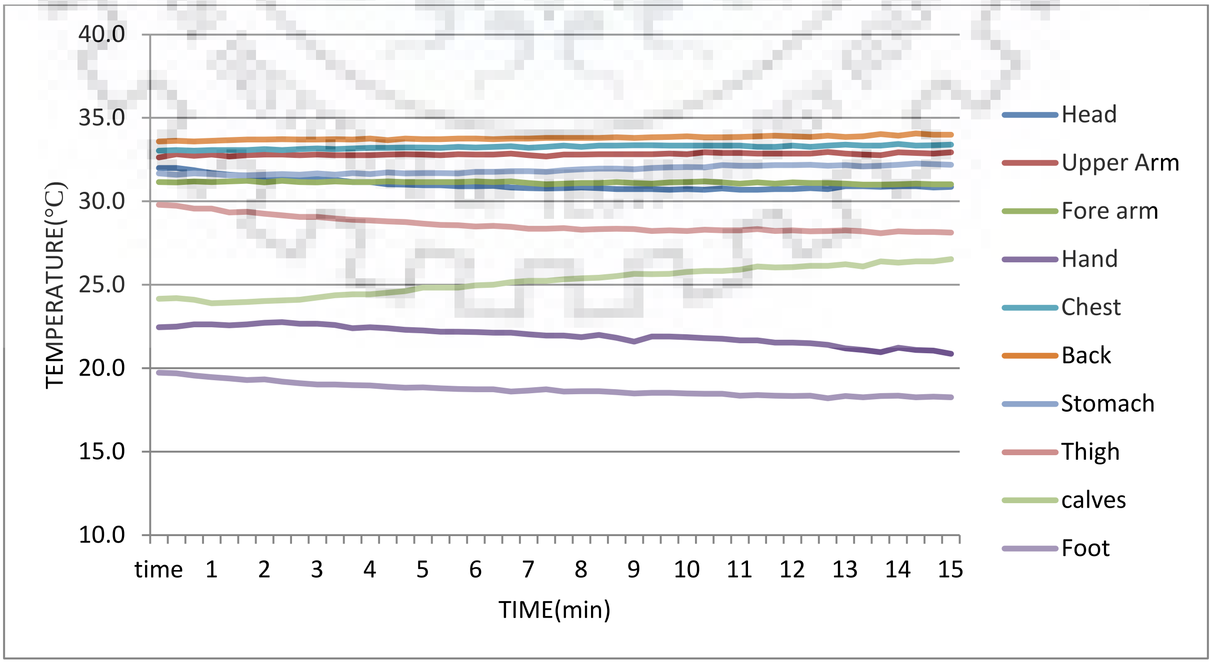

Fig 23: Temperature vs Time(min) at 8°C

From Fig 23, all body parts were almost constantly varies with respect to time

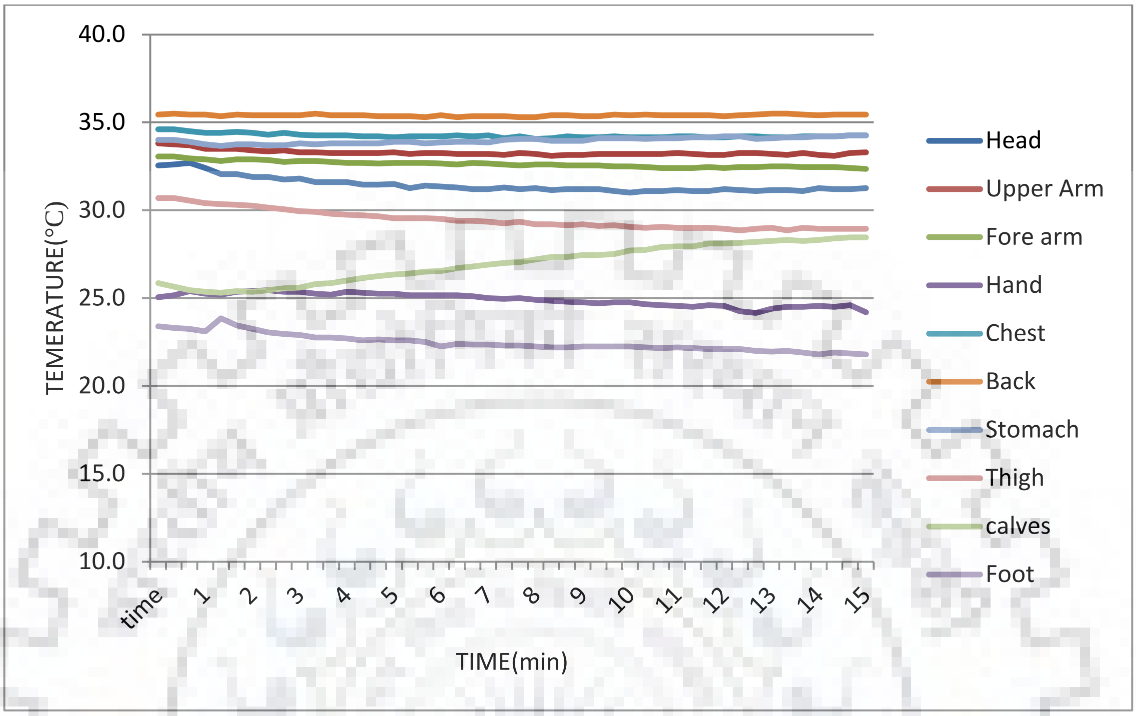

Fig 24: Temperature vs Time(min) at 11°C

5.2 Psychological results:-

In this thermal comfort indices is plotted as per the Questionnaire filled by the different subjects at both Hot and Cold thermal conditions as per the activity performed by the subject in both sedentary and walking conditions . Hence different plots have been drawn as TSV(thermal sensation vote) vs MET(metabolic activity) .And also plot between SET(standard effective temp) vs PMV(predicted mean vote).

5.2.1 At Hot conditions :-

Indices at different temp. and humidity

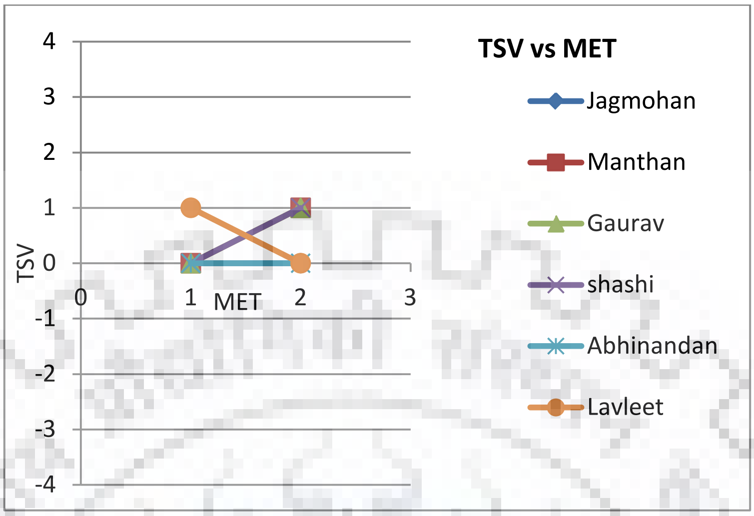

Fig 25: Indices At 30°C and 40% humidity

From above fig, it depicts that as the metabolic activity increases, subject's thermal sensation votes were "slightly warm" from "neutral" condition after running on treadmill (met =2).

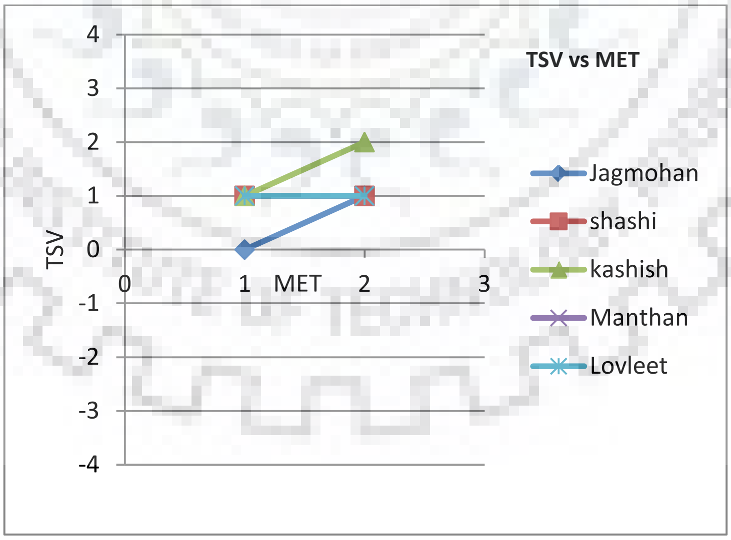

Fig 26: Indices At 30°C and 80% humidity

From above fig., it depicts that after running on treadmill some sensation votes were in "warm" conditions and rest at "slightly warm" category conditions.

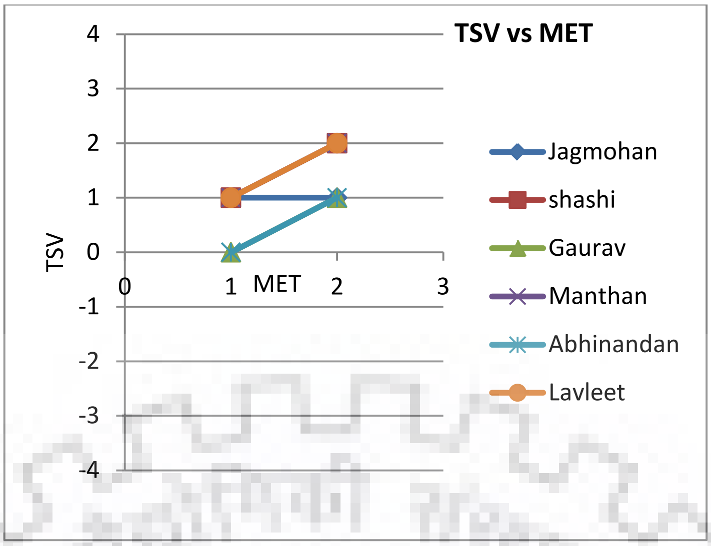

Fig 27: Indices At 34°C and 40% humidity

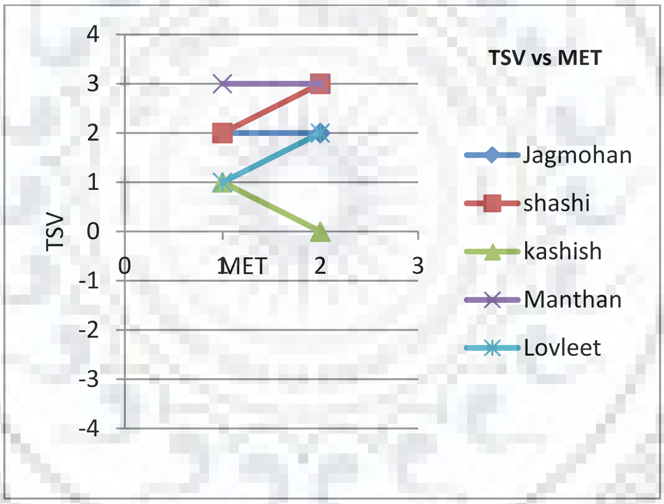

Fig 28: Indices At 34°C and 80% humidity

From Fig 27 & 28 , it depicts that as humidity increases the subjects sensation votes were more towards “Hot” conditions and some at “Warm” conditions.

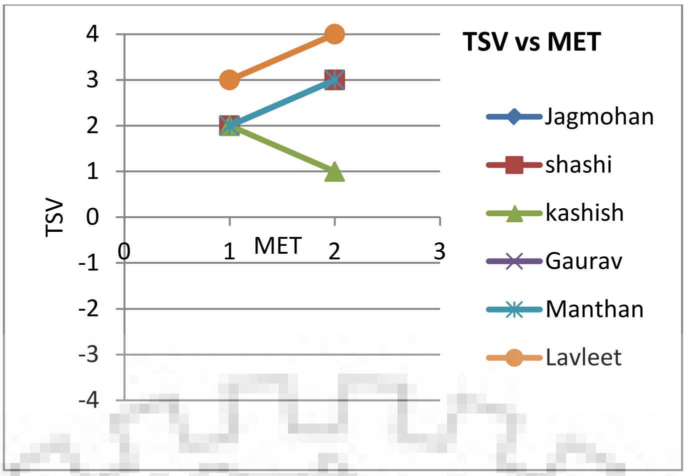

Fig 29: Indices At 38°C and 40% humidity

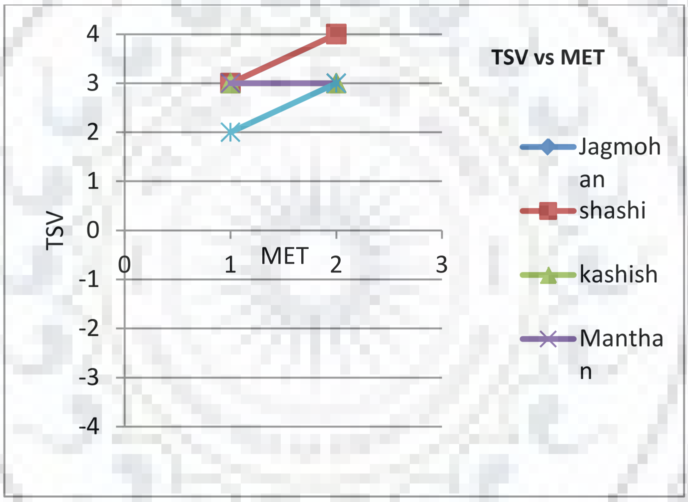

Fig 30: Indices At 38°C and 80% humidity

From Fig 29 & 30 , it shows that little sensation votes were inclined to “HOT” conditions at increased temp. but at low humidity. As humidity increases, little sensation votes were inclined to “VERY HOT” conditions and more on “HOT” conditions.

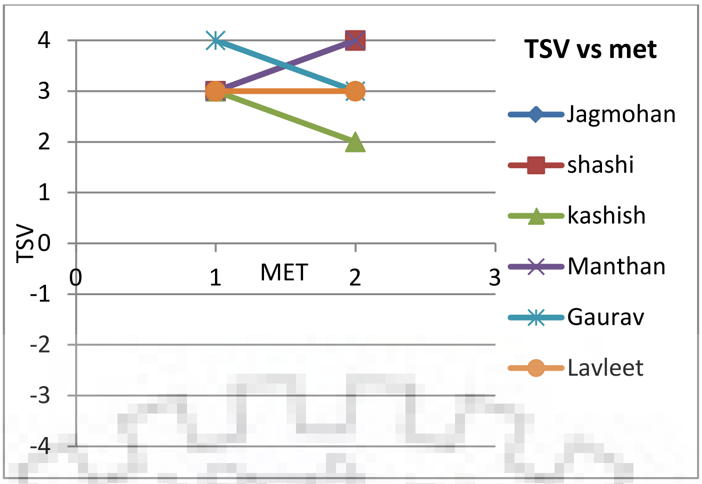

Fig 31: Indices At 42°C and 40% humidity

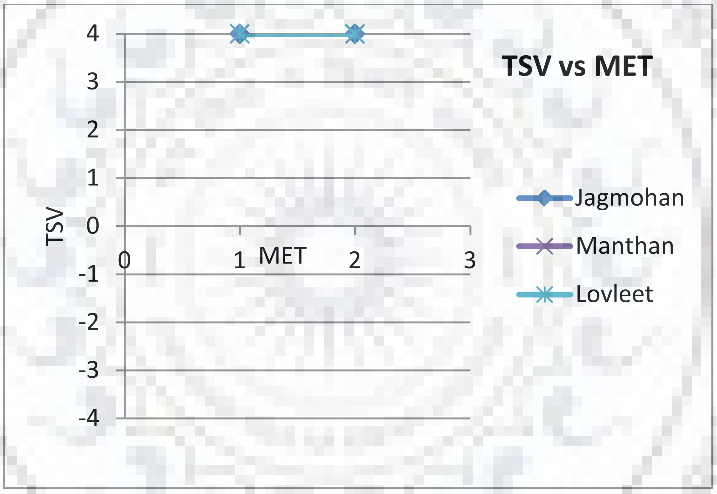

Fig 32: Indices At 42°C and 80% humidity

From Fig 31 & 32 , it shows that more sensation votes were inclined to "HOT" conditions and as humidity increases at higher temperature , the sensation votes were almost towards "VERY HOT" conditions.

- **<u>PMV vs SET</u> :-**

I. Plotted graph was at 40% Humidity and PMV value and SET (°C) value was calculated through ASHRAE calculator.

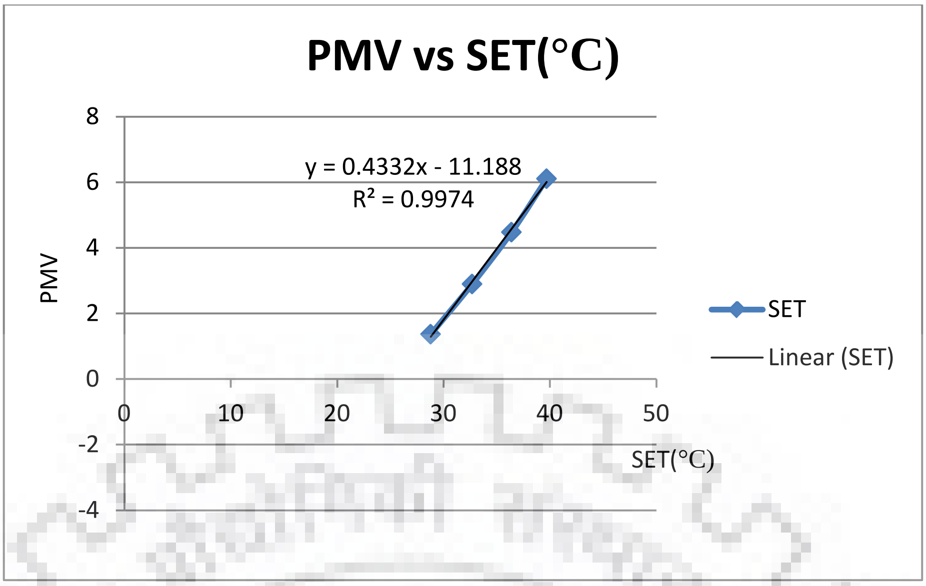

Fig 33: Before the Experiment at 40% Humidity

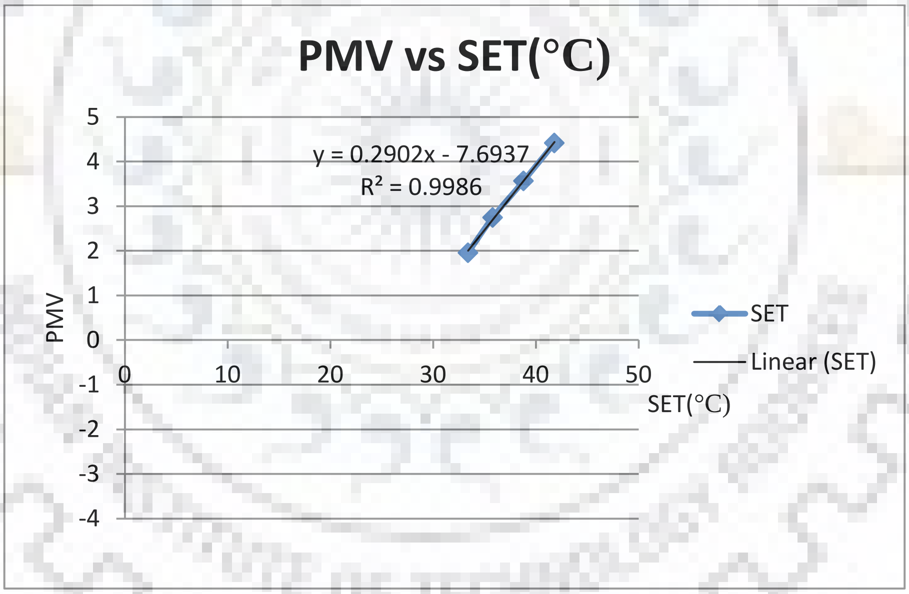

Fig 34: After the Experiment at 40% humidity

From Fig 33 & 34 , it shows that as the metabolic activity increases SET was also increased and slope of the graph also reduces. Also R^2 value was more than 0.6 so the subject would felt more comfortable.

II. Plotted graph was at 80% Humidity :-

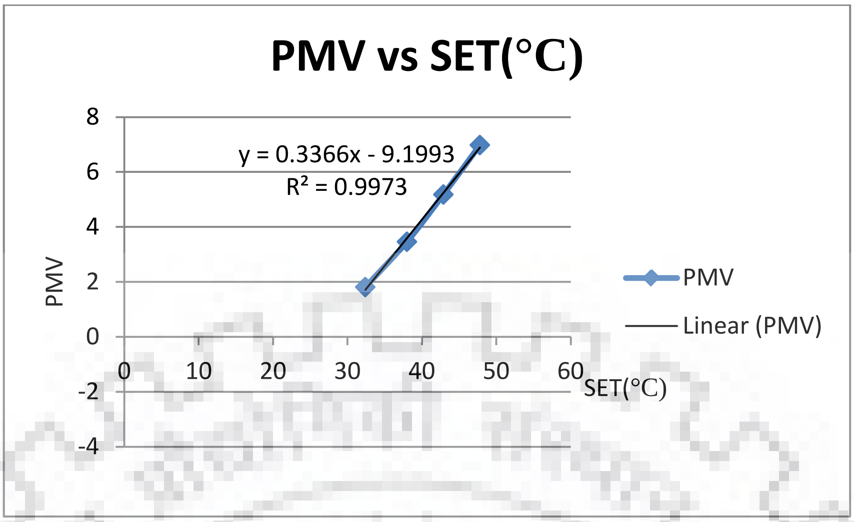

Fig 35: Before the Experiment at 80% humidity

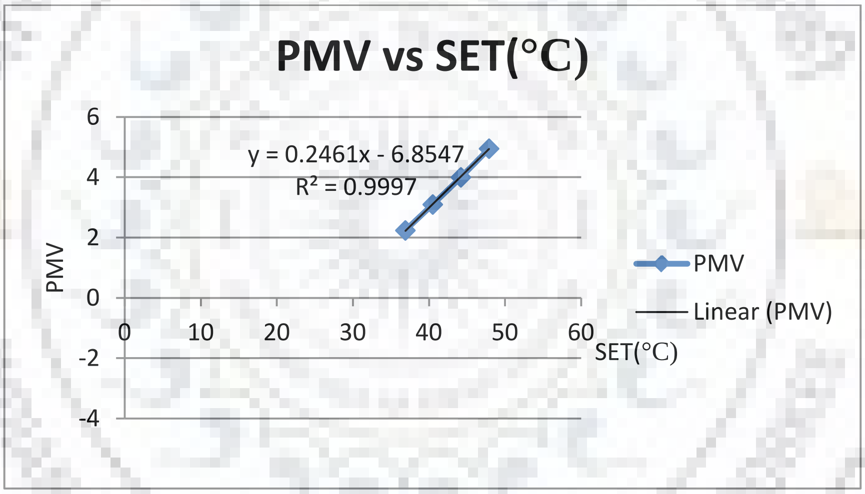

Fig 36: After the experiment at 80% humidity

From Fig 35 & 36 , it shows that as the metabolic activity increases SET was increased and slope of the graph also reduces. Also R^2 value was more than 0.6 so the subject would felt more comfortable.

5.2.2 At Cold conditions :-

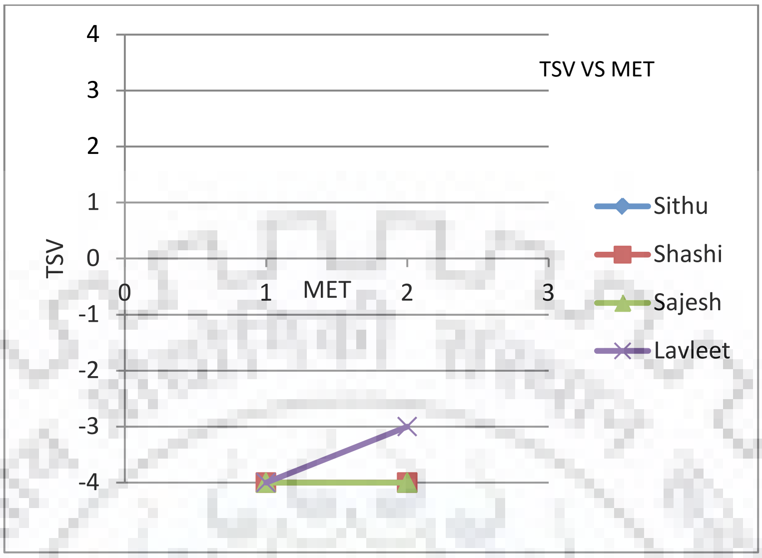

Fig 37: Indices At 2°C

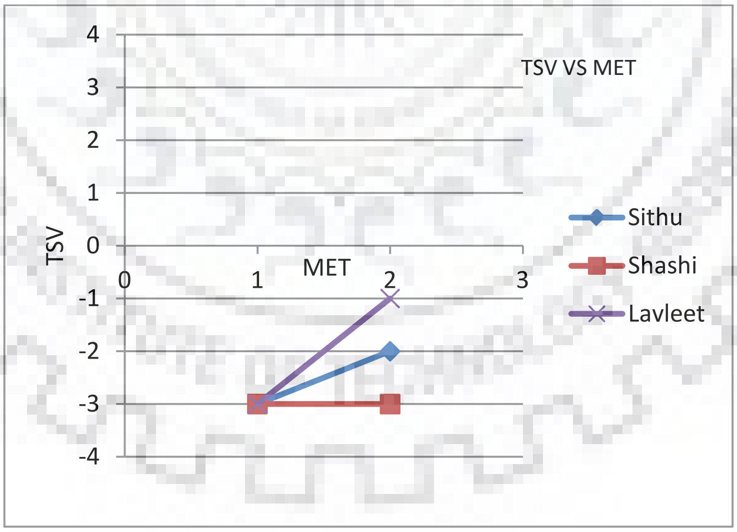

Fig 38: Indices At 5°C

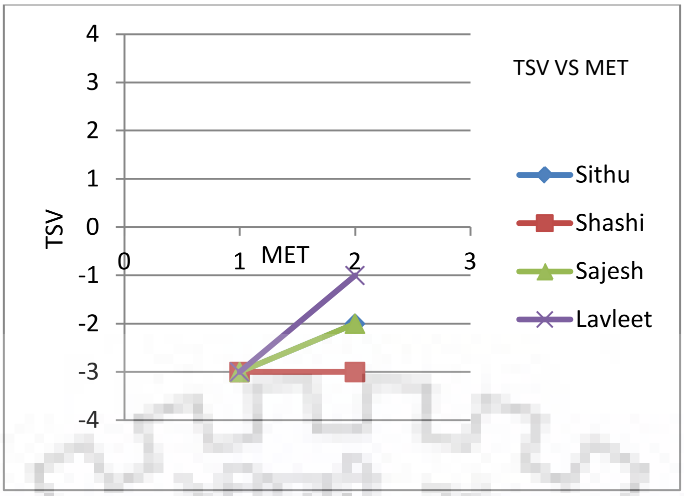

Fig 39: Indices At 8°C

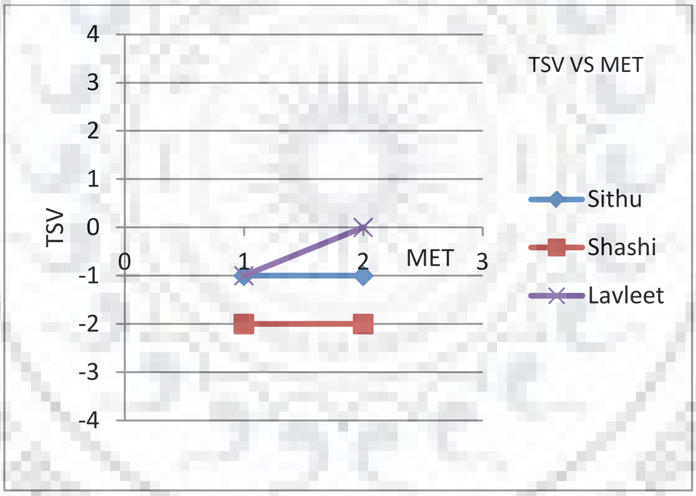

Fig 40 : Indices At 11°C

From Fig 39 & 40, it depicts that at 11°C more sensation votes were towards "SLIGHTLY COOL" conditions and as temperature reduces sensation votes would kept shift to "VERY COLD" conditions. At 2°C, more sensation votes were towards "VERY COLD" conditions as it was harsh at cold conditions.

- **PMV vs SET :-**

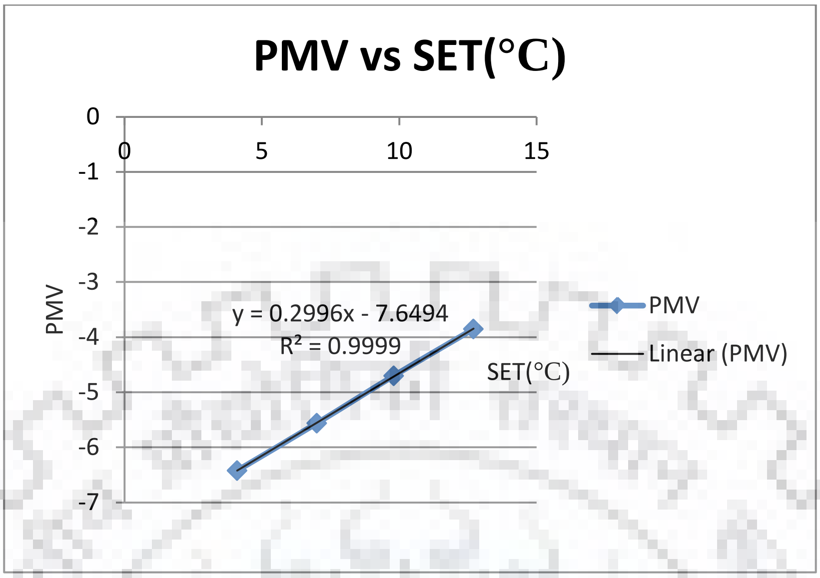

Fig 41 : Before the experiment at Cold conditions

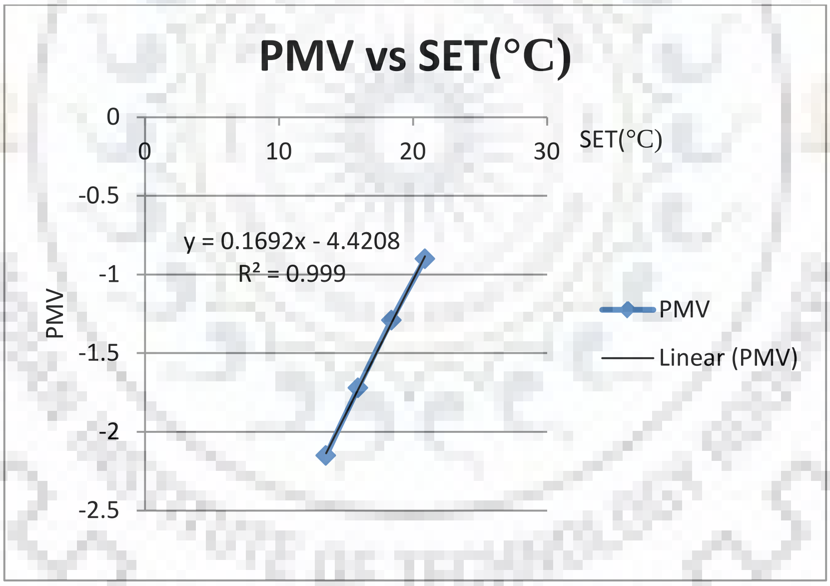

Fig 42: After the Experiment at Cold conditions

From Fig 41 & 42 , it shows that as metabolic activity increases, slope of graph tends to become steeper and also SET was also increased . R^2 value was also more than 0.6 , so subject would felt more comfortable.

CHAPTER 6

CONCLUSIONS

The whole experimental work and study was done in order to observe the thermal variations in different body parts in both Hot & cold conditions and Also taken thermal sensation Vote and predicted mean vote from Thermal Questionnaire provided to subjects. The following conclusions are drawn from the study:

- At hot thermal conditions , initially at 30°C all body parts approximately linearly in nature with respect to time.
- Also at starting temperature 30°C, foot having lower temperature and chest & back having higher temperature.
- As humidity increases bandwidth of temperature reduces and also calves slope reduces.
- As temperature more increases, stomach temperature gone lowest and head slope reduces.
- At higher extreme temperatures, all body parts vary more linearly and Foot & calves slope increases higher as compared to others.
- As in Cold conditions , at lower temp. constant slope was observed. And back was at highest temperature and calves showing increasing slope.
- As temp. increases, calves slope reduces and then again starts increasing.
- Thermal sensation votes were also plotted against metabolic activity which depicts the sensation of subjects at different temp. conditions.
- Sensation votes at extreme conditions were nearly at “VERY HOT” at higher temp. and “VERY COLD” at lower temp.
- PMV vs SET was also plotted which shows the nature of subject votes at both hot and cold conditions.
- At hot conditions, as metabolic activity increases ,the slope of PMV vs SET reduces and R^2 value was also more than 0.6.
- At cold conditions , as metabolic activity increases, slope increases and becomes more steeper.

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