Thermodynamics of human body

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- Generally hot climate is two types: hot-dry and hot humid
- Extreme Hot-dry (Example: Rajasthan: DBT: 43 ^{o}C to 49 ^{o}C, RH: 5-20%
- One particular characteristics of climate is the high contrast between day and nigh temperatures.
- During day time, intense solar radiation results in very high ground temperature which may occasionally shoot beyond 70 ^{o}C.
- On the other hand low humidity and clear sky in night cause rapid radiant cooling of the earth after sunset, so that nights are usually cool and sometimes chilly.
- Hot-humid
- Extreme-humid (Example: Assam, parts of West Bengal: DBT: 37 ^{o}C , RH:80%)
- Human is a homoexothermic machine and capable of maintaining relatively internal temperature over a wide range of climate conditions.

- Human body is thermal machine with thermal efficiency 20%.
- 80% of heat must be disposed off from the body to surroundings.
- Otherwise accumulation heat results and causes discomfort.
- The human body works best at a particular body temperature like any other machine but cannot tolerate wide range of variation in environmental temperature like thermal machines.
- Heat produced in the body is dissipated to the surroundings through three modes; convection, radiation and evaporation. The heat lost by the body to the atmosphere depends on the condition of the atmosphere.
- A comfortable condition of the human body can be maintained only if the heat is dissipated from the body at the same rate at which it is produced.
- If the heat lost from the body is higher than that at which it is produced, the temperature of the body slowly falls causing discomfort.

- The heat loss from the body is given by the following expression;

$$H_m - W_e = H_e + H_c + H_r + H_s$$

H_m = Metabolic heat produced in the body

W= Useful rate of working

$H_m - W_e$ = Heat to be dissipated to the atmosphere

H_e= Heat lost by evaporation

H_c= Heat lost by convection

H_r= Heat lost by radiation

H_s= Heat stored in the body.

It is positive when the temperature of the body rises and negative when the temperature of the body falls below equilibrium temperature (36.5 ^{o}C).

H_m = Metabolic heat produced in the body

It depends on the food consumption in the body.

Convective heat loss from the body:

H_c= UA (Tb-Ta)

U = Heat transfer coefficient on body surface

A = Body surface area= 1.8 m3 for normal man

T_b=Mean body surface temperature

T_a=Surrounding temperature

Heat will be gained = $T_a > T_b$ [This will increase with increase in U which is a function of air velocity.].

Higher velocity of air more discomfort when the surrounding air temperature is higher than body temperature.

Example: When DBT is 50 oC with wind speed 20 km/hr, the convective heat gain by an unclothed body is 1800 kJ/hr which is equal to the metabolic heat produced during heavy work.

When surrounding temperature is less than body temperature then, high velocity of air is recommended H_c increases with increase in velocity.

The radiation heat loss from the body to the surrounding;

$$H_r = \sigma\, (T_b^4 - T_a^4)\ W/m^2$$

σ = Stefan Boltzman constant

$T_a > T_b$: Heat gains the heat from the surroundings

$T_a < T_b$: Heat loses to the surrounding

All bodies emit radiation in the form of electromagnetic waves.

Intensity and wavelength depends on the temperature.

The hotter the object, the higher will be the radiation and shorter wave length.

Mostly all radiations except sun radiations are essentially long wave.

- The effect of short wave radiation is different from that of the long ones.
- Long wave radiations are practically all absorbed by the skin irrespective all the colour.
- The absorption of the colour wave depends on the colour of the skin and clothing.
- White clothing and fair skin reflect short wave radiation to the maximum extent.
- Various shades of skin and colours of clothing absorb these radiations in different degrees.
- In indoor, the colour of the skin or clothing does not play important role because most of the radiations are long wave radiations.
- It becomes a determining factor when the body is exposed to the direct sun (short wave radiations).

- The heat lost by evaporation is always positive and it is given as follows;

- $H_e = K_d A(P_{vs}\text{-}P_v)h_{fg}K_c$
- K_{ed} = Diffusion coefficient in kg of water evaporated /m2hrN pressure difference
- $P_{vs=}$=Saturation vapour pressure corresponding to skin temperature
- P_v=Vapour pressure of surrounding air
- H_{fg}=Latent heat of vapourization = 2450 kJ/kg
- K_c=It accounts for clothing

- H_e = 0 when P_{vs}=P_v: It means when the surrounding temperature across the skin is equal to the skin temperature and air is saturated or which is higher than body temperature and saturated.

- H_e never becomes negative even P_{vs}<P_v because Kd becoms zero under such conditions.

- Role of clothing;

- Clothing interferes with the air movement across the skin and as a result it decreases convection heat transfer and the potential for evaporation.
- Clothing also decreases heat transfer by radiation during out-door work in the sun.
- This decrease may vary from 20 to 50 percent depending on the colour of the clothing.

- White colour : Best effect
- Dark colour : Worst effect
- Desert climate (evaporative capacity of the environment is high)- relative thin, loose fitting and white or light colour dress is advisable.
- This would reduce convective heat gain and reflect a substantial fraction of solar radiation.

- In Humid hot climates;
- Evaporative capacity of atmosphere is small any clothing is disadvantageous.
- Clothing: should be light, porous and loose fitting to allow maximum possible sweat providing free movement of air.
- Weak body human has less metabolic heat production.
- If He, Hr, Hc are high and positive then Hs (heat stored) will become negative.
- [(He+Hr+Hc)]>(Hm-W)]= Sick/weak or old man feels more cold as he loses more heat than produced.
- A man gets fever when internal body activities increase Hm to such extent that Hs becomes positive for given He, Hr, Hc.
- When the maximum and minimum limits of the heat stored exceed then they cause death.
- Usual body temperature: Normal man : 37 ^{o}C (98.6 ^{o}F)
- When body temperature exceeds 40.5 ^{o}C (105 ^{o}F) and falls below 36.5 ^{o}C (98 ^{o}F) are dangerous.

- Some kind of thermostatic controlin human body tries to maintain temperature of the body at normal temperature level of 37 ^{o}C by automatic use of one or more modes of heat transfer.

- The heat transfer He, Hr, Hc are mostly dependent upon the environmental conditions which are the following;

- Dry-bulb temperature
- Relative humidity
- Air-velocity

- The rate of increase in heat loss by evaporation is more pronounced than by heat by convection (sensible heat) with the increase n metabolic rate.

- The main purpose of comfort air-conditioning system is to control the above mentioned factors of conditioned air in a such a s way that (He+Hr+Hc) must balance Hm for making Hs zero.

- $Hm' = (H + He + Hs)$

- $Hm' = (Hm - W)$
- Where $Hm' = (Hm - W)$

- $H = (Hr - Hc)$

- Hr and Hc are grouped together as both represent gain or loss in sensible heat.
- Metabolic rate Hm' depends upon the activity of the person.

- The experimental values of Hm' for different rates of working and their sensible and latent heat components are listed in various books.

Rate of Heat Gain from occupants in Air-conditioned Spaces

Degress of activity	*Typical Application*	*$Hm' = H_m - W$ & $H_s = o$. Total heat dissipated per person in kJ/hr*	*Sensible heat in kJ/hr*	*Latent heat in kJ/hr kJ/hr*	*O_2 – Consumed in litres per hour*
Heated at rest	Theatre	370	210	160	0.24
Heated with light work	Offices and hotels	420	210	210	0.30
Moderately active	Offices and hotels	480	210	270	
Handing with light work	Departmental stores	480	210	270	
king slowly	Banks	520	210	310	
t Bench work	Factory (small production parts)	800	230	570	0.7-1.1
derate Dancing	Dancing hall	900	250	650	2.5-3.1
oderately heavy work	Factory (Heavy production parts or foundry)	1050	310	740	-
Heavy work	Blowing factory	1550	480	1070	3.4-5.2
Maximum Activity possible	—	2900	—		

The body defence

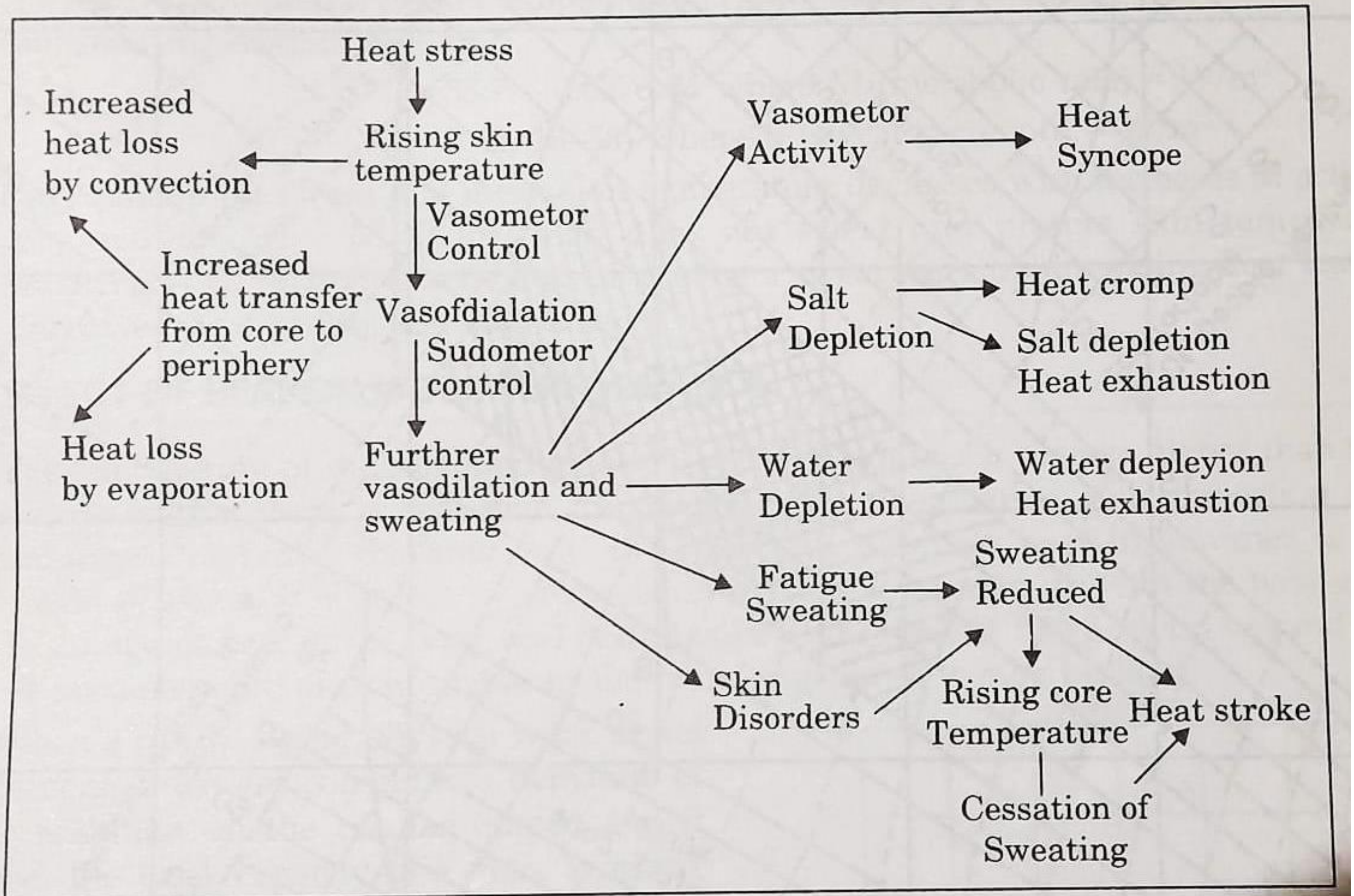
- Whenever a heat exerts on a stress on the body, the body tries many physiological adjustments to keep the deep temperature of the body of the body constanct.
- These adjustments are made by a control centre, located on hypothalamus in the brain.

- There are two types of adjustments generally adopted by the human control system;

  1. Vasomotor control 2. Sudomotor control

Vasomotor control:

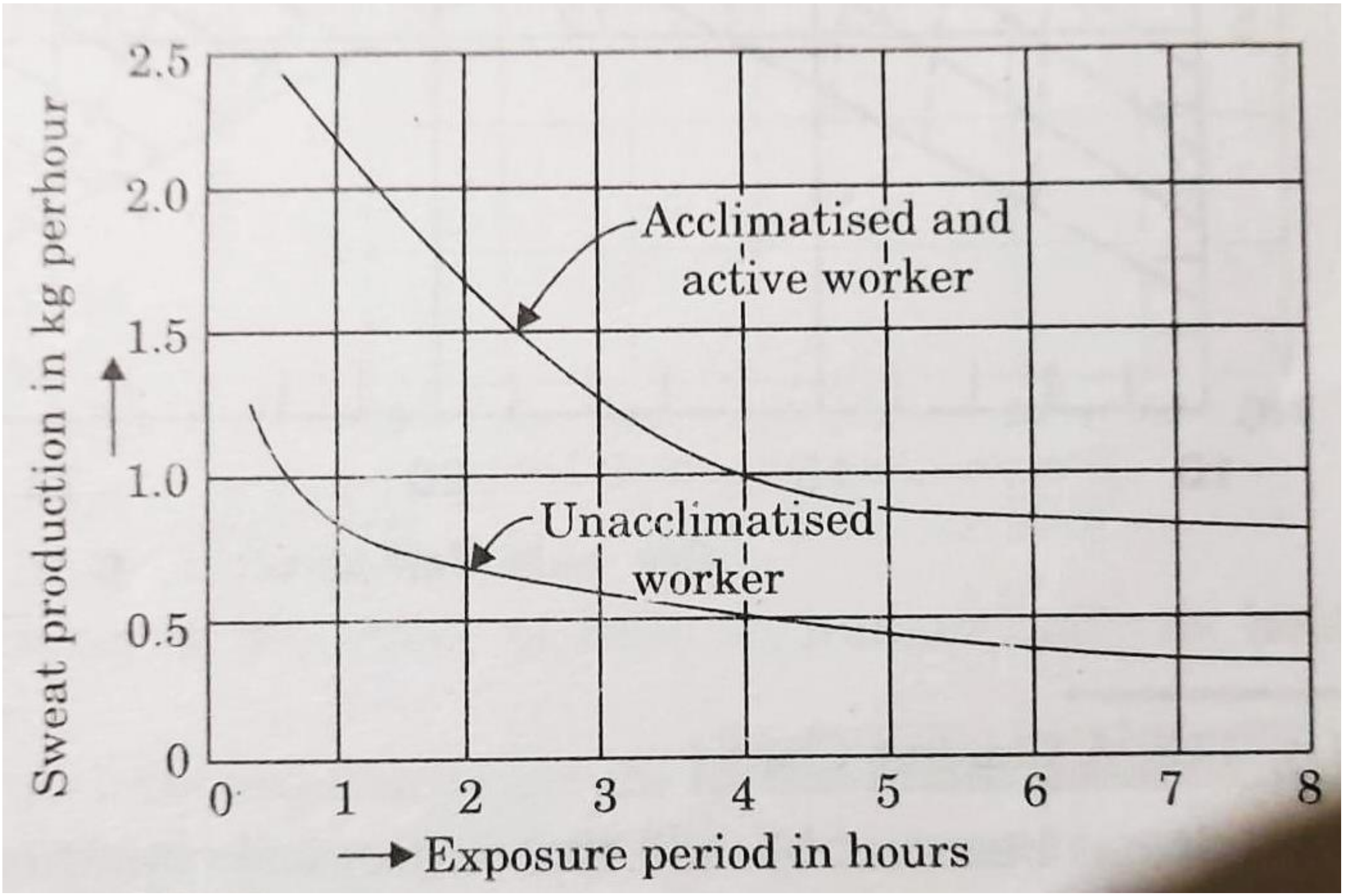
- It regulates the blood supply to the skin.
- It acts by causing vasodilation of the peripheral blood of vessels.
- The increased circulation of blood increases the convective transport of heat from the interior of the body to the surface.


Heat stress
Increased heat loss by convection
Rising skin temperature
Vasometor Control
Increased heat transfer from core to periphery
Vasofdialation
Sudometor control
Heat loss by evaporation
Furthrer vasodilation and sweating
Vasometor Activity
Heat Syncope
Salt Depletion
Heat cromp
Salt depletion Heat exhaustion
Water Depletion
Water depleyion Heat exhaustion
Fatigue Sweating
Sweating Reduced
Skin Disorders
Rising core Temperature
Heat stroke
Cessation of Sweating

- Otherwise the thermal conductance of the skin is increased.
- The increase in blood circulation is also associated with pulse acceleration and increase in cardiac out-put.
- All the processes have one common goal – rising the skin conductance so as to minimize the body heating.
- The vasomotor mechanism alone is sufficient to maintain the heat balance at a low level of heat load and therefore fore is known as "**First law of defence**".

- Sudomotor control
- It regulates sweat production.
- Whenever the heat loss by radiation and convection becomes negative due to high temperature of atmosphere compared to body temperature, the only mode of heat transfer to dissipate the heat is by evaporation.
- The sudomotor control acts by initiating sweat gland activity.
- The sweating capacity differs according to persons degree of acilimatization of heat and work.

- The sweat gland also get fatigued after working, some time, therefore there is progressive fall in sweat production almost exponential with time during work in severe heat.



- The further limitation of effective cooling by evaporation of sweat is imposed by the evaporative capacity of the atmosphere which in turn depends upon the **humidity and wind-speed**.
- The low-evaporative capacity of the environment is the major problem of humid heat.
- Sweat which drips off without evaporation is of no use and that which is absorbed by cooling is less effective for body cooling because it is evaporated at some distance from the skin (It does not absorb the required latent heat from the body).
- It tropical countries man's working capacity is impaired when he is exposed to hot environment.
- His performance efficiency decreases with increase in ambient temperature even by a few degrees above the comfort temperature.
- The important variables which influence human thermal balance are **air temperature, mean radiant temperature, relative air velocity, activity level and thermal resistance of clothing**.

- Man's thermal sensation is related to the state of his thermo regulatory system, the degree of discomfort being greater, the heavier the load on the body mechanism.

- There is a correlation between the skin-temperature and the sensarion of thermal comfort.

- Comfort condition is sensed by the person having skin temperature of 33 to 34 ^{o}C and no sweating on the body.

- Fnager chart (Comfort chart) shows that at higher activities than sedentary, the man prefers a low mean skin temperature and prefers to sweat.

- For sedentary activity (M= 58 W/m^2) man does not sweat and prefers skin temperature of approximately 34 ^{o}C.

- At higher activities, he prefers a sweat secretion involving heat loss of 42% of the increased heat production of the body.

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Hypothermia	<35.0 °C (95.0 °F)
Normal	36.5–37.5 °C (97.7–99.5 °F)
Fever	>37.5 or 38.3 °C (99.5 or 100.9 °F)
Hyperthermia	>37.5 or 38.3 °C (99.5 or 100.9 °F)
Hyperpyrexia	>40.0 or 41.0 °C (104.0 or 105.8 °F)

Effect of heat on work

The atmospheric temperature in summer is always higher than the body temperature so that there is heat gain by the body due to radiation and convection from the surroundings.

Practically, the only way the body can dissipate heat in summer is through evaporation of sweat.

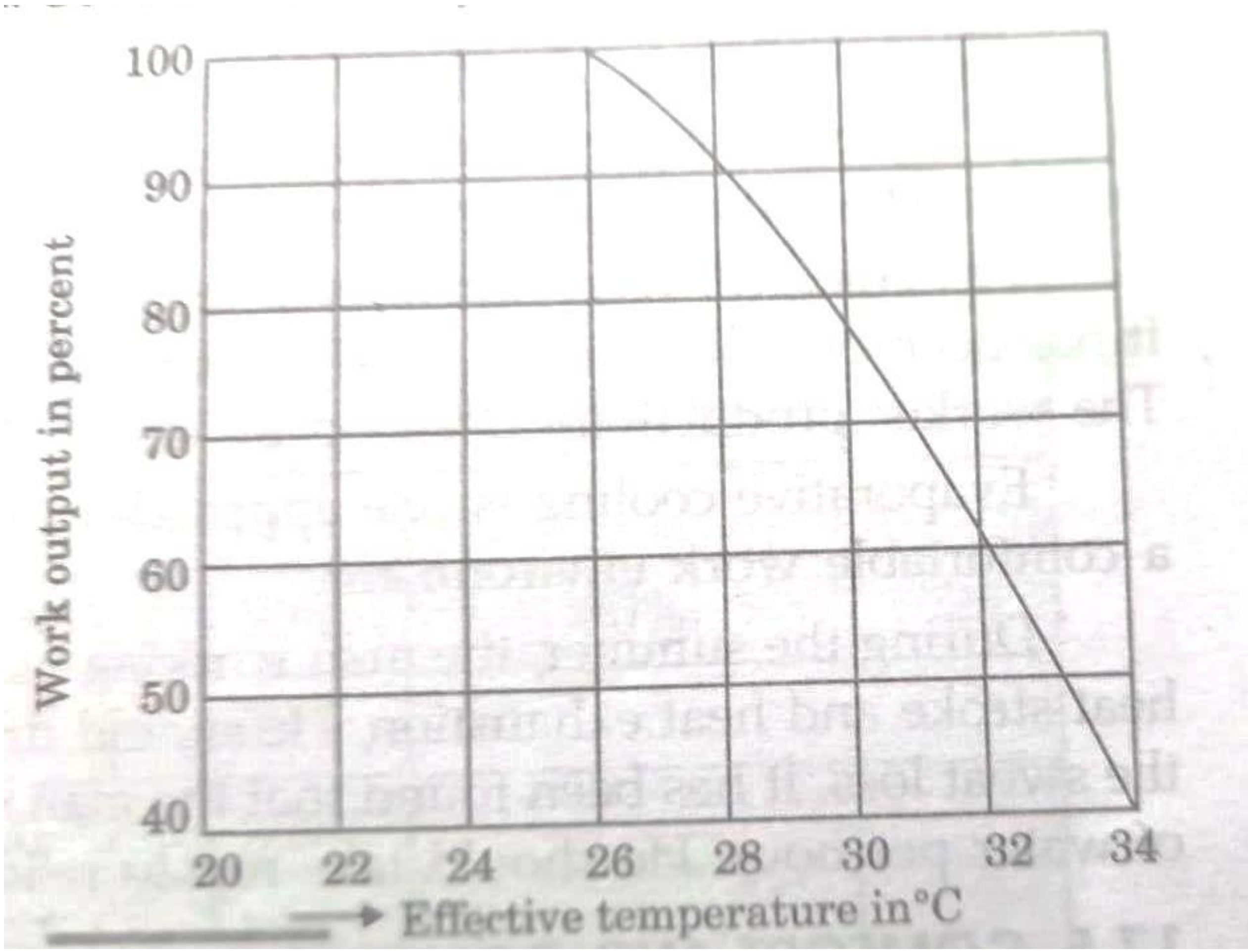
If heat loss by evaporation is not able to cope up with the heat gain, then there is a heat storage in the body and body temperature rises.

IF this goes beyond a critical temperature, it becomes uncomfortable to the skin. Some times it may be fatal.

When a man is preforming a physical work in hot environment, there are competitive demands of muscle and skin on the cardiac output and it decreases the work capacity of a man.

Working capacity of also falls due to an elevated body temperature.

The rate of fall in work efficiency with environmental heat load is shown below.



If the exposure to heat is prolonged beyond a critical period, the body mechanism crumbles.

To a layman, any ill effect of heat is known as “heat stroke”.

Heat stroke occurs suddenly when body temperature rises above 40.5 oC and is accompanied by loss of consciousness.

The heat stroke is the most serious effect of heat disorders but there are few more classifications of the effect of heat on body as **heat exhaustion, heat syncope, and heat cramps**.

Heat exhaustion

The body tends to feel fatigue in very hot climate.

This is due to strain brought about by the physiological adjustments to heat.

Heat exhaustion is attributed by two factors;

(a) Shortage of water in the body (b) salt deficiency

Water shortage: Symptoms: Head ache, extreme thristy and dryness of mouth. There will be a mild feve body temperature rising to 102 oF.

The person feels tired, giddy, nauseated and chilly.

He may have shallow breathing and weak, slow pulse and clammy and pale skin.

Blood vessels are dilated and there is not enough blood to circulate through enlarged vessels.

Heat exhaustion due to salt deficiency :

It is not a common issue

It accounts for 4% casualities

The salt deficiency is induced by heat exhaustion can be easily treated by taking cool saline drinks and rest.

2. Heat syncope;

It is a common ill-effect of heat and accounts for 60% of heat causalities.

The person standing in sun becomes pale, his blood pressure falls and he collapses suddenly.

This is not due to rise in body temperature but it results from pooling of blood returning to the heart is reduced which in turn responsible for lowering blood pressure and reducing blood supply to the brain.

A man can be recovered within 5 to 10 minutes if he is made lie in the shade with the head slightly down.

3. Heat cramp or shock;

The heat stricken person experiences severe pain in the calf and thigh muscles.

It is called cramp and is experienced after a prolonged exertion of sever heat.

The body loses excessive amount of fluid and salt. So there is not enough fluid to maintain circulation to all organs and therefore shock occurs.

Failure to take salt pills or drink salty beverages results in heat cramps, weakness, headache, fatigue or giddyness.

The person suffers from considerable mescle weakness.

4. Heat storke;

It is characterized by sharp rise in body temperature, angry behaviour, delirium and convulsions.

There is no sweating and skin becomes dry and warm

The most likely victims are overweight, older and those who have heart or respiratory ailments.

Heat stroke can be fatal.

A person facing heat stroke must be immersed immediately in water and then taken to a hospital.

Physiological reactions to heat and stress leave the worker tired and less able to perform.

In hot plant productivity decreases to 10 to 30 % below winter levels.

The worker productivity declines by 4% at 27 ^{o}C and by 50% at 34 ^{o}C.

Comfort and comfort chart

Ideal human comfort exists when rate of heat production becomes equal to the rate of heat loss.

This is achieved when proper conditions of temperature, humidity, air velocity and purity.

The comfort feeling of individual depends upon many factors; eating habits, cloth types, duration of stay, age and sex, rate of activity.

There is no proper method to measure the feeling of comfort as it is controlled by many variables.

A scientific method is introduced to measure the comfort feeling of human beings by introducing a concept of “ Effective temperature”.

Effective temperature is a measure of feeling warmth or cold to the human body in response to the air temperature, moisture content and air motion.

Factors governing optimum effective temperature

1. Climatic and seasonal differences
2. Clothing
3. Age and gender
4. Activity
5. Duration of stay
6. Air velocity.

References

C. P. Arora, A Course on Refrigeration and Air Conditioning, 4th Edition, McGraw Hill, 2021.