Textile Product Design and Development

Prof. R Chattopadhyay
Department of Textile and Fibre Engineering
Indian Institute of Technology - Delhi

Lecture - 14
Heat Exchange Between Human Body and Surrounding

One of the important uses of textiles is in clothing. Textiles originated from the fundamental need to protect human beings from rain, wind, heat and other natural calamities. Therefore, it is important to understand the basic science behind clothing. When discussing textiles, the first concept is to understand the heat exchange between the human body and surroundings or environment.

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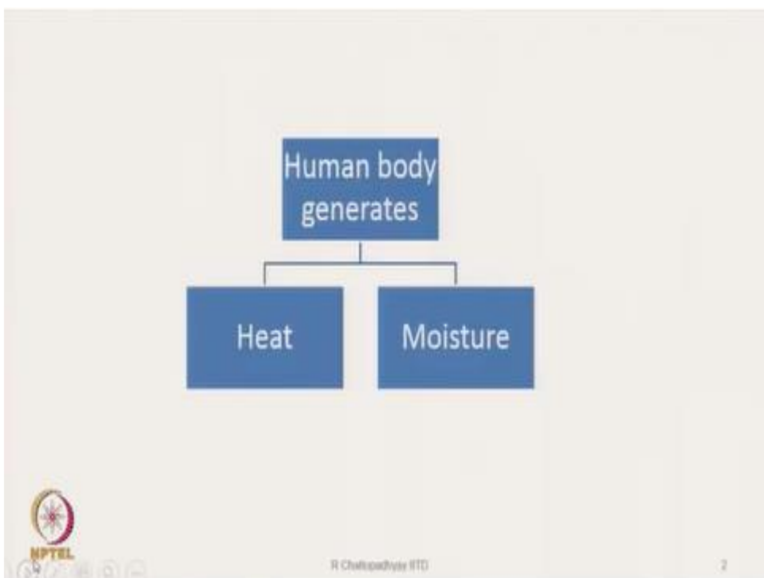

The human body generates both heat and moisture. Hence, clothing must manage both metabolic heat and the constant moisture release. It is important to address these two factors.

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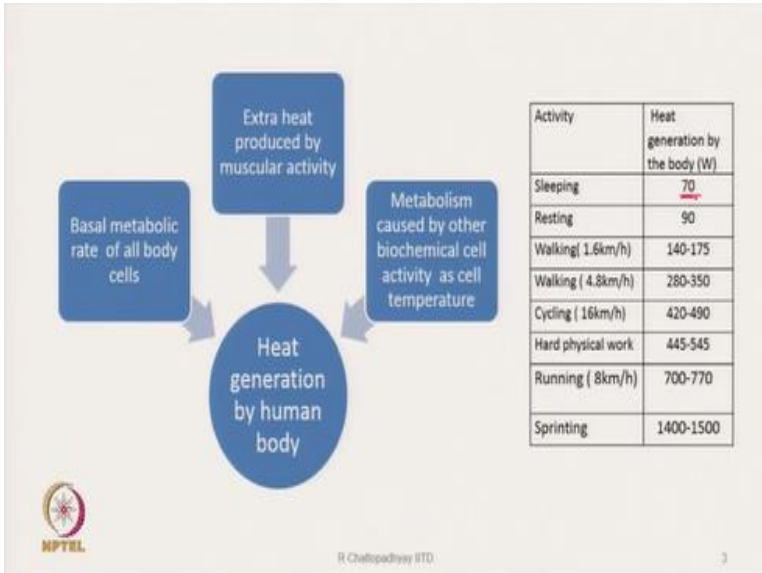

There are different sources of heat generation. The primary heat source is the basal metabolic rate of all body cells, called metabolic heat, which is continuously generated by the body. A deceased person's body is cold because of no heat generation. In contrast, from birth, human beings continuously generate heat, which manifests as being alive.

Another source of heat is produced by muscular activities. Additional heat is generated when engaging in activities like running and physical work. The other thing is metabolism, which is caused by biochemical processes within the cells and generates heat at cellular levels. These are the basic sources of heat in the body. The different activities and the amount of heat the body generates in each scenario are stated.

For example, while sleeping, the heat generated by the body is around 70 watts, and when resting, it increases to about 90 watts. Various activities such as walking, cycling, hard physical work and the corresponding heat generated by the body are stated. This heat must be dissipated; otherwise, heat accumulates, causing a rise in skin temperature and ultimately leading to discomfort.

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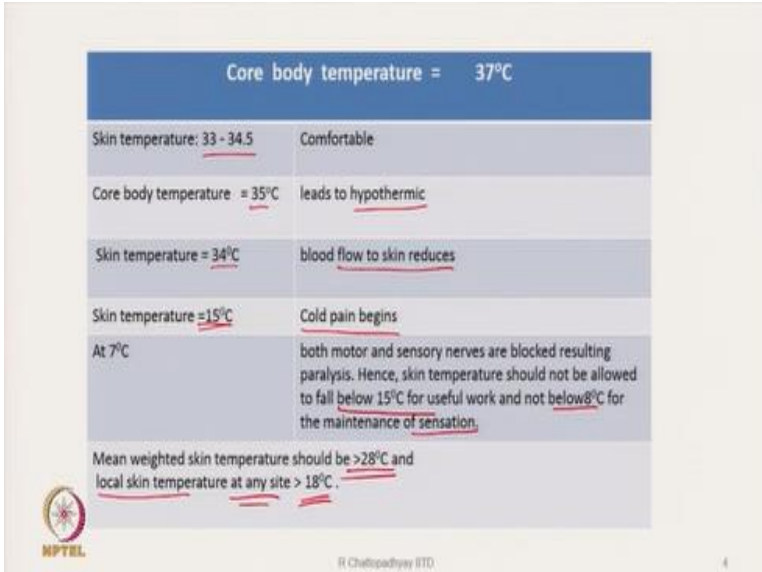

The core temperature of the body is typically around 37˚C, while the skin temperature ranges from 33˚C to 34.5˚C. Human beings feel comfortable as long as the skin temperature stays within this range. However, if the core body temperature drops to 35˚C, it leads to hypothermic reactions, which is not good for humans. When the skin temperature reduces to 34˚C, even for the small temperature difference of 1˚C, the blood flow to the skin starts reducing. This happens because blood continuously circulates from the heart to the entire body, and the heated blood transports heat all over the body.

When the skin temperature drops to 15˚C, cold pain starts and causes noticeable pain due to cold. If the temperature of the fingers and toes drops to 15˚C, the problem of cold pain and numbness occurs. If it lowers to 7˚C, both motor and sensory nerves become blocked, resulting in paralysis. Therefore, it is important to ensure skin temperature should not be allowed to fall below 15˚C, as it affects the ability to perform useful work. This is essential for a person working in cold environments to maintain sensation. These temperature values are critical, and understanding the consequences of body or skin temperature falling below these values is important.

The mean weighted skin temperature should always be above 28˚C. The skin temperature varies throughout the body and is not uniform everywhere, i.e., they are not exactly constant. However, the weighted skin temperature must always be greater than 28˚C, and the local skin temperature at any site should remain above 18˚C to prevent cold pain. These temperature thresholds are important considerations while designing clothing for cold climates or environments.

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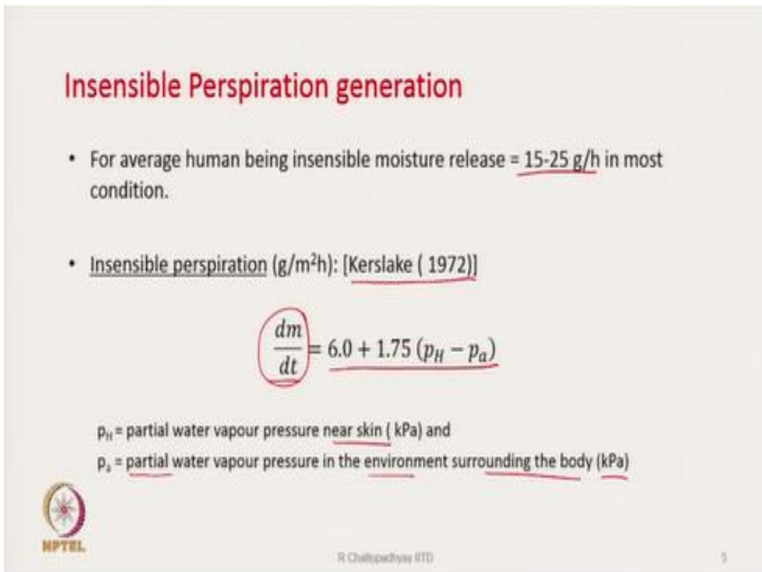

The body also generates some insensible moisture. Insensible perspiration, which refers to the moisture produced by the body without the noticeable feel of wetness, typically ranges from 15 - 25 g/h under most conditions. This type of perspiration occurs constantly released from the skin and evaporates into the atmosphere without any feeling of wetness. Hence, it is called insensible perspiration.

The insensible perspiration as a function of time has been shown by this scientist with the following equation,

$$\frac{dm}{dt} = 6.0 + 1.75(p_H - p_a)$$

where 'p_H' represents the partial water vapour pressure near the skin (in kilopascals) and 'p_a' is the partial water vapour pressure in the environment (in kilopascals). This means the rate at which perspiration is generated depends on the difference between the vapour pressure near the skin and in the environment. The greater the difference, the higher the rate of perspiration.

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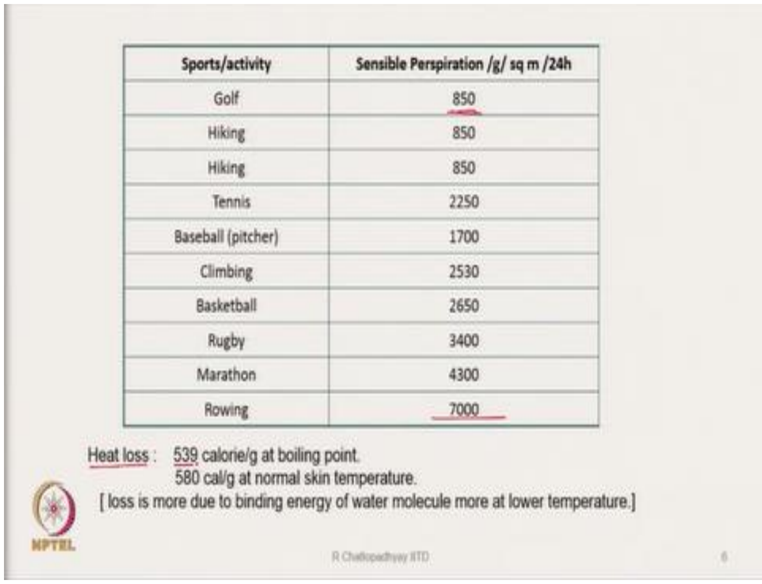

Sports/activity	Sensible Perspiration /g/ sq m /24h
Golf	850
Hiking	850
Hiking	850
Tennis	2250
Baseball (pitcher)	1700
Climbing	2530
Basketball	2650
Rugby	3400
Marathon	4300
Rowing	7000

Sensible perspiration refers to the liquid sweat generated and it is not vapour. The different kinds of activities and kinds of sensible perspiration generated are stated in the table. for example, activities like playing golf cause the body to generate 850 grams of sweat per square metre in 24 hours. Similarly, different activities like hiking, tennis, baseball, and climbing lead to different levels of sensible perspiration, which are listed.

These activities give us an idea of how much sweat can be generated per unit of time. By adjusting the time from 24 hours to per minute or even per second, the amount of sweat produced can be more precisely estimated, and it helps to manage various activities. For designing clothing where sweat management is a critical factor, such as for sportswear, sweat management is one of the important issues to address.

During sports activities, people generate a significant amount of sweat, and the clothing design has to manage the sweat generated effectively. The heat loss is due to the liquid sweat being vaporized. When sweat evaporates, there is a phase change from liquid to vapour. The heat required to transform the liquid into vapour is 539 calories per gram at the boiling point.

But, at normal skin temperature, it requires approximately 580 calories per gram. This means that when 1 gram of sweat evaporates from the skin, it removes 580 calories of heat from the body. So it has effective cooling power. While sweat is essential for cooling, it also has negative aspects. It often creates an irritating sensation. For example, the discomfort of sweat rolling down our faces, and when it accumulates on the skin, the sensation is not soothing.

Therefore, we naturally try to wipe the sweat away using a towel and then seek relief by standing under a fan or in a breezy area to dry off and cool down. Hence, the remaining sweat on the skin starts evaporating; it draws heat away from the body during the process. The net result is that the skin temperature decreases, creating a comfortable feel.

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Next is the heat exchange between human skin and the ambient environment.

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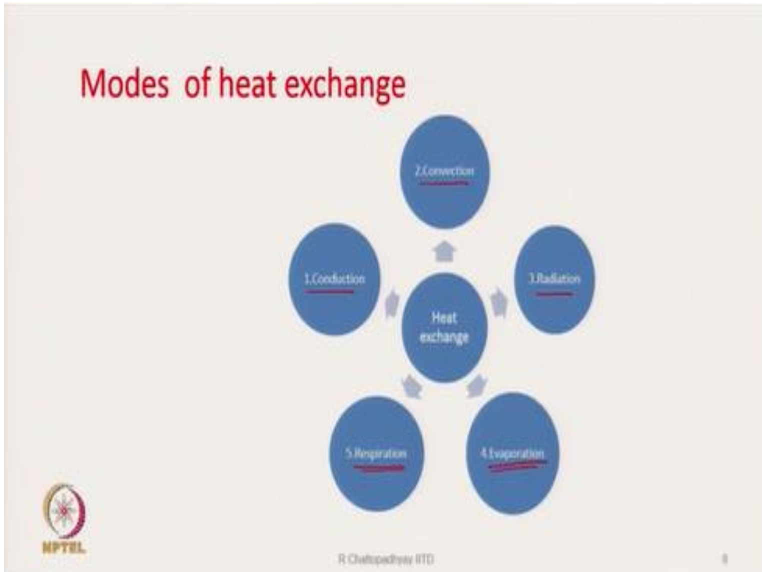

This slide highlights the various modes of heat exchange between the human body and the environment. Heat can escape from the body to the surroundings, but in certain situations, the body may also absorb heat from the environment. If the environmental temperature is higher than the skin temperature, heat flows from the environment into the body. Conversely, if the environmental temperature is lower than the skin temperature, heat will flow from the body to the surroundings. There are five modes of heat exchange by the human body to the environment. They are conduction, convection, radiation, evaporation and respiration.

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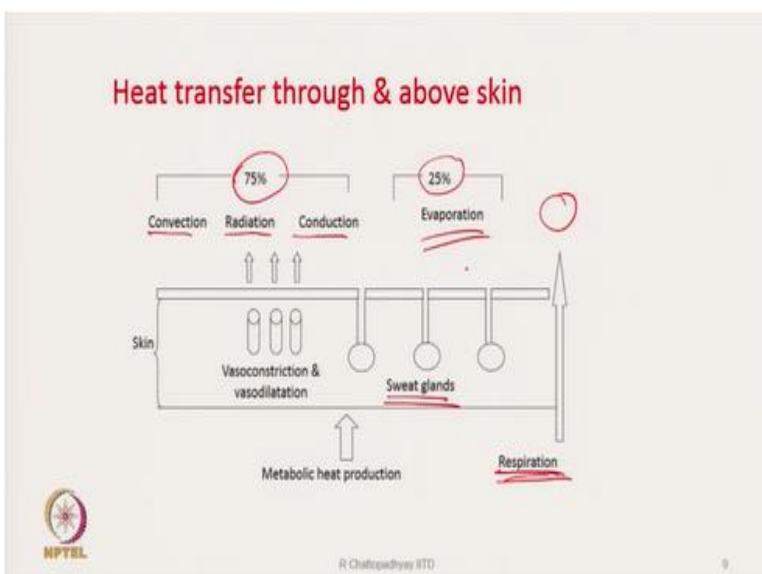

This diagram illustrates heat transfer both through and above the skin. It explains how body heat moves outward, with part of the heat passing through the skin and some escaping above it. The main three modes of heat transfer such as conduction, convection and radiation, account for 75% of the body's heat loss. The heat generated in the body's core travels through flesh and bones, reaching the skin. Once it reaches the skin, it is then released into the surroundings.

Conduction, convection and radiation are the three primary heat transfer modes through which 75% of the body's heat is lost. The remaining 25% is lost through evaporation, which includes both the evaporation of sweat and the evaporation of continuously generating moisture vapour. The heat lost through respiration is minimal, less than 1%. Hence, a major portion of the heat escapes through convection, radiation, and conduction from the human body to the environment, and around 25% of it escapes through evaporation, primarily from the sweat glands.

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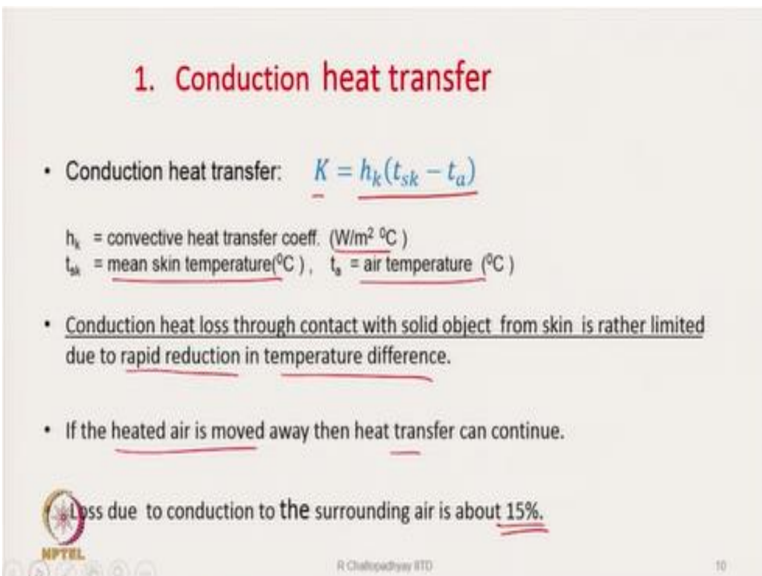

Conductive heat transfer is given by the equation, '$K = h_k(t_{sk} - t_a)$' where 'h_k' is the conductive heat transfer coefficient, 't_{sk}' represents the skin temperature and 't_a' is the air temperature. This simple equation helps calculate the amount of heat transferred from the body to the environment through conduction.

Conduction heat loss through contact with solid objects from the skin is limited in the human body because the temperature difference between the skin and the object decreases rapidly. As a result, this mode of heat exchange is limited in the case of humans. The heated air near the skin must be moved away for effective heat transfer to continue. When the air next to the skin receives heat, its temperature rises, reducing the temperature difference between the skin and the air layer in close contact.

As a result, the heat transfer slows down over time. However, if there is a mechanism to move the heated air away either by movement of the body or by the air circulation, in that case, heat transfer continues. Heat loss due to conduction to the surrounding air is about 15%.

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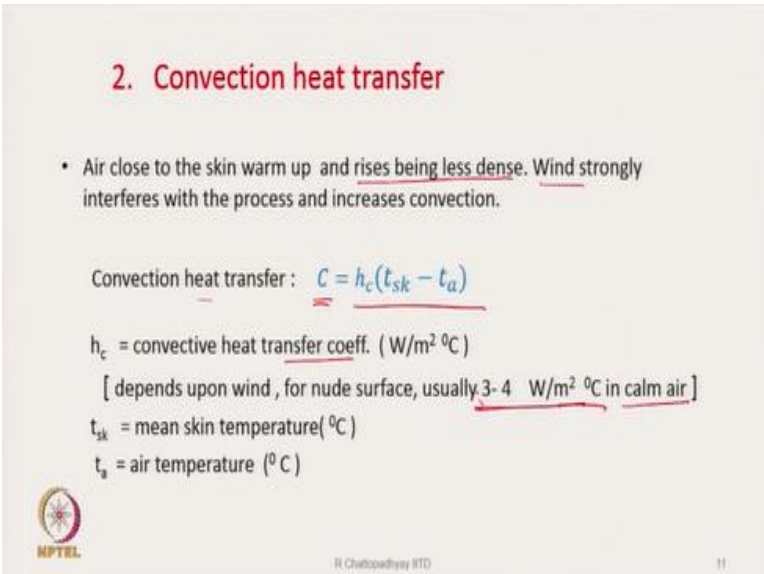

Convection heat transfer involves the movement of air close to the skin, which warms up by the heat radiating from the body, leading to decreased air density. As the air temperature rises, it becomes lighter because of the reduced density. Hence, the warm air moves up, and the cold air moves down, which is explained in basic physics.

Hence, in convective heat transfer, the air close to the skin gets warmer and rises, generating an air current. If there is additional wind or air movement, this process becomes faster. The formula for the convective heat transfer is given by '$C = h_c(t_{sk} - t_a)$' where 'h_c' is the convective heat transfer coefficient, 't_{sk}' and 't_a' are the skin temperature and the air temperature. 'h_c' depends on wind or air movement. For a nude surface, in calm air, it usually ranges between 3 – 4 W/m^2˚C.

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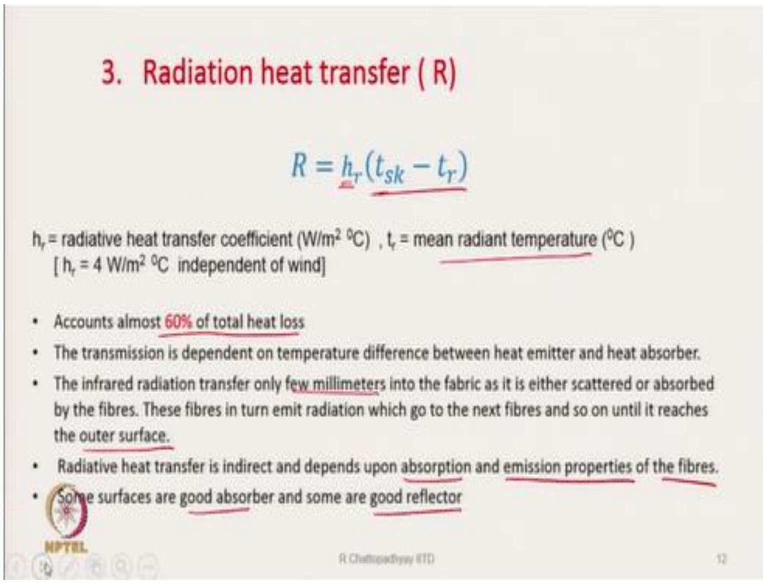

The other mode of heat exchange is radiation heat transfer, and the formula for radiative heat transfer is given by '$R = h_r(t_{s_k} - t_r)$' where 'h_r' is the radiative heat transfer coefficient, and 't_r' is the mean radiant temperature. Radiative heat transfer accounts for about 60% of the total heat loss. Compared to convection and conduction, radiation is a much more efficient mode of heat transfer for the human body.

Approximately 60% of body heat escapes through radiation. The heat transfer rate through radiation depends on the temperature difference between the heat emitter and the absorber. In this case, the human body acts as the heat emitter, and the surrounding environment absorbs heat. The infrared radiation transfers only a few millimetres into the fabric as it is either scattered or absorbed by the fibres.

The clothing layer consists of millions of fibres packed together. Hence, infrared heat radiation transfers only a few millimetres into the fabric, either scattered or absorbed by the fibres. These fibres, upon absorbing radiation, transfer their radiation to the neighbouring fibre. Even though the fabric thickness is less, it still contains many fibres in the cross-section of the yarn. Comparing the dimension of fibre, which is in microns, with the dimension of the fabric, the fabric consists of a large number of fibres along its thickness.

As the heat radiates from the body, it travels from one fibre to another and from that fibre to the next layer. Eventually, it reaches the outer surface of the fabric. Radiative heat transfer is indirect and depends upon the absorption and emission properties of the fibre. This is important because it depends not only on the temperature difference but also fundamentally on the emission properties of the fibres. Therefore, it is essential to understand the emission characteristics of various fibres.

With this knowledge, fibres can be selected for developing clothing that protects the human body in very cold environments. Some surfaces are effective absorbers, while others serve as good reflectors. There are some surfaces which reflect the radiative heat. Hence, it is important for a designer to use this information when designing clothing for a particular end-use.

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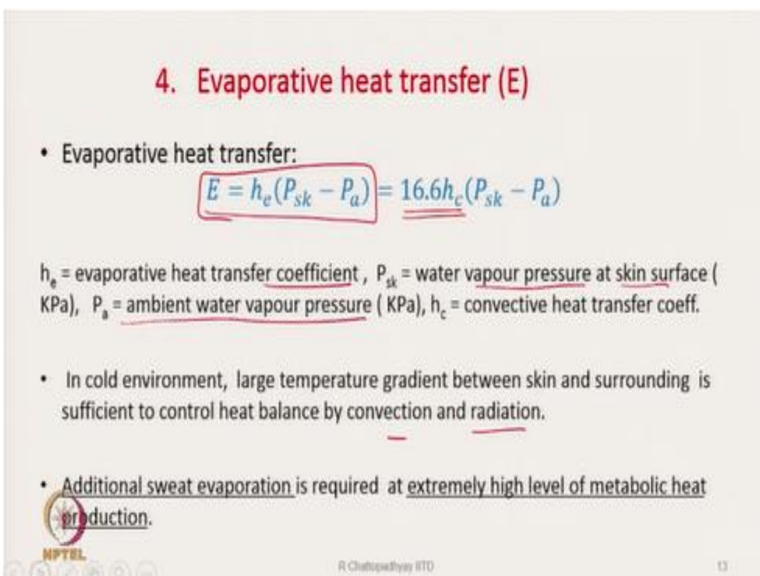

Evaporative heat transfer is given by the formula, '$E = h_e(P_{sk} - P_a)$', where 'h_e' is the evaporative heat transfer coefficient, 'P_{sk}' is the vapour pressure at the skin surface and 'P_a' is the ambient water vapour pressure. This formula allows us to calculate the evaporative heat transfer from the skin. The amount of heat being transferred can be determined by considering the evaporation of liquid sweat from the skin.

Insensible evaporation occurs continuously, and we can determine the amount of heat lost through this process using these equations. The evaporative heat transfer coefficient 'h_e' can be replaced by '$16.6 \times h_c$', where 'h_c' is the convective heat transfer coefficient. This establishes a relationship between 'h_c' and 'h_e'. In cold environments, a significant temperature gradient between the skin and the surroundings is sufficient to regulate heat balance through convection and radiation.

When the outside temperature is very low in cold environments, the large temperature gradient will be diverted. The skin temperature in comfortable conditions is approximately 34˚C to 34.5˚C. The surrounding temperature varies based on the environment; in hilly regions, it can be much lower, and during winter, temperatures may drop to 1˚C or even below 0˚C, resulting in negative values. A large temperature gradient can lead to a high rate of heat loss, and it is essential to arrest this heat loss. Otherwise, humans may suffer from the cold.

Additional sweat evaporation is required at an extremely high level of metabolic heat production. However, in cold climates, sweat generation is typically minimal during normal activities. The metabolic heat generation may increase significantly if engaging in high-intensity activities, such as exercising while fully clothed. In this case, the heat transfer rate through the clothing could be much lower than the rate at which the body generates heat. If this occurs, heat will accumulate in the body because it is being produced at a faster rate than it can be lost through the clothing.

The net effect is that the person will begin to sweat because the body's thermoregulatory mechanism triggers sweat production, hoping the sweat will evaporate from the skin and remove some heat, thereby cooling the body down. This is an automatic body reaction due to sweating during physical activities, and the heat balance gets lost. This situation will arise when the generation of heat per unit of time significantly exceeds the rate of heat loss from the body.

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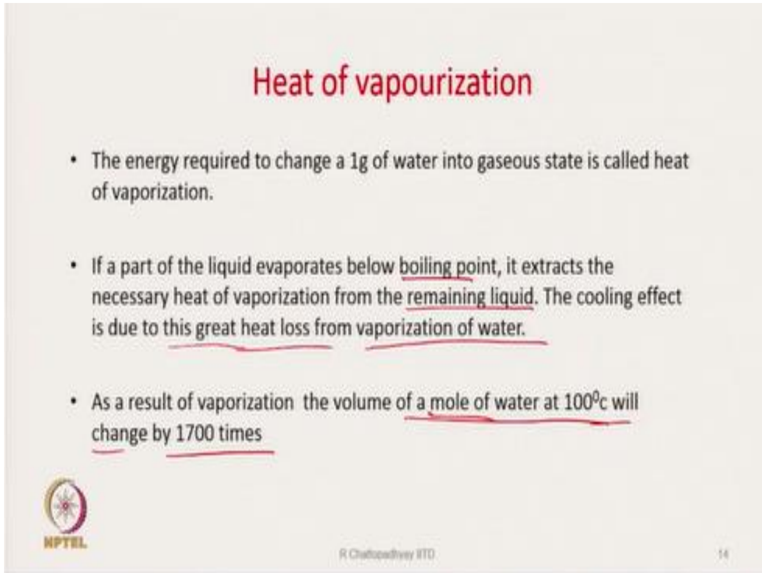

The heat of vaporization refers to the energy required to convert 1 gram of water into a gaseous state. This is also known as latent heat. When a portion of the liquid evaporates below its boiling point, it extracts the necessary heat of vaporization from the remaining liquid. The cooling effect arises from this significant heat loss during the vaporization of water. For example, in a container with some water, there will be continuous evaporation of water molecules from the container.

As the water changes its phase from liquid to vapour, it takes away certain heat. Consequently, the temperature of the water gradually decreases because the latent heat is taken away from it. As a result of vaporization, the volume of one mole of water at 100˚C increases by 1700 times. This information is crucial because in certain situations where water vaporizes, leading to a sudden increase in volume that must be managed. This is especially important when considering the design of firefighter clothing, where external temperatures can be extremely high.

If water which is there enters the clothing due to high temperatures, it may convert to vapour or steam, resulting in a sudden and significant volume change. This creates additional challenges. While the fabric can easily absorb one gram of water, its vaporization leads to a volume increase of 1700 times. It is essential to manage such situations. Therefore, designers must also consider worst-case scenarios when creating critical products.

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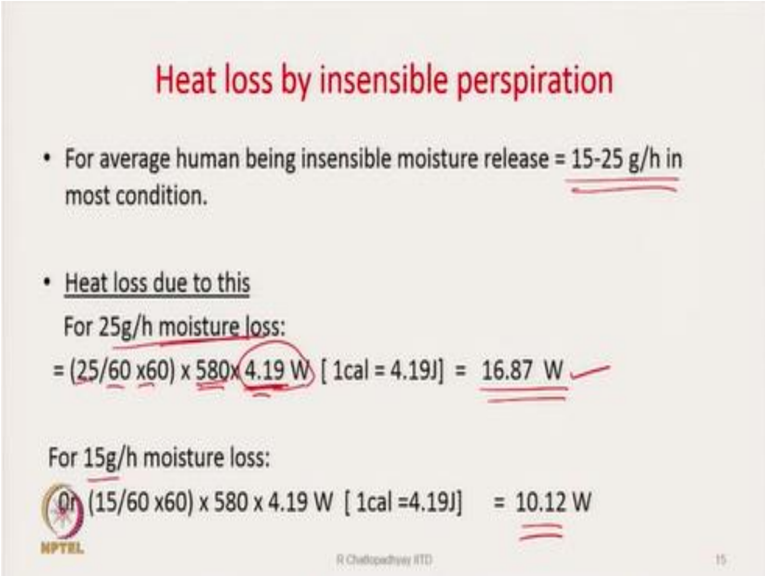

Heat loss through insensible perspiration typically ranges from 15 to 25 g/h. To calculate the heat loss associated with a moisture loss of 25 g/h, it is calculated that the heat loss of approximately 16.87 watts. This is obtained by converting 25 g/h into g/s and then multiplying by 580, which is the latent heat at normal temperatures. Multiplying by 4.19, the measurement is converted from calories to joules, as 1 calorie equals 4.19 joules.

This conversion gives us the value in watts since power is defined as joules per second. Therefore, heat loss amounts to approximately 16.87 watts. If the body releases about 25 grams of moisture per hour, around 17 watts of heat will be lost. In another scenario, if 15 grams of moisture per hour is generated, the heat loss would be approximately 10 watts. The insensible moisture-generating continuously helps lose some body heat, typically around 10 to 17 watts.

However, this varies depending on the activity; for example, during certain activities, heat generation may reach up to 150, 200, or even 300 watts, depending on the nature of the activity. Thus, the heat loss through insensible perspiration is not relatively high.

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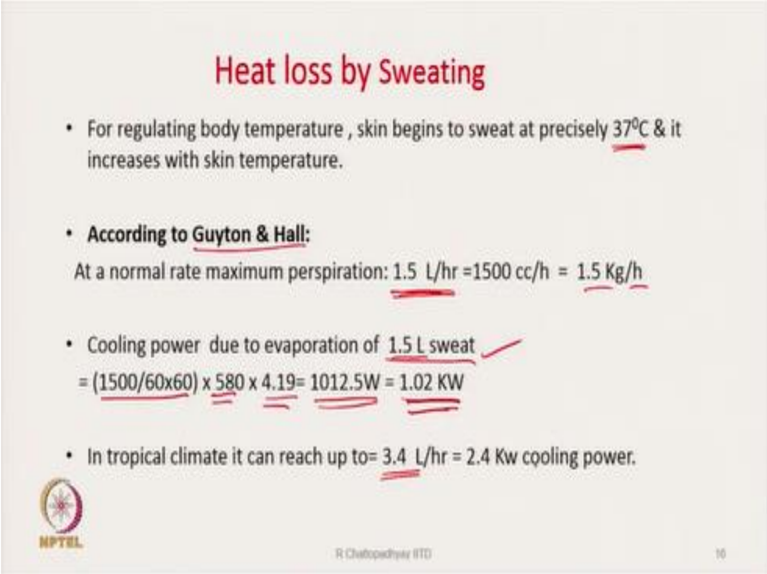

Heat loss through sweating varies depending on the amount of sweat produced. The skin typically begins to sweat when its temperature reaches around 37˚C. In comfortable conditions, the skin temperature is usually between 34˚C and 35˚C; once it rises to 37 degrees Celsius, sweating is generated. According to Guyton and Hall, the maximum perspiration rate under normal conditions is 1.5 L/hr.

This translates to 1.5 kg of sweat per hour, assuming the density of sweat is approximately equal to that of water. To determine the cooling power from the evaporation of 1.5 litres of sweat, the amount of sweat produced in 1 hour is calculated, equivalent to 1500 grams. Multiplying this by 580 (the latent heat in calories) and then by 4.19 (to convert to joules) gives 1012.5 watts, i.e., 1.02 kW. This means that if we sweat at this rate, approximately 1 kilowatt of heat can be lost, assuming all the sweat evaporates. This represents the cooling power of sweating.

However, it is important to note that all sweat will not evaporate; some will drip away. Additionally, the accumulation of sweat on the body and its rolling down can create an uncomfortable sensation. Some sweat will be lost simply by dripping down, while some may be wiped away due to discomfort. It is important to understand that if we generate 1.5 litres of sweat per hour, it is one of the extreme situations. Then, the cooling power of that sweat, assuming complete evaporation, is approximately 1.02 kW. In tropical climates, sweat production can increase significantly, reaching up to 3.4 L/hr.

Interestingly, sweat production can exceed 1.5 litres, reaching up to 3.4 litres per hour, more than double the previous amount. In this case, the cooling power would be approximately 2.4 kW, assuming all the sweat evaporates without any loss. Therefore, the body is cooled because it will take away the energy from the skin.

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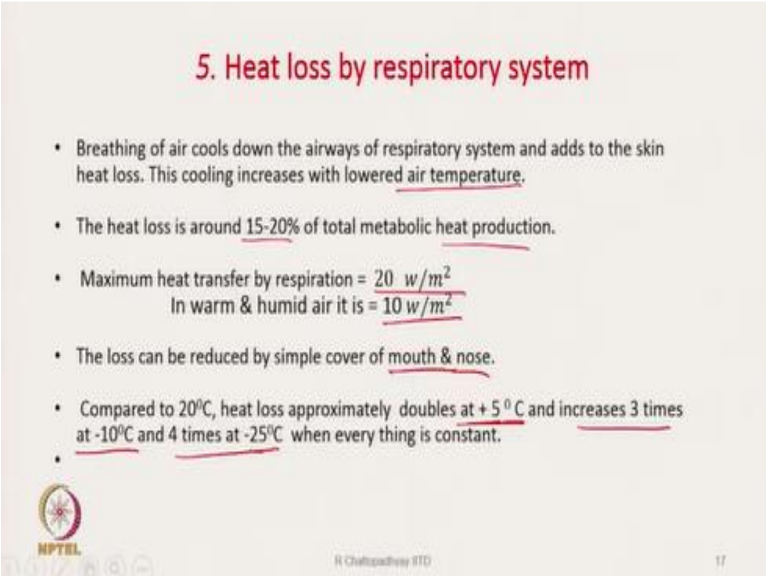

Heat is also lost through the respiratory mechanism. Breathing occurs continuously, whether awake or asleep, which cools the airways of the respiratory system and contributes to overall heat loss from the skin. This cooling increases with the lowered air temperature. So, the temperature of the outside air is lower than the body temperature. When inhaling, cold air enters the body and warms up. The warm air is then exhaled, contributing to cooling.

The heat loss through respiration is around 15 to 20% of the total metabolic heat production. Studies have shown that the maximum heat transfer by respiration is around 20 W/m^2 in cooler conditions, while in warm and humid air, it decreases to approximately 10 W/m^2. Heat transfer happens through the respiratory mechanism during breathing, and this loss can be minimized by simply covering the mouth and nose. In cold climates, to reduce heat loss, a simple cloth covering can help retain warmth.

Many people experience this effect when walking in winter; covering the nose and mouth makes them feel warmer. Outside in cold weather, we often cover our nose and mouth with a muffler or shawl to reduce heat loss and stay warmer. This simple act can significantly reduce the amount of heat lost through respiration. It is also important to note that heat loss nearly doubles as the temperature drops from 20˚C to 5˚C.

Compared to 20˚C, heat loss doubles at 5˚C, increases 3 times at -10˚C and 4 times at -25˚C when everything is constant. By extrapolating, we can estimate the heat loss as the temperature decreases from 20˚C to 5˚C, then from 5˚C to -10˚C, and finally from -10˚C to -25˚C. Hence, as the temperature increases, heat loss increases progressively.

Therefore, understanding the potential temperature drop in a given situation helps in designing clothing that will effectively protect a person in such an environment. This information is important in determining the requirements needed when designing cold-weather clothing.

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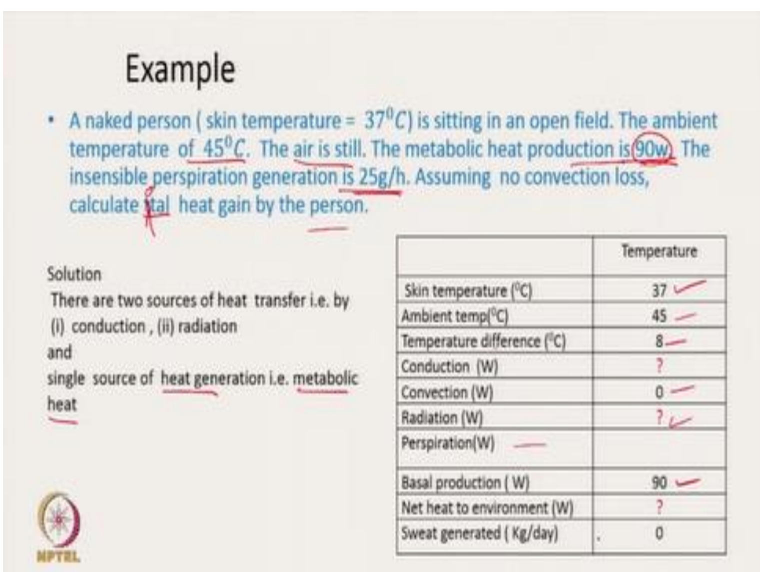

For example, a naked person is sitting in an open field with a skin temperature of 37˚C, assuming this as skin temperature. Typically, the core body temperature is around 30˚C, while the skin temperature is about 34˚C. In this case, the ambient temperature is 45˚C, indicating the person is in a very hot environment. The air is still, and the metabolic heat production is 90 W because the person is sitting idle.

The insensible perspiration generation is 25 g/h. Assuming no convection loss, the total heat gain can be calculated in the following steps. The solution is that there are two sources of heat transfer: conduction and radiation. Convective heat transfer is not there because air is still. There is a single source of heat generation, that is metabolic heat generation. The body is generating 90 watts of heat. In addition, the body will absorb heat from the surrounding environment, as the ambient temperature, which is 45˚C, is higher than the skin temperature.

There are two different modes by which the body receives heat: conduction and radiation. The data provided is also presented in this table. The skin temperature is 37˚C, while the ambient temperature is 45°C, resulting in a temperature difference of 8˚C. Heat transfer through conduction and radiation has to be calculated to get the net heat gain by the person.

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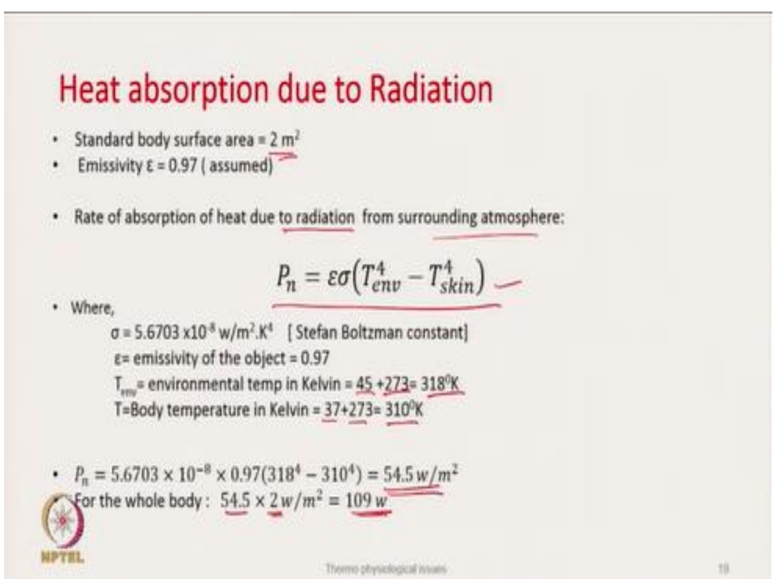

The standard body surface area is usually 2 m^2. Though it can vary from person to person depending on their size and height, a standard value of approximately 2 m^2 is often used. The emissivity of the skin has been assumed to be 0.97. The rate of heat absorption due to radiation from the surroundings can be determined using the following equation: '$P_n = \varepsilon\sigma(T_{env}^4 - T_{skin}^4)$'.

Both environmental temperature and skin temperature need to be in Kelvin. To convert, the environmental temperature is '45 + 273 = 318 K', and the body temperature is '37 + 273 = 310 K'. After substituting the environmental temperature (318 K) and skin temperature (310 K), along with the emissivity of 0.97, we obtain a value of 54.5 W/m^2. For the entire body, this value is multiplied by 2 m^2, which is 109 W, which is the heat that the body will receive through radiation mode from the surrounding air.

So, in this case, the air acts as the source of heat, transferring heat from the surrounding air to the human body.

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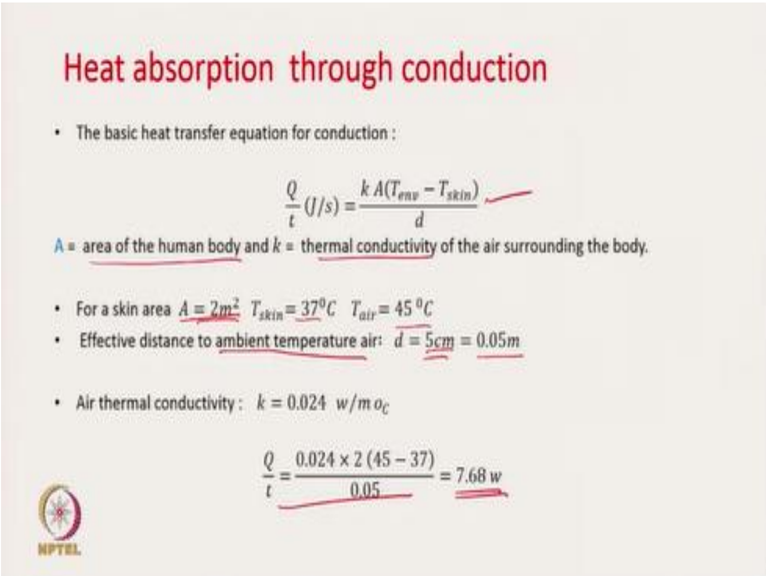

Next is heat absorption through conduction. Since the air is in direct contact with the human body, heat transfer from the air to the body through conduction is calculated by the following equation: '$\frac{Q}{t} = \frac{kA(T_{env} - T_{skin})}{d}$' where '$k$' is the thermal conductivity, 'A' is the area of the human body and 'd'is the thickness of the air layer. The effective distance of ambient temperature air is considered around 5 cm or 0.05 m, and using the standard skin area of 2 m^2, substituting the given skin temperature and environmental temperature into the conduction heat transfer equation.

It is found that the calculated heat transfer through conduction amounts to 7.68 W. In comparison, the heat received from radiation was calculated to be 109 watts. So, while the body absorbs around 8 watts through conduction, it receives a significantly larger amount of 109 W through radiation.

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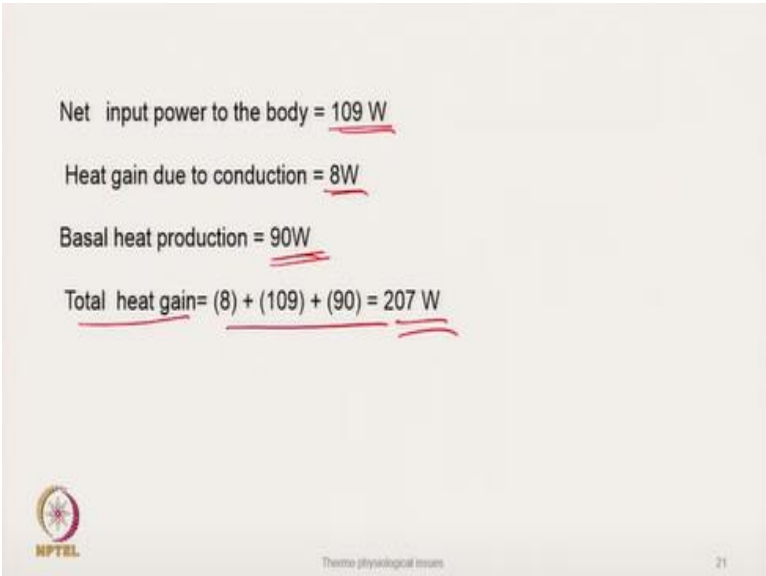

Therefore, the net heat input to the body consists of 109 watts from radiation, 8 watts from conduction, and 90 watts from basal heat production due to body metabolism. The total heat gain by the body is the sum of these three: '109 W + 8 W + 90 W = 207 W'.

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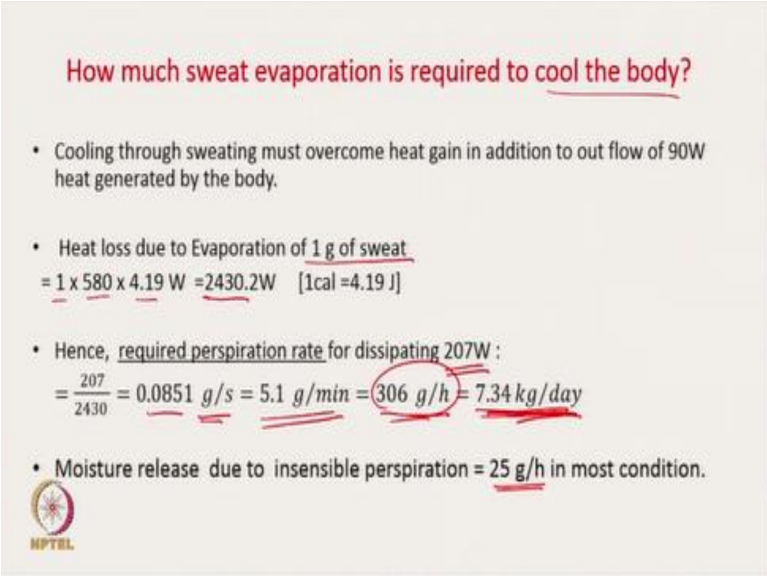

To make the person feel comfortable, he has to generate sweat, which has to evaporate and cool down the body. This means that the heat generated needs to be lost through the sweating mechanism. The heat loss due to the evaporation of 1 gram of sweat is 2430 joules derived from '1 x 580 x 4.19 W'.

The required perspiration rate to dissipate 207 W of heat is calculated as '$\frac{207}{2430} = 0.0851\ g/s$', which is equal to 5.1 g/min, 306 g/h, or 7.34 kg/day. Thus, the person would need to generate 7.34 kg of sweat per day to dissipate the heat, which far exceeds the normal human capacity for sweat production.

Since the required sweat rate to cool the body in this scenario is 7.34 kg per day, it is obvious that the body cannot generate enough sweat to cool down effectively. If the individual stays in that environment for an extended period, their body will overheat, which could ultimately lead to fatal consequences. To prevent this, the person can move to a cooler environment where the heat absorption rate is reduced.

To conclude, it is considered moisture release due to insensible perspiration, estimated earlier at 25 g/h. The required sweat rate for effective heat dissipation in this scenario (306 g/h) far exceeds what the body can manage. As discussed, even with both sensible and insensible perspiration, the body cannot produce enough sweat to maintain a safe temperature in such conditions. Thank you.