Textile Product Design and Development
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Lecture - 15
Thermal Properties of Clothing

This lecture focuses on the thermal properties of clothing. Various factors that affect the thermal behaviour of clothing are listed on the below slide.

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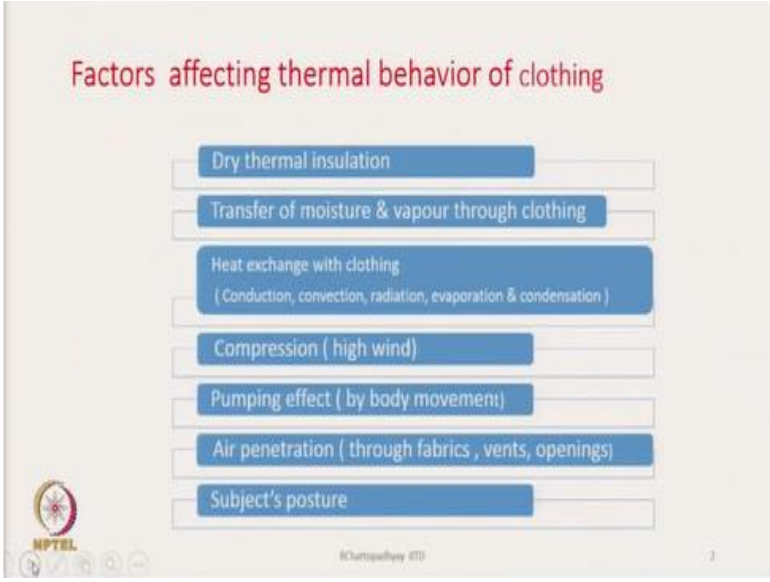

A list of factors is provided in the flow chart. Dry thermal insulation refers to the insulation value of clothing in its dry state. When the clothing becomes wet, the insulation value changes, as water is a good conductor of heat. This reduces the insulation capacity of the clothing. Therefore, dry insulation is crucial. The second factor is the transfer of moisture and vapour through the clothing. The third factor is the heat exchange between the clothing and the environment.

It includes conduction, convection, radiation, evaporation, and the potential for condensation, all of which are critical to understanding the thermal behaviour of clothing. Another important factor is compression, particularly due to high wind. When going outside and encountering strong winds, the wind compresses the fabric. This compression can significantly alter the insulation value of the clothing.

Next is the pumping effect caused by body movement. When we move while wearing clothing, the dynamic state creates a bellowing effect, which is important to consider. Another key factor is air penetration through the fabric and vents. Clothing often has multiple openings, some of which are adjustable, allowing air to enter through these openings. This allows for the exchange between environmental air and the air next to the skin.

Air can penetrate depending on the location of these openings, such as vents like collars. If the collars are not tightly buttoned, they act as vents. Similarly, in shirts, there are openings that function as vents. Through these openings, there is potential for air exchange and penetration. Even if the fabric used to make the clothing is very thin or has an open construction, air can still penetrate when the wind blows. These factors also influence the thermal behaviour of the clothing. Additionally, the subject's posture plays a role.

Certain postures may apply pressure to specific parts of the clothing, leading to changes in fabric thickness. Posture can also cause changes in the openings of the fabric, further affecting the thermal behaviour. These are some of the key factors that influence the intrinsic insulation properties of the fabric itself. Additionally, it depends upon the design of the clothing and the way the person works with it. This determines the overall thermal behaviour of the clothing.

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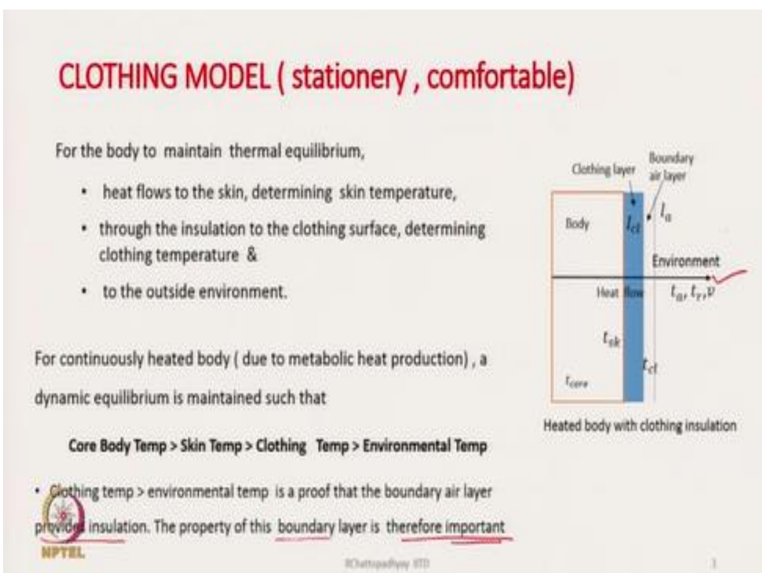

The next aspect to consider is the clothing model in a stationary state, in a comfortable posture. The diagram on the right-hand side illustrates this concept. The rectangle represents the body, while the blue area signifies the clothing layer. The arrows indicate the direction of heat flow, which is moving from the body to the environment. In this case, the environmental temperature is less than the body temperature.

In the diagram, 't_{Core}', 't_{sk}' and 't_{cl}' represent the temperatures of the body core, skin, and clothing, respectively. The parameters, 't_a', 't_r' and 'v' are related to the environmental conditions. For the body to maintain thermal equilibrium, heat flows from the core to the skin, which in turn determines the skin temperature. Heat will then flow through the insulation to the clothing surface, as the clothing acts as an insulator.

Since the clothing is in contact with the skin, heat transfers from the skin through the clothing to its outer surface, determining the clothing temperature. From there, heat will continue to flow into the environment. For a continuously heated body, such as the human body, heat is consistently produced due to metabolic activity.

A dynamic equilibrium is maintained where the core body temperature is greater than the skin temperature, which in turn is greater than the clothing temperature, and the clothing temperature is higher than the environmental temperature. In this scenario, we assume the environmental temperature is lower than the body core and skin temperatures.

The clothing temperature is greater than the environmental temperature, proving that the boundary air layer provides some insulation. The reason the clothing temperature is higher than the environmental temperature is that the adjacent boundary layer of air next to the clothing enhances the overall insulation value. The properties of this boundary layer are crucial for understanding thermal behaviour.

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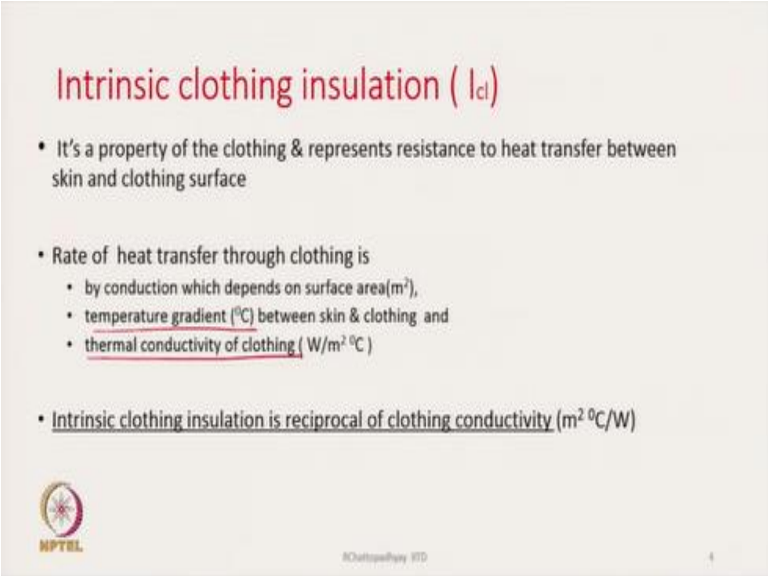

Intrinsic clothing insulation refers to the inherent property of the clothing material that indicates its resistance to heat transfer between the skin and the clothing surface. The rate of heat transfer through the clothing can occur through various means. One of these methods is conduction, which depends on factors such as surface area and the temperature gradient. The rate of heat loss through conduction also depends on the thermal conductivity of the clothing material.

Thus, the amount of heat lost through conduction is influenced by the contact surface area, the temperature gradient, and the thermal conductivity. Consequently, intrinsic clothing insulation is the reciprocal of clothing conductivity because the conductivity and insulation are physically reciprocal to each other.

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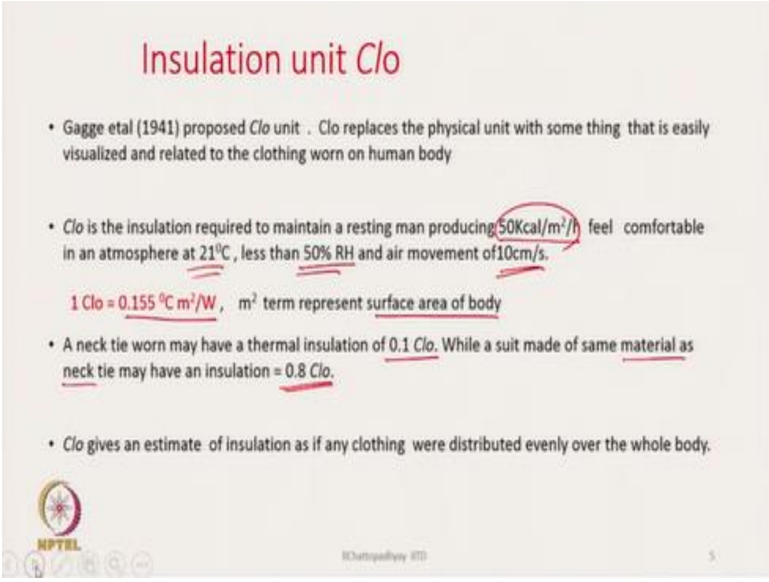

The unit of insulation for clothing material is ‘Clo’. Gagge proposed the Clo unit, which replaces the physical unit with something easily visualized and related to the clothing worn by the human body. Clo is the insulation required to maintain a resting man producing 50 cal/m^2/h feel comfortable in an atmosphere at 21˚C, with humidity less than 50% and low air movement of 10 cm/s.

In such an environment, the clothing material required for a person to feel comfortable is a kind of subjective assessment. For example, if a person is asked to remain in an atmosphere where the temperature is 21˚C, the relative humidity is less than 50%, and air movement is minimal, in this situation, the minimum amount of clothing needed for a person to feel comfortable while producing 50 kcal/m^2/h is referred to as 1 Clo. Researchers have attempted to relate this to the actual insulation value.

Specifically, 1 Clo is equivalent to 0.155 ˚Cm^2/W, where the square metre term represents the surface area of the human body. A necktie typically has a thermal insulation value of 0.1 Clo, while a suit made from the same material may have an insulation value of 0.8 Clo. This difference arises because a necktie covers a very small body area, whereas a suit covers a larger portion. So, Clo value is directly related to the clothing and the area it covers on the body. Clo estimates insulation as if clothing were distributed evenly over the whole body.

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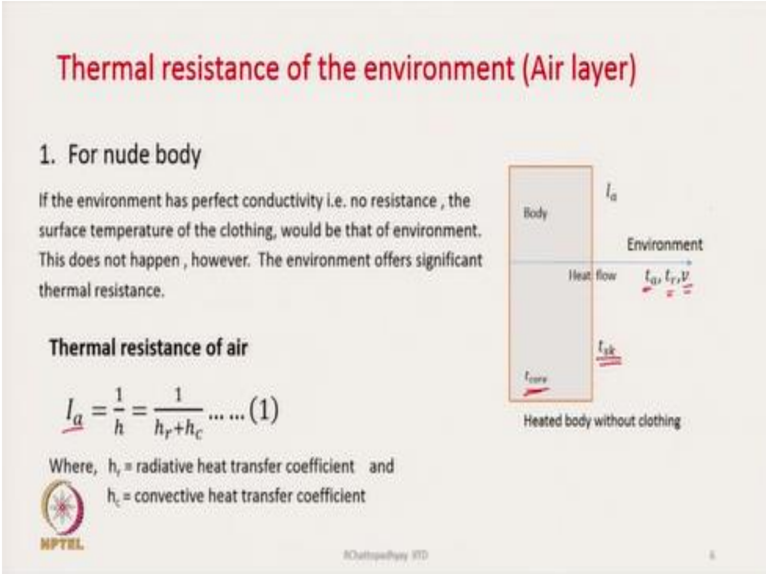

Next is the thermal resistance of the environment, specifically the air layer. If the environment has perfect conductivity, i.e., no resistance, the surface temperature of the clothing would be that of the environment because the surface of the clothing is in contact with the outside air. However, the environment offers significant thermal resistance, which means that the boundary layer of air gives a certain resistance. In this case, a nude body with heat flow occurs, as depicted in the diagram. Even without clothing, the air around the body offers thermal resistance. 't_a', 't_r' and 'v' represents air temperature, mean radiant temperature and air velocity, respectively and 't_{sk}' is the skin temperature, and 't_{Core}' is the body core temperature.

These symbols represent the various parameters involved in heat transfer. The thermal resistance of air is calculated as '$I_a = \frac{1}{h}$', where '$h = h_r + h_c$'. In this equation, 'h_r' represents the radiative heat transfer coefficient and 'h_c' is convective heat transfer coefficient. Since insulation is the reciprocal of conductivity, '$I_a = \frac{1}{h}$'. In this equation, 'h' reflects the combined effects of radiation and convection on heat transfer from the body to the environment.

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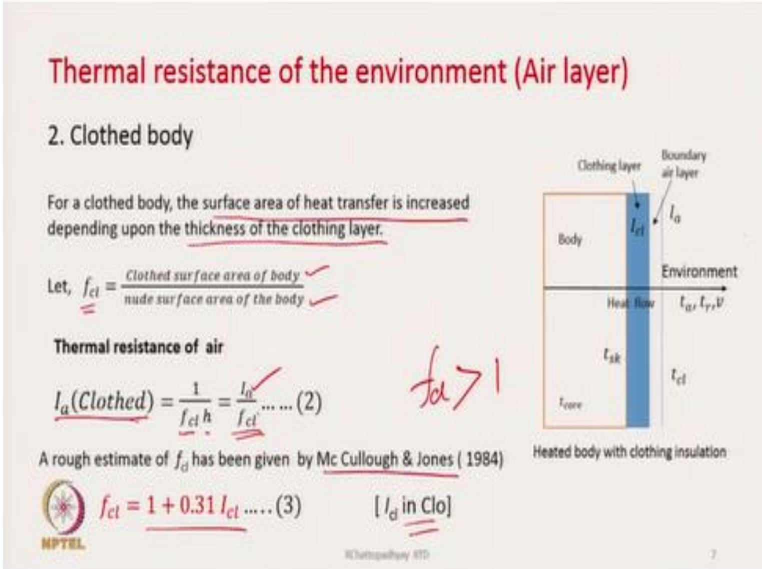

When the body is covered by a layer of clothing, as shown in the diagram on the right, the thermal resistance of the environment changes. The blue part in the diagram indicates the clothing layer. When a body part is naked, it has a certain surface area exposed to heat transfer. However, when that part is covered by fabric, the surface area of heat transfer increases due to the additional fabric layer. As a result of adding the clothing layer, the total surface area of the boundary air layer around the clothed body increases. 'f_{cl}' is defined as the ratio of the clothed surface area to the nude surface area of the body.

Since the clothed surface area is always slightly larger than the nude surface area, 'f_{cl}' will always be greater than 1. The thermal resistance of the air for a clothed body is given by

$$I_a = \frac{1}{f_{cl}\,h}$$

Previous equation was,

$$\frac{1}{h}$$

but the body here dimension has changed because of the layer of clothing. the thermal resistance of the air for the clothed body becomes,

$$I_a(clothed) = \frac{I_a}{f_{cl}}$$

Because,

$$\frac{1}{h} = I_a$$

where 'I_a' is the insulation value of the air without any clothing.

The empirical relationship for 'f_{cl}' is given by researchers, and it states that '$f_{cl} = 1 + 0.31I_{cl}$' where 'I_{cl}' is the intrinsic clothing insulation. Hence, if 'f_{cl}' is known, 'I_a' value of the clothed body can be calculated. Since 'f_{cl}' is always greater than 1, the thermal resistance of the air layer in the clothed state '$I_a(clothed)$' becomes less than the thermal resistance of the air layer in the nude state 'I_a'. Hence, by putting a layer of clothing around the body, the boundary air layer resistance decreases because the surface area has increased.

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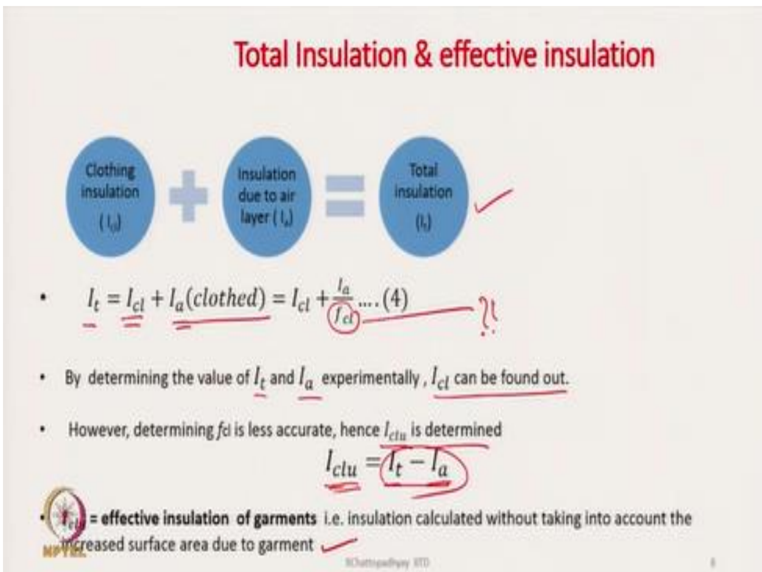

Next is the total insulation and effective insulation. The total insulation is the summation of clothing insulation and insulation due to air. The formula for the total insulation is given by,

$$I_t = I_{cl} + I_a(clothed)$$

As 'I_a' is in the clothed state, it becomes

$$I_t = I_{cl} + \frac{I_a}{f_{cl}}$$

By determining the value of 'I_t' and 'I_a' experimentally, which is done with the help of manikin, 'I_{cl}' value can be found. However, determining 'f_{cl}' is less accurate hence, 'I_{clu}' is determined. 'I_{clu}' is the difference of 'I_t' and 'I_a' which is expressed as,

$$I_{clu} = I_t - I_a$$

This is because 'f_{cl}' value is a bit difficult to determine, hence the formula, which is an empirical formula.

The total value of the clothing when the 'f_{cl}' is not taken into account, 'I_{clu}', therefore, is called effective insulation of garments. This insulation is calculated without considering the increased surface area due to the garment. i.e., 'f_{cl}' is not taken into account. Ignoring this, the clothing insulation value can be determined by the difference between total clothing resistance 'I_t' and only the air layer resistance 'I_a' that is known as 'I_{clu}'.

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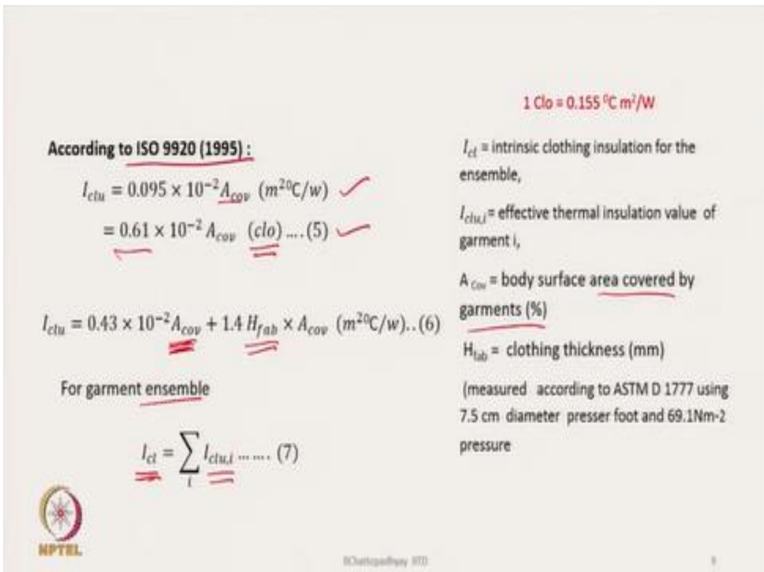

The 'I_{clu}' value has also been determined through experimentation, and empirical relationships have been found. One such equation is stated according to ISO 9920 (1995), and the corresponding equation, when converted to 'Clo' values are also stated. To convert 'I_{clu}' into *Clo* units, the value must be divided by 0.155. Another equation expresses

$$I_{Clu} = 0.43 \times 10^{-2} A_{Cov} + 1.4\ H_{fab} \times A_{Cov}$$

where 'A_{Cov}' refers to the body surface area covered by the garment. For example, a full outfit typically covers almost the entire part of the body, whereas a glove covers only the palms.

So, there are various types of garments, and the body area they cover will vary depending upon the garment type. Equation 6 considers both the percentage of body surface area covered 'A_{Cov}' and the fabric thickness 'H_{fab}'. In contrast, the previous Equation 5 does not account for fabric thickness when determining clothing resistance. Equation 6 addresses this by incorporating the thickness of the clothing.

These are empirical equations derived through experimentation. These equations are also used to estimate the resistance of the clothing value without performing actual measurements. For a garment ensemble, when a person wears multiple garments together, the overall insulation value of the ensemble can be determined. The 'I_{cl}' for the ensemble is the sum of the individual '$I_{clu,i}$' values, which represent the insulation of each garment.

A person may wear inner clothing, a shirt, and additional layers like jackets, sweaters, trousers, or socks. For example, if 8 to 10 garments make an ensemble, then the sum of the effective thermal insulation of each garment ($I_{clu,i}$) is equal to the total insulation value of the entire outfit (I_{cl}).

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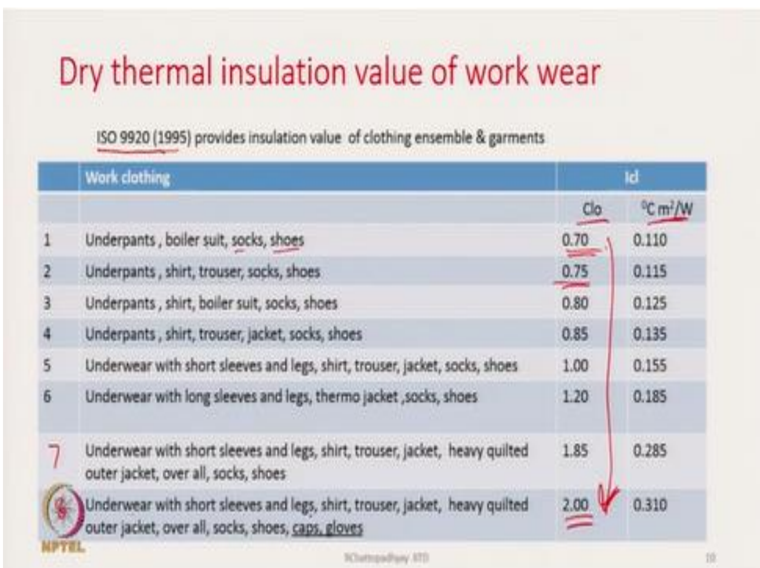

	Work clothing	Icl	
		Clo	°C m²/W
1	Underpants, boiler suit, socks, shoes	0.70	0.110
2	Underpants, shirt, trouser, socks, shoes	0.75	0.115
3	Underpants, shirt, boiler suit, socks, shoes	0.80	0.125
4	Underpants, shirt, trouser, jacket, socks, shoes	0.85	0.135
5	Underwear with short sleeves and legs, shirt, trouser, jacket, socks, shoes	1.00	0.155
6	Underwear with long sleeves and legs, thermo jacket, socks, shoes	1.20	0.185
7	Underwear with short sleeves and legs, shirt, trouser, jacket, heavy quilted outer jacket, over all, socks, shoes	1.85	0.285
8	Underwear with short sleeves and legs, shirt, trouser, jacket, heavy quilted outer jacket, over all, socks, shoes, caps, gloves	2.00	0.310

This table presents 'I_{cl}' values in both Clo units and °C m²/W, based on ISO 9920 standards. The values were measured for various combinations of ensembles. These standards serve as a guide when designing an ensemble for a specific environment. For example, if someone wears underpants, a boiler suit, socks, and shoes, the total Clo value will be approximately 0.70. If someone wears underpants, a shirt, trousers, socks, and shoes, the total Clo value will be 0.75. This table represents different combinations of garments and the corresponding Clo values in increased order.

For example, a combination with a Clo value of 2 would include underwear, short sleeves and legs, a shirt, trousers, a jacket, a heavy quilted outer jacket, socks, shoes, a cap, and gloves. When a person wears the ensemble, the total Clo value reaches 2. This value represents the sum of the individual Clo values of each garment.

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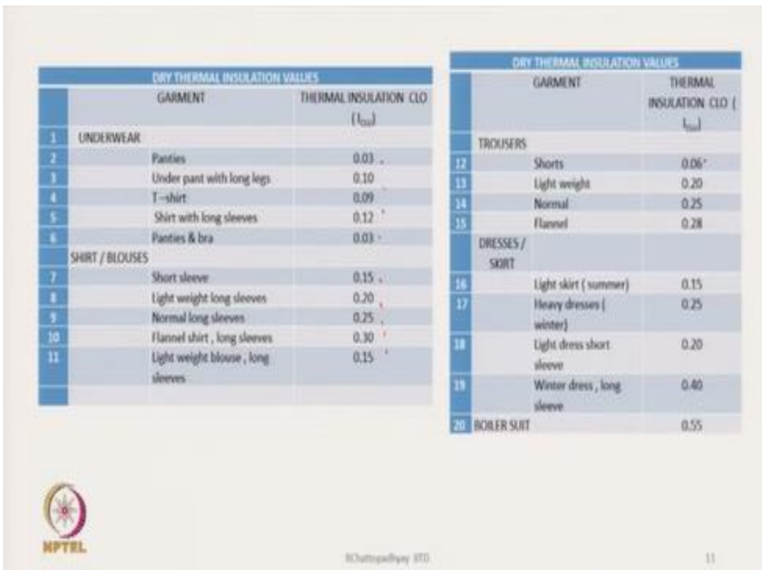

DRY THERMAL INSULATION VALUES

	GARMENT		THERMAL INSULATION CLO (I_{clu})
1	UNDERWEAR		
2		Panties	0.03
3		Under pant with long legs	0.10
4		T-shirt	0.09
5		Shirt with long sleeves	0.12
6		Panties & bra	0.03
	SHIRT / BLOUSES		
7		Short sleeve	0.15
8		Light weight long sleeves	0.20
9		Normal long sleeves	0.25
10		Flannel shirt , long sleeves	0.30
11		Light weight blouse , long sleeves	0.15

DRY THERMAL INSULATION VALUES

	GARMENT		THERMAL INSULATION CLO (I_{clu})
	TROUSERS		
12		Shorts	0.06
13		Light weight	0.20
14		Normal	0.25
15		Flannel	0.28
	DRESSES / SKIRT		
16		Light skirt (summer)	0.15
17		Heavy dresses (winter)	0.25
18		Light dress short sleeve	0.20
19		Winter dress , long sleeve	0.40
20	BOILER SUIT		0.55

The Clo values for the individual garments are listed here. The Clo values for various types of underwear, shorts, blouses, and shirts are provided. Similarly, the Clo values for trousers and dresses are also listed. These standards established by ISO offer valuable insights into the Clo values of individual garments.

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Similarly, the Clo values for sweaters and jackets are provided. For instance, a typical sweater has a Clo value of around 0.28. Thin sweaters are rated at 0.20, while thick sweaters have a value of 0.35. Sweaters are categorized into three types: thin (0.20), normal (0.28), and thick (0.35). However, the details regarding the materials used, whether they are wool, polyester, or blends, are not mentioned. Typical Clo values have been provided, indicating that a thick sweater typically has a Clo value of 0.35.

Similarly, Clo values for various types of jackets are also listed. For example, socks have a Clo value of 0.02. We often prefer to wear longer socks in winter, as they cover a larger portion of the leg. In summer, we tend to wear shorter, ankle-height socks to facilitate faster heat exchange between the skin and the environment, as we don’t want to increase insulation. various types of socks and their corresponding Clo values are provided. thick ankle socks have a value of 0.1, while nylon stockings are rated at 0.03.

For footwear, thin-soled shoes have a Clo value of approximately 0.02, thick-soled shoes are around 0.04, and boots can reach up to 0.10. Gloves typically have a Clo value of 0.05. These tables provide valuable insights when designing an ensemble for a person. Selecting different types of garments and knowing their individual Clo values are added together to determine the total Clo value for the ensemble.

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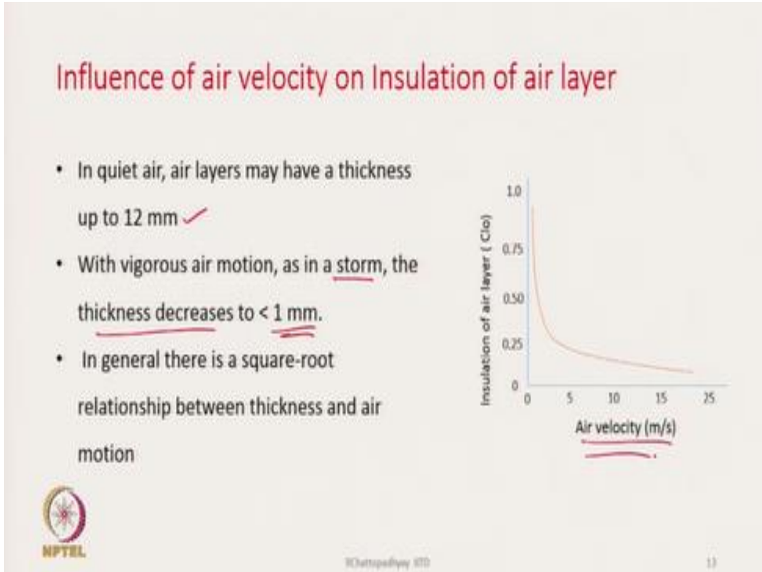

Next comes the influence of air velocity on the insulation of the air layer. The boundary layer of air, if it remains still, provides a certain level of insulation. However, as air velocity increases, the situation changes. In quiet air, the boundary air layer can be as thick as 12 mm, but with vigorous air movement, such as during a storm, the thickness can decrease to less than 1 mm.

Generally, there is a square root relationship between thickness and air motion. A graph on the right-hand side shows air velocity and insulation of the air layer and how it is declining.

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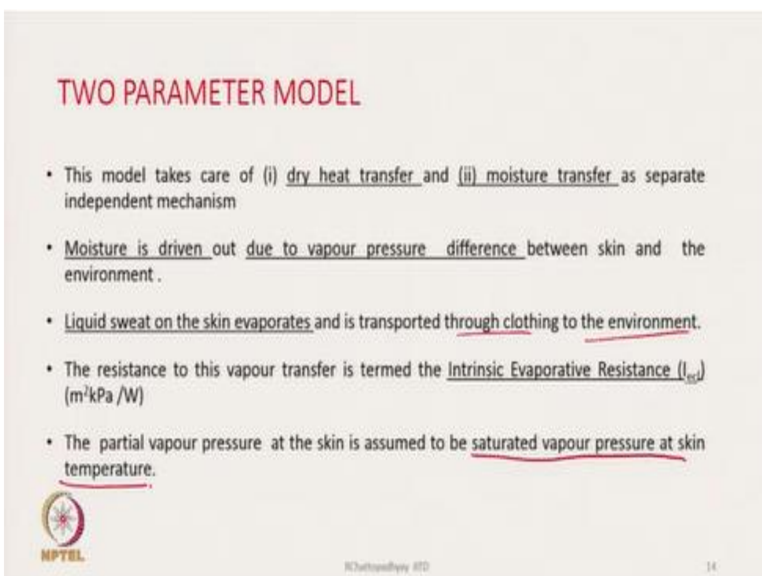

Next is the two parameter model. This model considers dry heat transfer and moisture transfer as separate independent mechanisms. The human body generates both dry heat and moisture; moisture transfer is equally important since it removes body heat. Additionally, the sensation of comfort depends on whether moisture transfer through the clothing is occurring effectively. While developing a model, both heat and moisture transfer must be considered.

Heat is driven out due to temperature differences, while moisture is driven by vapour pressure differences. This vapour pressure difference acts as the driving force. Moisture cannot move away from the skin without a difference in vapour pressure between the skin and the environment. Liquid sweat on the skin evaporates and is transported through the clothing to the environment. When sweat is on the skin, and a layer of fabric covers it, the sweat gradually evaporates, and the vapour passes through the fabric.

If there is excessive sweat, it may also be transported into the fabric through wicking action. The resistance to this vapour transfer is referred to as intrinsic evaporative resistance. The partial vapour pressure at the skin is assumed to be the saturated vapour pressure at skin temperature. In this model, two key factors have to be addressed. They are dry heat and moisture. The primary driver of heat transfer is the temperature difference.

Similarly, moisture moves from the skin to the environment due to the vapour pressure difference, which is equally important. When the outside relative humidity is very low, the vapour pressure difference becomes quite high. This is typically the case in summer, especially in dry regions, where high temperatures and low humidity prevail. In such conditions, body moisture can be quickly transported through the fabric due to the large vapour pressure difference.

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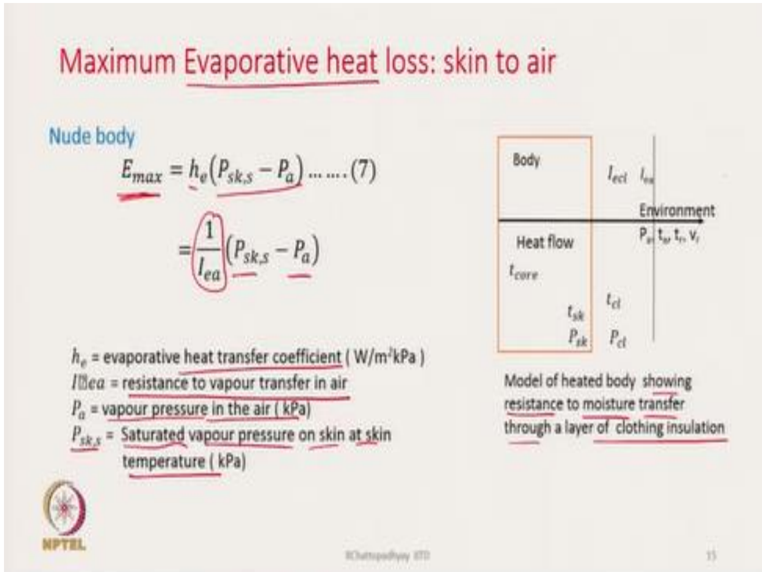

Maximum evaporative heat loss from the skin to the air refers to the heat lost through the evaporation of moisture, not dry heat loss. For a nude body, the maximum evaporative heat loss can be represented as

$$E_{max} = h_e\left(P_{sk,s} - P_a\right)$$

where '$P_{sk,s}$' is the saturated vapour pressure on the skin at skin temperature and 'P_a' is the vapour pressure in the air or the vapour pressure in the environment.

The vapour pressure next to the skin, '$P_{sk,s}$' represents the saturated vapour pressure at the skin temperature, 'h_e' is the evaporative heat transfer coefficient and

$$\frac{1}{h_e} = I_{ea}$$

where 'I_{ea}' is resistance to vapour pressure transfer. Therefore, the maximum evaporative heat loss, 'E_{max}' is equal to

'$h_e\left(P_{sk,s} - P_a\right)$' or '$\frac{1}{I_{ea}}\left(P_{sk,s} - P_a\right)$'

This diagram illustrates a model of the heated body, showing the resistance to moisture transfer through a layer of clothing insulation. It is important for us to determine the values of $P_{sk,s}$ (saturated vapour pressure at skin temperature) and P_a (vapour pressure in the environment).

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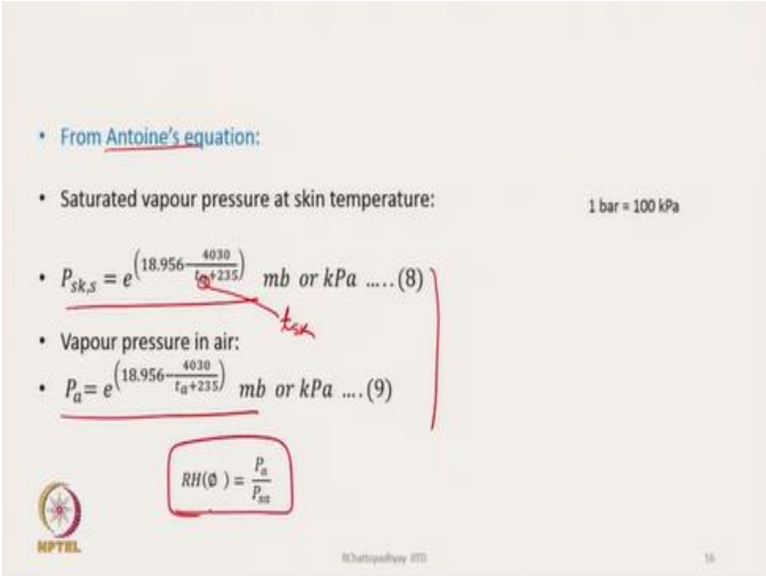

From the equation developed by the researcher Antoine, the saturated vapour pressure '$P_{sk,s}$' at skin temperature can be given by this equation,

$$P_{sk} = e^{\left(18.956 - \frac{4030}{t_{sk}+235}\right)}$$

while the vapour pressure of the air 'P_a' can be determined by another equation. Both equations have similar forms, allowing us to find these values based on the skin temperature.

The vapour pressure in the air 'P_a' can be calculated using the equation

$$P_a = e^{\left(18.956 - \frac{4030}{t_a+235}\right)}$$

These equations allow us to determine the vapour pressures at the skin and atmosphere. The two vapour pressures are related by relative humidity

$$RH = \frac{P_a}{P_{sa}}$$

By knowing these values, the maximum evaporative heat loss can be calculated (E_{max}).

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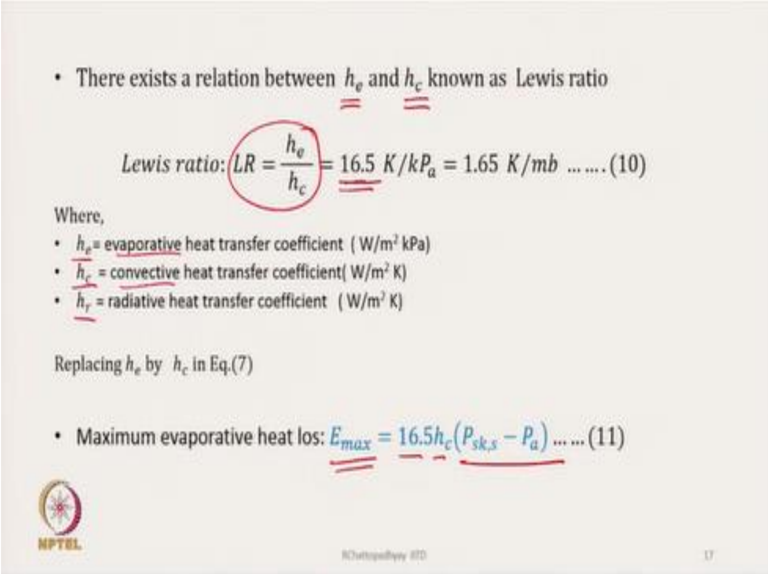

An interesting relationship exists between the evaporative heat transfer coefficient 'h_e' and the convective heat transfer coefficient 'h_c'. The ratio of these two coefficients, known as the Lewis ratio, is given by the formula

$$LR = \frac{h_e}{h_c}$$

This relationship is useful because using the convective heat transfer coefficient can effectively estimate the evaporative heat transfer coefficient.

Since we know that the ratio of the evaporative heat transfer coefficient 'h_e' to the convective heat transfer coefficient 'h_c', which is 16.5, 'h_e' can be expressed as

$$h_e = 16.5\ h_c$$

By substituting this into the equation for maximum evaporative heat transfer,

$$E_{max} = h_e(P_{sk,s} - P_a)$$

This equation allows us to calculate the maximum evaporative heat loss, which helps us understand how effectively moisture is transferred away from the skin through the clothing.

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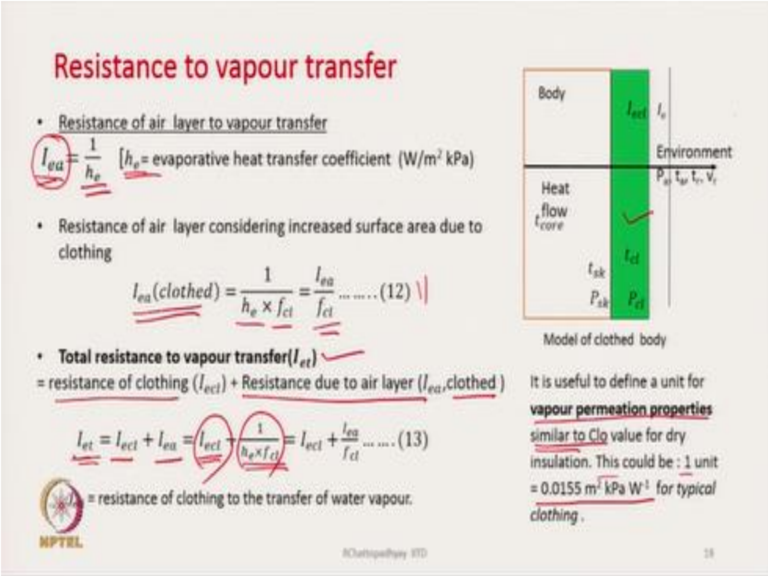

As discussed, there is a resistance to heat transfer, as well as resistance to vapour transfer. Similarly, air has a resistance to dry heat transfer as well as resistance to vapour transfer. If 'h_e' is the evaporative heat transfer coefficient, then the resistance of the air layer to vapour transfer is given by

$$I_{ea} = \frac{1}{h_e}$$

in which 'I' stands for insulation, 'e' is evaporative heat transfer and 'a' is air. There is an indirect relationship between these 'h_e' and 'I_{ea}'.

The resistance of the air layer to vapour transfer will be exactly the same as in the case of dry heat transfer. The equation becomes,

$$I_{ea}(clothed) = \frac{1}{h_e \times f_{cl}}$$

where 'f_{cl}' accounts for the increased surface area due to clothing. 'I_{ea}' is resistance to air layer to vapour transfer without considering the increased surface area.

This equation is for the naked body. Equation 12 represents the resistance of the air layer considering increased surface area due to a clothed body. The green rectangle in the diagram represents the clothing material. It also offers some resistance to heat flow and transfer of moisture vapour, similar to resistance offered by air. Clothing also contributes to the overall resistance to vapour transfer.

Therefore, the total resistance can be calculated by summing the intrinsic resistance of the clothing material with the resistance due to the air layer, denoted as '$I_{ea}(clothed)$'. This combined resistance represents the total resistance to vapour transfer of the air from the body to the environment when the body is covered by clothing. The total resistance to vapour transfer, denoted as 'I_{et}', where 't' stands for total, is the sum of the intrinsic resistance of the clothing (I_{ecl}) and the resistance of the air layer (I_{ea}).

This can be expressed as

$$I_{et} = I_{ecl} + I_{ea}$$

This calculation helps us determine the overall resistance to vapour transfer when multiple layers of clothing cover the human body. Establishing a unit for vapour permeation properties is beneficial, similar to the Clo value for dry insulation. This unit can be defined as 1 unit of vapour permeation, corresponding to a value of 0.0155 m^2kPaW^{-1} for typical clothing.

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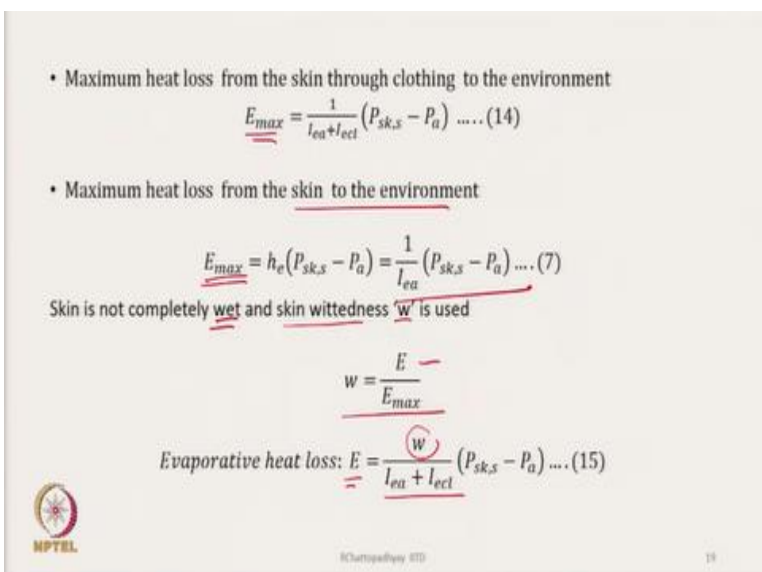

The maximum heat loss from the skin through clothing to the environment is denoted as,

$$E_{max} = \frac{1}{I_{ea} + I_{ecl}}(P_{sk,s} - P_a)$$

Maximum heat loss from skin to environment from equation 7 is changed to equation 14. The key difference between the two equations lies in the incorporation of the total resistance to vapour transfer, which is '$I_{ea} + I_{ecl}$'. Therefore, 'E_{max}' for a naked body, where only a layer of air is present, can be distinguished from 'E_{max}' in the clothed condition, representing the evaporative heat transfer in both scenarios.

In certain situations, the skin may not be completely wet, leading to the concept of skin wettedness, denoted as 'w', which is defined by

$$w = \frac{E}{E_{max}}$$

One is the maximum possible value of 'w' provided the entire skin is covered by liquid sweat. The value of 'w' can vary, reflecting different levels of skin wittedness at any given time. The evaporative heat loss 'E' can now be expressed in terms of the skin wettedness factor 'w' as follows,

$$E = \frac{w}{I_{ea} + I_{ecl}} \left(P_{sk,s} - P_a\right)$$

When the skin is completely wet, 'w' will equal 1. In cases where the skin is not fully saturated, 'w' will take on a value less than 1, indicating varying degrees of wettedness, such as 70%, 30%, or 80%, depending on the amount of moisture on the skin.

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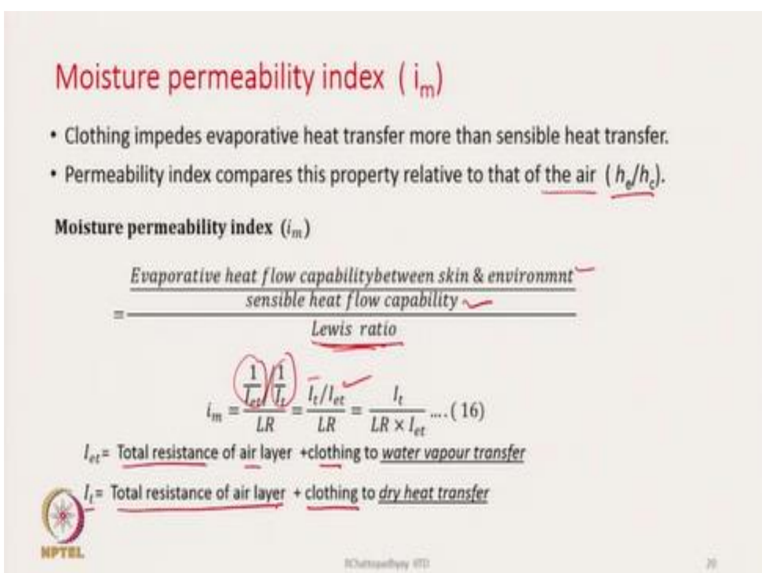

Two primary mechanisms were discussed: dry heat transfer through clothing and evaporative heat transfer through clothing. Another important concept is the moisture permeability index. Clothing impedes evaporative heat transfer more than sensible heat transfer. The permeability index compares this property relative to that of air. Moisture permeability index is the ratio of evaporative heat flow capability between skin and environment by sensible heat flow capability to the Lewis ratio.

Lewis ratio is the ratio of the evaporative heat transfer coefficient (h_e) to the convective heat transfer coefficient (h_c). In the numerator, a ratio representing the evaporative heat flow capability between the skin and the environment, compared to the sensible heat flow capability. The moisture permeability index (i_m) is expressed as

$$i_m = \frac{\frac{1}{I_{et}}\frac{1}{I_t}}{LR}$$

In other words, it is

$$i_m = \frac{I_t \ / \ I_{et}}{LR}$$

where 'I_t' is the total resistance of the air layer and clothing to dry heat transfer, 'e' stands for evaporative heat transfer and 'I_{et}' is the total resistance of the air layer and clothing to water vapour transfer. 'I' represents the insulation, which essentially means resistance.

The Lewis ratio applies when no clothing between the skin and the environment exists. Therefore, the moisture permeability index becomes,

$$i_m = \frac{I_t}{LR \ X \ I_{et}}$$

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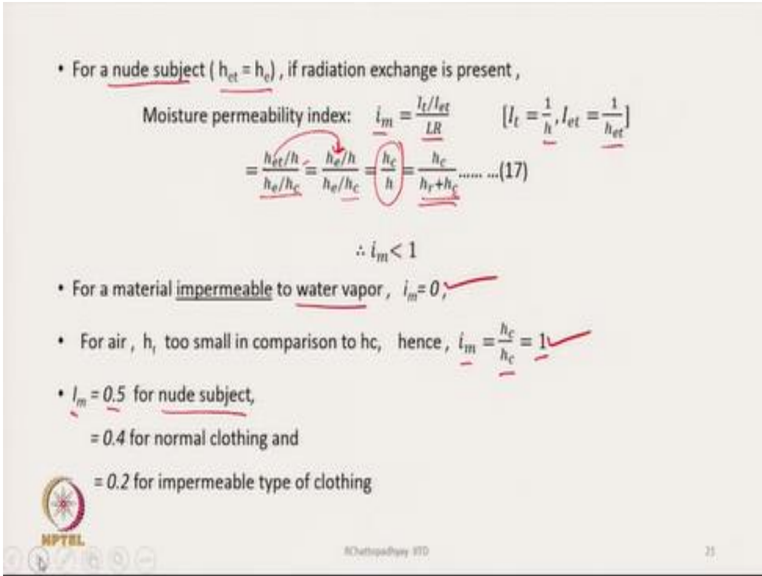

For a nude subject, 'h_{et}' and 'h_e' are the same because no clothing is involved, so both apply only to the air. Hence, without clothing, '$h_{et} = h_e$' are identical. Hence, the moisture permeability index becomes

$$\frac{I_t}{LR\ X\ I_{et}}$$

While

$$\text{'}I_t = \frac{1}{h}\text{' and '}I_{et} = \frac{1}{h_{et}}\text{'}$$

i.e., the resistance values are replaced by heat transfer coefficient values.

Hence, the numerator is substituted by '$\frac{h_e}{h}$' because they are the same for nude persons and denominators by '$\frac{h_e}{h_c}$'. Hence,

$$i_m = \frac{h_c}{h}$$

'h' is the total heat transfer coefficient, which is the sum of the heat transfer coefficient due to radiation and the transfer coefficient due to convection, i.e., '$h = h_r + h_c$'. From equation 17, the moisture permeability index becomes

$$i_m = \frac{h_c}{h_r + h_c}$$

Mathematically, the numerator will always be less than the denominator.

Because the denominator has an additional term, 'h_r'. This means that 'i_m' value is always less than 1 as the numerator is less than the denominator. For a material impermeable to water vapour, '$i_m = 0$' and for air 'h_r' is too small compared to h_c. Hence, '$i_m = \frac{h_c}{h_c}$' which is equal to 1. The typical value of the moisture permeability index for a nude subject is 0.5, 0.4 for normal clothing and 0.2 for impermeable clothing.

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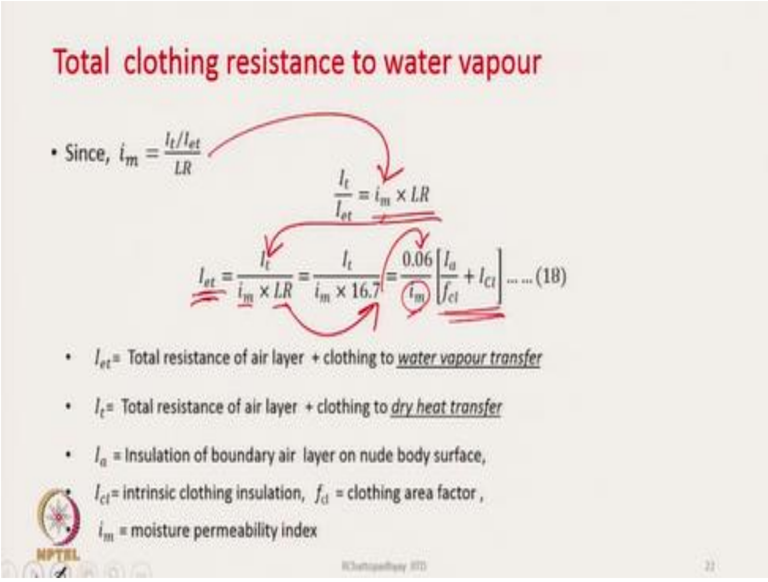

To find the total clothing resistance to water vapour, the equation of 'i_m' can be written as

$$\frac{I_t}{I_{et}} = i_m \times LR$$

This is simply derived from the previous equations. From here, we generate this new equation. By keeping 'I_{et}' on one side and substituting the value of 'LR' as 16.7 into this equation.

Equation 18 is not simply rewriting the previous one but introduces a new factor. There is '$\frac{1}{16.7}$' which becomes '$\frac{0.06}{i_m}$'. The equation for the total resistance of the clothing, including the air layer, is known as

$$I_t = \frac{I_a}{f_{cl} + I_{cl}}$$

Therefore, 'I_{et}' becomes this new equation, which is represented in equation 18.

The total evaporative heat transfer is thus linked to the permeability index. If the properties of the clothing material and the values of 'I_a', 'f_{cl}', 'I_{cl}' is known, the evaporative heat transfer coefficient can be calculated. The total clothing resistance to water vapour can be expressed as

$$I_{et} = \frac{0.06}{i_m}\left(\frac{I_a}{f_{cl} + I_{cl}}\right)$$

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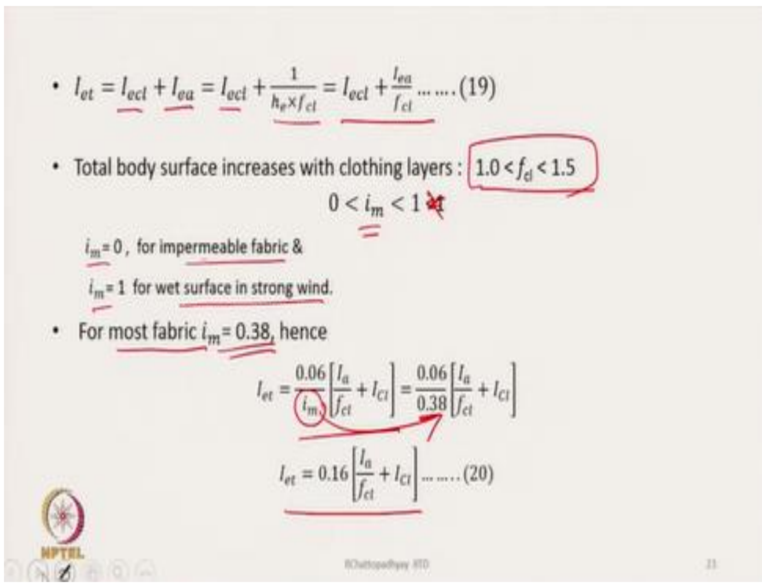

It can be further expressed as '$I_{et} = I_{ecl} + I_{ea}$' and therefore becomes

$$I_{et} = I_{ecl} + \frac{I_{ea}}{f_{cl}}$$

The total body surface area increases with the addition of clothing layers, which means 'f_{cl}' can vary within certain limits. 'f_{cl}' will always be greater than 1, typically ranging between 1 and 1.5. Additionally, the 'i_m' value, which represents the moisture permeability index, will always be less than 1, usually between 0 and 1. It is mentioned before that 'i_m' equals 0 for impermeable fabrics and 'i_m' equals to 1 for a wet surface in strong wind.

For most fabrics, 'i_m' is around 0.38, or close to 0.4. Therefore, 'I_{et}' for most fabrics becomes

$$\frac{0.06}{0.38}\left[\frac{I_a}{f_{c_l}} + I_{cl}\right]$$

The equation remains the same but simply replaces ‘i_m’ with its typical value for a normal fabric. Researchers have determined these values through experiments, which are the results obtained. Numerical problems will help reinforce these ideas. It is important to understand that dry heat is transferred from the human body to the environment through clothing.

Initially, it starts by calculating the resistance of the air and then the resistance of the clothing, combining both to determine the total resistance of the clothing to dry heat transfer. The same approach is followed for vapour transfer. First, the resistance of air to moisture transfer for a nude person, then, for a clothed person, is assessed, and the combined resistance to vapour transfer is determined. Since air and the fabric layer contribute to vapour transfer resistance, they must be considered together to calculate the total insulation value and the resulting heat loss, whether dry heat or evaporative heat loss. Thank you.