Course Name: Bioclimatic Architecture: Futureproofing with Simple and Advanced Passive Strategies

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Week: 03

Lecture 04

Thermal Comfort and Thermal Comfort Models

Hello students. So we have so far seen about climate, climate classification, the nature of, or rather, the characteristics of each climate type we have seen. So why are we doing all this? We are doing all this to understand how to design sustainable buildings for each of the climate types to ensure that the indoors are comfortable because that is the ultimate aim. To make the indoors comfortable is our ultimate aim. Then what do you mean by making indoors comfortable? So what is the meaning of thermal comfort, and what are the various thermal comfort models? In today's class, we will be seeing: What is thermal comfort, and what are the thermal comfort models? So what is thermal comfort? Thermal comfort is that condition of mind. So thermal condition is about how you feel, how the mind perceives, or how it feels.

It is the condition of the mind that expresses satisfaction with the thermal environment. And this is assessed by subjective evaluation. So how do you feel? How do you feel? How do you feel thermally in this environment? The answer to that should be -Then we say that it's a comfortable environment. Then what is an acceptable thermal environment? A thermal environment that most people, most people means what? For more than 80% of people, the occupants should feel that it is a thermally acceptable environment.

That is the definition of thermal comfort. An environment where at least 80% or more than 80% of people feel comfortable is known as a thermally comfortable environment. So how do you assess thermal sensation? How do you feel? How do you answer that question? If it is comfortable, well and good, comfortable. If not, then it can be either cold, it can be cold, it can be cool, or it can be neutral. Okay, I am okay with this, or we can even say comfortable, or it can be warm or it can be hot.

This is five ways of describing how you feel. You can even have a seven-point scale where it can be cold, very cool, cool, neutral, warm, or slightly warm. Sorry, it should be slightly warm, warm and hot. So this is a 7-point scale, and this is a 5-point scale. A thermally comfortable environment is essential to providing occupant satisfaction.

For the occupants to feel satisfied, it is essential to have an environment that is comfortable, which enhances health as well as increases productivity, because it becomes very important in spaces like office buildings where people work for continuous hours or classrooms where students sit for long hours in a class. If it is not thermally comfortable, then it affects their health and also their productivity. So thermal comfort refers to the state of mind in which a person feels satisfied with the temperature of the environment. It is highly subjective And depends on several factors, including your personal preferences, clothing level, activity level and the surrounding environment. So what is your preference about how you should, for example, a person coming from a very cold place? would feel slightly warm in a place where the native feels comfortable.

So what is your personal preference? Then what clothing levels you wear? Suppose in a hot, dry place, you end up wearing a sweater, then you are going to feel warmer or hotter. What is your activity level? We have seen how athletes who run sweat so much, they pant so much, they feel so hot, and they drink a lot of water. Marathon runners pour water on their heads because of the activity level. And of course, the surrounding environment, such as temperature, humidity, wind speed, and the radiant temperature. So, these are all the factors on which thermal comfort depends.

So thermal comfort is crucial for an occupant's well-being and productivity in buildings, making it an important consideration in architectural as well as HVAC design. So when the productivity of a person is impacted, then the whole point of designing goes for a toss. If you are going to design a school building where a student is not able to give his 100%, then the whole point of designing the school is lost. Similarly, if you design an office space where the person who works there is not able to give his 100%, then the whole point of designing the office building is lost, and therefore, it is very important that we design thermally comfortable buildings. So why is it necessary? Why should we design thermally comfortable buildings? So human beings are homotherms.

So human beings are homotherms. Therefore, in different environments, even in extreme cold or hot situations, people can maintain their core body temperature in a narrow scope through thermoregulation. So what are these thermoregulations? We will see a little later. So thermal comfort can also be defined as a person's own awareness of the thermal atmosphere, and it is defined as a person's neutral feeling in relation to a given thermal environment without sweating or shivering. The person's location as well as the climatic conditions within and outside the enclosure influences the thermal comfort standards.

People feeling uncomfortably hot or uncomfortably cold are more likely to behave unsafely. Their ability to take decisions or perform manual tasks deteriorates. Now there are ways in which the body exchanges heat to the environment. So how does the body exchange heat? One is through conduction. So through physical contact, probably with the ground or maybe with holding something in the hand.

The body conducts heat exchange with the object. The second is through convection. So convection is not necessarily through a solid medium. And third is radiation. Apart from this sweat, exhalation and insensible perspiration through evaporation also happen with the atmosphere.

Now there are various factors that determine your comfort in the environment. That is personal parameters. In personal parameters, metabolic rate is one and clothing insulation is one. What do you mean by metabolic rate? What do you mean by clothing insulation? Are these measurable? Are these measurable? Yes, very much measurable. Then you have the environmental parameters.

So what are the environmental parameters? The environmental parameters are air temperature, radiant temperature, air speed and humidity. So these factors are considered. and incorporate into steady state heat transfer models, which was developed by Franger, one of the first few to have done it. (a) So what is your perception? That becomes very important. So what is the environment you prefer? Somebody may prefer an air-conditioned environment at 24 degrees Celsius.

Somebody may prefer a natural environment at 28 degrees Celsius. So what is your preference? (b), how do you feel? I feel warm. I feel hot. I feel comfortable.

It is very cold here. Third is humidity. Fourth is air movement. Next is our behavior. Whether there is controllability of the behavior, whether we are able to adapt, whether we can control ability means whether we can control the environment, whether we can open the windows.

Second is adaptation. Can I adapt? For example, human beings have learned to live even in the Tundra region. That is adaptability. Not everyone can go and live in Tundra region the way an Eskimo lives there. Third is expectation. We have a certain expectation of how we would feel in an environment.

Also, what matters is the background. What is the living lifestyle, and what is the culture that you are exposed to? Okay, I come from a culture where air conditioning is not a norm. Then even without air conditioning, when it is sultry and sweaty, I would just wipe off the sweat and not complain about feeling uncomfortable. So what is the background, living lifestyle, culture? All this crux forms what is called thermal comfort. So thermal comfort depends upon the metabolic rate, the clothing insulation, the air temperature, the radiant heat, the air velocity, the relative humidity, and other factors such as age.

An old person tends to feel more warm or cold as compared to a younger person. Gender: women feel differently compared to men in the same atmosphere. Thermal history, what is your context? From where are you coming? Are you coming from a hot-dry place like Rajasthan, or are you coming from a wet and humid place like Chirapunji? So what is the context? All these factors affect thermal comfort or influence thermal comfort. And it is important for us to consider thermal comfort in order to provide a thermally comfortable environment. In order to boost the productivity of a place.

In order to have good mental health. In order to have good physical health. To enhance the performance of the person who works there. in order to have good social development, in order to have learning and cognitive skill and general well-being. Therefore, thermal comfort is a very important aspect to be considered in design.

So let us look at each parameter separately. We will first see metabolic rate. The rate of transformation of chemical energy into heat and mechanical work by metabolic activities of an individual per unit of skin surface is expressed in units known as met. For example, the customers in a restaurant may have a metabolic rate near 1 met.

Assessing metabolism is MET. So we call it MET units. So someone sleeping would have a MET unit of 0.7. Whereas someone who is sitting in a reclining pose would have a MET of 0.8. So this person will have 0.88 met. Someone who is seated and quiet would have a met of 1.0. Whereas someone who is standing in a relaxed manner would have a met of 1.2. Walking depending on the speed. So at a speed of 0.9 meters per second, the metabolic rate met is 2. At 1.2 meters per second, it is 2.6, whereas at 1.8 meters per second, the met units are 3.4. There are certain office activities for which we can also have met. So mammals use thermoregulation to keep the body within a tight temperature range. The ultimate objective of our metabolism is to regulate our temperature with minimum effort.

And this is essential for health as it allows organs and bodily processes to work effectively. Now if a person strays too far from the inner body temperature of 37 degrees Celsius, say the inner body temperature must be 37 degrees Celsius. This is inner body, okay, not outer body, inner body temperature. What happens when the inner body temperature increases? The body desperately tries to bring down the inner body temperature because it's a question of survival. And in the process of trying to bring down the inner body temperature, a person sweats profusely.

Because sweating releases moisture from the body, causing it to evaporate. And we know that evaporation causes cooling. And the body's way of cooling, when the inner body temperature increases, is by sweating, whereas if the inner body temperature decreases, it becomes cold, then what does the body do? It starts to shiver because through the movement it tries to increase its metabolism and therefore increase the heat generated. So the body has its own system. To regulate heat.

Now let us look at clothing insulation. The resistance to sensible heat transfer. Provided by a clothing ensemble. Is through units known as Clo. Clo is the unit expressed. To understand a clothing ensemble. It includes uncovered parts also. So trousers with a short-sleeve shirt have a CLO of 0.57. A person who is extremely bare-bodied has a CLO of 0.

So here you can see what a CLO of 0.3 would mean. clothes on, 0.3. Whereas a person who has trousers, full pants, and a shirt has a cloth of about 0.5. A two-piece suit jacket would mean a CLO of 0.96, and a 5-plus suit jacket with long underwear bottoms would mean a CLO of 1.3. Like this, for every clothing level there are various values that are measured in CLO. So you decide what the MET and CLO for which you are going to think about understanding or assessing thermal comfort.

Then we move on to environmental parameters. Now air temperature. Air temperature is the temperature of the air surrounding the body, and it is given in degree Celsius. Right temperature and air freshness are most important about a building. Optimizing air temperature is crucial to maintaining indoor thermal comfort without excessive reliance on mechanical heating or cooling systems. Air movement significantly affects body heat transfer by convection and evaporation.

The temperature of the air surrounding the body is usually given in degrees Celsius. It can be measured using thermometers, but on its own, this will not give an indication of thermal comfort. You should provide a minimum working temperature in workrooms, usually at least about 16 degrees Celsius for strenuous work or extremely strenuous work. There is no law for maximum working temperature or when it is too hot to work. This is because in many indoor workplaces, high temperatures are not seasonal but created by work activities.

For example, bakeries or foundries where there are ovens. Then radiant temperature. Now radiant temperature will have a greater influence than air temperature on how hot or how cool you feel about a particular place. The rate of air movement. Now we move on to air velocity and air movement. How quickly air is moving across a person is an important factor in thermal comfort.

Even if the air temperature is not reduced, moving air in a warm or humid office can increase heat loss by convection, which explains why a fan can help us to feel so cool. You would have noticed when it becomes very warm and moist that people use a paper piece, a handkerchief or a piece of cloth or anything they can lay their hands on in order to move the air around their skin so that they feel comfortable. So, if it is a very, very cold place, then even a small amount of breeze will feel like a cold draft. So in warmer environments, increasing air speed will enhance convective heat loss and promote sweat evaporation, creating a cooling effect that can make a person feel more comfortable.

Now let us understand humidity. A general reference to the moisture content of the air is called humidity. It is expressed in terms of several thermodynamic variables, including vapor pressure, dew point temperature, wet bulb temperature, humidity ratio, and relative humidity. Whereas air speed is normally measured in meters per second. It is spatially and temporally averaged in the same manner as air temperature. So, air temperature, air speed, humidity, a combination of all this is what you will perceive as the real comforting temperature.

Now let us look at the Fanger's body heat balance equation. So according to Fanger in 1970, the physiological process of the human body strives to maintain a balance to quantify the discomfort level. So even if somebody feels uncomfortable about being warm or cold, the body automatically tries to make itself comfortable by sweating or shivering. This is to ensure that the internal heat production and the external work activities should be equated to the dry heat exchange through skin. So M is the internal heat production and W is the external work or activity. This should be equal to the dry heat exchange through skin in the form of convection and plus radiation plus the skin evaporation, the moisture on the skin which causes evaporation and cools, plus respiration heat exchange because of breathing, which is a form of convection and respiratory evaporatory heat exchange.

So the body, at its internal heat production minus the outdoor work, which causes extra heat, has to balance each other. Now what is the input for energy balance? The input for energy balance is your metabolic rate, which depends upon your age, gender and the clothing insulation level, which I said is measured in CLO, the air temperature of the place, the velocity of the place, the mean radiant temperature and the relative humidity. All of these put together will determine the energy balance about how you feel, whether you feel hot, you feel warm, you feel slightly warm, you feel neutral, which is comfortable, you feel slightly cool, cool, or cold. So the body heat equation is that the metabolic heat that you produce. By virtue of your activity, because of your age—by age, what I mean is even to breathe, even to do your daily activities—even in a sedentary place you require some energy, you emit some heat. Your gender, the heat that is produced because of convection, radiation, conduction, shivering must be equal to the heat that is lost by the body in the form of evaporation, convection, radiation, conduction.

In order to have a deep body temperature of 37 degrees Celsius. even though the normal skin temperature may be 31.4-34 degrees Celsius. So this balance is very important. So when the human body is in its extreme thermal disorder and the regulation of the human body is out of balance, the core temperature will be much higher or lower than the normal value. When the core temperature exceeds a certain limit for a longer time, say more than one hour, which is say higher than 37 degrees Celsius or lower than 35 degrees Celsius, then the human body will be damaged to a certain extent.

And that is what we call the impact of heat stress. So when the inner body temperature exceeds 37 degrees Celsius heat stress starts in and symptoms of heat stress will be giddiness, vomiting, fainting, and sometimes even fatality—death. When it becomes very cold and the inner body temperature is less than 35 degree Celsius, hypothermia sets in. You would have seen so many movies now where hypothermia is predicted. Even there was a recent one with Janhvi Kapoor where she gets stuck in a freezer and so on. And heat stress—we just saw what had happened to people who went to watch the air show in Chennai.

It was just pure heat stress, because of which four precious lives were lost. So to maintain the inner body temperature is very important, apart from the fact that we have to design buildings to be comfortable to the users. So how do we assess if the particular condition is comfortable or not? For that, we need what is called thermal comfort models. So it is very important to establish thermal comfort models in case extreme thermal disorders happen. In addition, it is important to predict thermal comfort in a built environment because the thermal comfort model has a great potential for energy savings.

If the comfort temperature in different environments can be predicted accurately, a reasonable set temperature can be determined. Through the thermal comfort model, comfortable environments can be predicted for various different environments. Let us now look at the thermal comfort model that relates indoor design temperature or acceptable temperature ranges to outdoor meteorological or climatological parameters. This is a thermal comfort model. Comfort models are frameworks that are used to predict and evaluate human thermal comfort in various environments.

In architecture and building design, thermal comfort models are essential for designing energy-efficient buildings that will maintain occupant comfort while using very little energy. So that we have to try and work towards designing sustainable buildings. Now thermal adaptation to indoor environments happens in three ways. First is adjustment. Which is behavioral or technological changes? So you need to adjust to a particular setting.

Second is acclimatization. Which is physiological and which is based on a thermal history. What do you mean by thermal history? If a body has been exposed continuously to very warm weather. Then their ability to tolerate heat becomes more. to tolerate heat, okay, not to tolerate the inner body temperature to shift, that will not happen. Then habituation, which is a psychological adaptation with changing expectations.

So there are various thermal comfort models; there is Fanger's PMV model; there is an adaptive thermal comfort model; and there is Olgay's bioclimatic chart. There is Givoni's psychrometric chart. So these we will be looking at, say, the psychrometric chart and so on, a little later. We will be dealing with it in detail in another class, in another lecture.

So there are two main classifications of thermal comfort. First is the steady state model. So, the predicted mean vote model stands amongst the most recognized thermal comfort models. It was developed using principles of heat balance and experimental data collected in a controlled climate chamber under steady-state conditions. Therefore, the PMV model can be applied to air-conditioned buildings only. Under a steady state, what do you mean by under steady state? For say 24 hours, the temperature, humidity, wind speed—everything is fixed, and in that, people are assessed how they feel, but that is not the reality.

In reality, the temperature indoors will not change only in air-conditioned buildings because it is set so. Therefore, the steady-state model is applicable to air-conditioned buildings. Second is the dynamic state model. So, the adaptive model was developed based on hundreds of field studies with the idea that occupants dynamically interact with their environment. Occupants control their thermal environment by means of clothing or operable things like opening the windows when they feel very sultry, switching on the fans, using personal heaters, and then having some shades, and so on.

The adaptive model can be applied only to buildings where no mechanical systems have been installed. As of now, there is no consensus on which comfort model should be applied for buildings that are partly air-conditioned and partly naturally ventilated. I am going to talk to you about at least four models of thermal comfort, and there is a reason for it. Later on, we will be learning about certain tools. to assess appropriate strategies for designing, and in those tools, there is mention of these models.

So for you to understand what these models are, I am going to talk to you about these models. The first is the ASHRAE Standard 55 and current handbook of fundamentals model. So ASHRAE 55 was first introduced in 1966 to establish guidelines for maintaining thermal comfort in indoor spaces. Over a period of time, the standard evolved, becoming more precise in identifying environmental and personal factors that influence comfort. The PMV or predicted mean vote and PPD or predicted percentage of dissatisfied people, this model, which was developed by Franger has been the foundation of this standard book.

This approach was suited for climate-controlled environments where variables such as air temperature, radiant heat, air speed and humidity could be managed precisely. The model was based on assumptions made in controlled environments like climate chambers and it didn't fully consider behavioral adaptation of occupants. The ASHRAE standard 55 and current handbook of fundamental models are widely recognized standards for defining thermal comfort in indoor environments, and it was developed and maintained by ASHRAE, which is American Society of Heating, Refrigeration and Air Conditioning Engineers. The standard specifies conditions under which a majority of people will feel comfortable and provides guidelines for designing HVAC systems that ensure thermal comfort in buildings.

This model is applicable to both mechanically conditioned and naturally ventilated spaces. So the key components of ASHRAE Standard 55 are that acceptable thermal conditions. This standard provides acceptable temperature ranges and guidelines based on different levels of humidity, clothing, and activity. It talks of comfort zones. So it uses comfort zones to define an acceptable temperature and humidity combination that would keep most people comfortable.

Then local thermal discomfort. This considers issues like draft, radiant temperature asymmetry, vertical temperature difference, and floor temperature. ASHRAE Standard 55 uses two main models to predict thermal comfort. PMV- PPD model, which is predicted mean vote and predicted percentage of dissatisfied model as well as adaptive comfort model. Now what is a PMV? Predicted mean vote model. So PMV predicts the thermal sensation felt by a large group of people in a particular indoor environment.

It is calculated using factors such as air temperature, which is the temperature of the air surrounding the occupants. The mean radiant temperature is the average temperature of all the surrounding surfaces that emit heat. Next is the relative humidity, which is the amount of moisture present in the air. The air velocity, which is measured in meters per second. The clothing insulation, the clothing insulation provided by the occupant's clothing measured in clothes.

The metabolic rate measured in METS indicates the level of physical activity. These factors are integrated into a complex equation that outputs the PMV score, and that score ranges between hot, warm, slightly warm, neutral, slightly cool, and cold. The goal is to achieve a PMV value as close as possible to zero. This indicates that the majority of people will find the indoor conditions neutral and comfortable. So, this is an index that predicts the mean value of votes of a group of occupants on a 7-point thermal sensation scale that is based on the balance of heat within the body. This balance, much like thermal neutrality, is obtained when an occupant's internal heat production is the same as the heat loss.

Our thermoregulatory system modifies our temperature by sweat secretions to keep us thermally balanced and to avoid thermal discomfort. Different methods can be used to assess this for different combinations of metabolic rate, insulation, temperature, air speed, mean radiant temperature, and relative humidity, and our computation method will be addressed later. The PPD- PPD provides a statistical prediction of how many people will be dissatisfied with the particular thermal environment. Even in the best environments, when PMV is neutral, that is, when PMV is zero, a certain percentage of people will still be dissatisfied because individual preferences vary.

This is why achieving 100% satisfaction is practically impossible. PPD of 5% is an ideal range. Which means suppose there is a PPD of 5%. A PPD of 5% is an ideal range. where only 5% of people are predicted to be uncomfortable. The target is to maintain a PPD value below 10 to 20%. So PPD is an index that establishes a quantitative prediction of the percentage of thermally dissatisfied occupants who feel extremely warm or extremely cold.

The PPD is calculated from the PMV, as it can be found from the distribution of individual thermal sensation boards compiled collectively. The second is the adaptive comfort model in ASHRAE Standard 552010. So there was a need for a new approach. Before 2010, ASHRAE Standard 55 focused heavily on mechanically conditioned buildings.

These require precise control over the indoor environment. You set the AC temperature at 26 degrees Celsius or 24 degrees Celsius. So it's a set temperature. As interest grew in naturally ventilated buildings because that's more efficient, that is sustainable, and that is environmentally friendly, it became very clear that the PMV-PPD model wasn't always applicable. People in naturally ventilated spaces tend to adapt to varying temperatures, accepting a wider range of conditions.

Third is the ASHRAE Handbook of Fundamentals comfort model up through 2005. So, pre-2005 comfort model, which is before 2005, the PMV-PPD model dominated thermal comfort calculations. This approach was suited for climate-controlled environments where variables like air temperature, radiant heat, air speed, and humidity could be managed very precisely because these were air-conditioned environments. You have to set it on your remote. The model was based on assumptions made in controlled environments like climate chambers, and it did not fully consider the behavioral adaptation of occupants.

That was its flaw. So the adaptive comfort model in ASHRAE Standard 55 2010 came up. So this primarily relied on TMV and PPD models, which were based on controlled laboratory settings. These models assumed that indoor environments would be mechanically controlled and maintained within a narrow range of temperature and humidity levels. These assumptions were not well suited to naturally ventilated buildings where indoor conditions fluctuate based on the weather and where occupants can take actions to adjust their comfort. In response to the growing emphasis on sustainable building design and the desire to reduce energy consumption, the adaptive comfort model was introduced in the 2010 revision of ASHRAE standard 55. This enables building designers to set higher or lower indoor temperatures based on outdoor conditions, reducing the need for energy-intensive heating, ventilation, and air conditioning systems and promoting the user to use natural ventilation.

The adaptive comfort model, or ACM, in ASHRAE 55-2010 is a paradigm shift from earlier models of thermal comfort, which were designed for tightly controlled indoor environments with mechanical heating, ventilation, and air conditioning systems. The adaptive comfort model acknowledges that people in naturally ventilated spaces tend to adapt to variations in indoor temperature by modifying their behavior, such as by changing clothing, using fans, or opening windows. This model moves away from the notion of strictly fixed indoor temperature ranges. Instead, it links acceptable indoor temperatures with outdoor climate conditions, particularly in naturally ventilated buildings. The ACM allows for broader temperature fluctuations in indoor environments while still maintaining thermal comfort based on the idea that occupants can adapt to changing conditions over time.

So, what was noticed is that in the predicted or the lab-based scenario, it was found that in air conditioned buildings, whatever was predicted to be the comfort condition correlated with what was observed; people also wanted that but in naturally ventilated buildings, it did not match the predicted values, the values which were predicted to make people comfortable did not match with the actual values that people said made them feel comfortable. So the adaptive comfort model is based on the principle that individuals adapt to their environments and that acceptable indoor temperatures vary depending on outdoor conditions. The model considers the following:. Outdoor temperature: As the mean outdoor temperature rises, people tend to accept a warmer indoor temperature.

Conversely, in cooler climates, people prefer cooler indoor conditions. Second is behavioral adaptation. These words you would have seen in my previous slides. So what is behavioral adaptation? Occupants are more tolerant of temperature fluctuations. When they take, they can take actions like opening windows to get fresh air, using personal fans, adjusting clothing layers, changing the location within the space, like moving closer to a window or away from a window or moving closer to a heat source, etc. So an occupant can tolerate temperature variations or fluctuations if he has the option of operating windows as per his desire, using personal fans, or changing his clothes.

If it is very warm, he can change his clothes to something very light, decrease the clove value. And by these two we mean altering the environmental parameters. like wind, relative humidity, and sometimes even temperature. Changing the location within space, like moving closer to or away from windows or heat sources. Third is indoor temperature range. Instead of a fixed comfort range, this model provides a dynamic range of indoor temperatures that are acceptable depending on the outdoor temperature.

So instead of saying no, comfort means only 26 degrees Celsius at 60% RH relative humidity at a wind speed of 1 meter per second. That is extremely rigid. So this is a very rigid way of approaching. Whereas this model gave a range of saying something like 26 to, or rather, 24 to something like this 24 to 28 degrees Celsius at an RH of 55 to 65 percent, and so on. So, this allows for indoor temperatures to drift higher or lower than what would be acceptable in HVAC-controlled spaces while still ensuring thermal comfort.

So what is this adaptive thermal comfort, and where can we use it? The adaptive thermal comfort metric relates indoor design temperature to outdoor temperatures. The acceptability criteria under this metric allow for warmer internal conditions, like the outside range of typical criteria of 21 degrees to 24 degrees centigrade when conditions are very warm outside. The adaptive thermal comfort model can be used if the following conditions are met:.

This is as per Section 5.4 of ASHRAE Standard 55. The space is naturally conditioned or naturally ventilated through occupant control. So naturally ventilated with occupant control. Second, the space should have no mechanical cooling system.

So, it should be an unconditioned air environment. Third, no heating system is operated in the space. However, the adaptive method does not apply when this is in operation. The occupants in the space must be engaged in near-sedentary physical activities. That is, they should be sitting or in a seated position. They should not do some kind of cardio activity or weight lifting or something like that.

Fifth, the occupants are free to adapt their clothing to the indoor and outdoor thermal environment within a range of 0.5 to 1 kilo, not more than that, not less than that. The prevailing mean outdoor temperature must be greater than 10 degrees Celsius and less than 33.5 degrees Celsius. The acceptable indoor temperature range in the adaptive comfort model is like this. From the graph, we can see at lower outdoor temperatures, that is at 10 degrees Celsius, The acceptable indoor temperature can range between 18 degrees and 22 degrees.

At higher outdoor temperatures, say when the temperature is 27.5 degrees Celsius, the acceptable temperature also increases. It ranges between 22.5 degrees to 22.5 and 28.5 degrees centigrade. So the broader range is possible because people in naturally ventilated spaces are more accustomed to outdoor temperature variations and have access to adaptive behavior.

So what happens is here when, but this is also true: when the person is exposed to an environment that is cold outside, his ability to shift to a much warmer environment automatically is very difficult. So this model provides a graph of acceptable indoor operative temperature based on the outdoor running mean temperature, which is the average outdoor air temperature over a few previous days. So what are the benefits of this system? So one of the key benefits is energy efficiency. So the adaptive comfort model gives us energy efficiency because it does not say that you can feel comfortable only at 26 degrees Celsius, irrespective of what the outdoor condition is.

It says if the outdoor temperature is 10 degrees Celsius, you can feel comfortable at 18 to 22 degrees Celsius. By doing so, what happens? The load on heating the room will get reduced. You know, you can heat the room until the temperature reaches, say, a maximum of 22 degrees Celsius. You don't have to heat it till it reaches 26 degrees Celsius. Similarly, if the outdoor temperature is 27.

5 degrees Celsius, you can have the room, or the person can feel comfortable between 28 degrees Celsius to 22 degrees Celsius. So when you have to air-condition the building, you don't have to necessarily target the mandatory 26 degrees centigrade only. You can even target 27 degrees Celsius because of which a lot of energy can be saved. Second is occupant control and satisfaction. Now the occupant is able to control his or her environment. So, by giving occupants more control over their environment by, say, adjusting windows, fans, or their clothing, the model increases satisfaction while still maintaining comfort, especially in warmer countries.

Most of the warmer countries are along the tropics, and these are the countries where the economy or economic feasibility is also something that we must consider. Third is sustainability. So the adaptive comfort model supports sustainable building practices by reducing the need for mechanical systems and utilizing climatic conditions to achieve thermal comfort. It's particularly useful in warm climates where passive cooling can substitute for air conditioning, helping buildings to reduce the carbon footprint.

Next is the broader comfort range. This is needed. It can't be one number, especially in developing countries. So, the adaptive comfort model expands the acceptable range of indoor temperature, which allows for more flexible building design that caters to seasonal outdoor conditions. This approach aligns with modern green building standards such as LEED, which encourages natural ventilation and reduced energy use. The fourth one is the California Energy Code Comfort Model 2013. This is not really relevant to the Indian condition, but I have put it for a reason because you will come across this code in another context, and at that time you should not be wondering what that is.

So I am just going to tell about this very briefly. So the California Energy Code is one of the strictest energy codes in the US, and this aims to reduce energy consumption in buildings. The 2013 update incorporated thermal comfort models to encourage both comfort and energy efficiency. This model is largely influenced by the adaptive comfort model and encourages the use of passive design strategies such as natural ventilation and day lighting to reduce energy demand for cooling as well as heating. The court's purpose is to advance the state's energy policy, develop renewable energy sources, and prepare for energy emergencies. A 2020 study found that the 1978 energy court successfully reduced energy consumption and that the implementation of the policy did definitely have benefits in terms of energy efficiency, in terms of being more flexible, and in terms of being more sustainable.

You also have what is called EN ISO 7730. So this is a European adoption of the international ISO 7730 standard. And this defines thermal comfort, as thermal comfort is a subjective way to define if the surrounding climate is comfortable or not. And the perfect environment can be summarized as the environment where the occupant feels thermally neutral, does not wish the environment to be colder or warmer, and is not exposed to any local cooling or heating at any place on their body. Then you have the IMAC, Indian model for adaptive thermal comfort. So the IMAT 2014 model was developed from the data collected through four survey campaigns in office buildings across five Indian cities, representing different climate zones such as warm and humid, hot and dry, composite, moderate and cold, all of which we have studied in our previous classes.

Four equations provided for different building types: naturally ventilated, mixed mode, which is naturally ventilated plus air conditioned. Then you had air conditioning. The IMAP models are also compared with ASHRAE 55 and EN 15251 adaptive models. The models show that the occupants in naturally ventilated buildings adapt to outdoor temperatures.

The neutral temperature for naturally ventilated buildings ranges from 20.5 to 28.5 degrees Celsius with 90 percent acceptability within a range of plus or minus 2.4 degrees Celsius from the neutral temperature. So, I will quickly briefly tell you, this is the, if this is the neutral temperature, then plus or minus 2.

4, so this is plus or minus 2.4 is acceptable to 90 percent of people. So this is acceptable to 90 percent people, and this range is acceptable to 80 percent people, which is 3.6. From the neutral temperature plus or minus 3.

6 is acceptable to 80 percent of people, and from the neutral temperature 2.15 degrees Celsius is acceptable to 90% of people. Then you have the NBC. So, according to the National Building Code 2016, air-conditioned systems for interior spaces intended for human occupancy shall be sized for not more than 26 degrees Celsius for cooling and not less than 18 degrees Celsius for heat. In NBC 2016, the adaptive comfort model was first introduced, duly emphasizing indoor thermal comfort, occupant well-being, and energy-efficient operation of HVAC. The adaptive comfort model for the design and operation of naturally ventilated buildings was done by Manu et al.

and this was also added in NBC 2016. Now quickly let us compare all four. So I am taking all these four for a reason, which you will understand later when we start looking at the tools that I had told you. So the ASHRAE standard 55 handbook fundamentals of the handbook of fundamentals, the adaptive comfort, the ASHRAE handbook pre-2005, and the California Energy Code. If we look at the comfort approach, ASHRAE Standard 55 follows the PMV-PPD model for controlled environments, just like the ASHRAE Handbook 2005, whereas the Adaptive Comfort ASHRAE 55-2010 follows the Adaptive Comfort model, just like the California Energy Code. If we look at environmental control, the ASHRAE standard 55 is valid only for mechanical ventilation, just like the 2005 handbook.

Whereas adaptive comfort ASHRAE model is valid for naturally ventilated spaces. And California Energy promotes passive strategies to reduce HVAC reliance. Third is occupant adaptation. So the ASHRAE standard 55 does not account for adaptation. Similarly, pre-2005 also has no adaptation assumed, whereas adaptive comfort accounts for behavioral and physiological adaptation just like the California energy code, which encourages adaptation. For this temperature range, ASHRAE Standard 55 has a strict, narrow comfort range, the same as the ASHRAE Handbook pre-2005, whereas the adaptive comfort model looks at a broader range linked to outdoor temperature, and the California Energy Code looks at a broader range to minimize energy consumption.

Fifth is energy efficiency. ASHRAE Standard 55 focuses on comfort and not energy. Similarly, the pre-2005 ASHRAE handbooks also focus less on energy efficiency, whereas the adaptive model promotes energy savings through reduced HVAC use, and the California Energy Code has a high focus on energy efficiency and passive design. Sixth is key applications. So ASHRAE Standard 55 Handbook of Fundamentals, along with

ASHRAE Handbook Pre-2005, looks at conditioned office buildings and commercial spaces, all reliant on HVAC systems. Whereas the ASHRAE comfort model looks at naturally ventilated buildings, and the California Energy Code again follows energy-efficient buildings in residential and commercial.

Next is main influencing factors. So air temperature, humidity, air speed, activity, and clothing levels are the influencing factors. This is the same as the ASHRAE handbook pre-2005. Whereas the adaptive comfort model looks at mean outdoor temperature with clothing adjustment. The California Energy Code follows outdoor temperature with naturally ventilated buildings.

Eight is usage. So both the ASHRAE 55 pre- and post-2005 models look at common HVAC-dominated designs that are mechanically controlled. Whereas adaptive comfort looks at energy-efficient and naturally ventilated spaces. And the California energy code looks at buildings in California to be designed for energy efficiency. So in today's class, we saw what the meaning of thermal comfort is. What is thermal comfort? What does it mean to people? What are the factors influencing thermal comfort? Do not forget what is MET, what is CLO because all this will be useful for you when I teach you certain tools.

And then we looked at various comfort models. I am looking at these four comfort models that are right now on your slide because this is what is used in the tools that we will be adopting later. But you must also learn about IMAC, which is specific to the Indian conditions. So with this, I will stop today's class, and we will meet in the next class with yet another topic pertaining to simple and advanced passive strategies. Thank you.