Sustainable Architecture
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Lecture – 16
Fundamentals of Thermal Comfort

Good morning. Welcome to this lecture on Fundamentals of Thermal Comfort for the online course on Sustainable Architecture and I am your instructor Dr. Alvokita Agrawal, Assistant Professor at Department of Architecture and Planning IIT, Roorkee. In the previous lecture, we have discussed about the green building rating programs and components and prior to that we have seen the process of designing green and sustainable buildings.

In that we have seen that the first step towards designing any green building any sustainable building is to understand the climate. Now, to understand the climate why at all are we doing this need to be understood. So, the fundamental purpose of a building for humans is that it provides the human beings, the level of comfort that they cannot get outdoors.

Now, this comfort could be of many types. One of the most important ones is the thermal comfort. So, people want to reside inside buildings because they want to be thermally comfortable. Now, what is thermal comfort?

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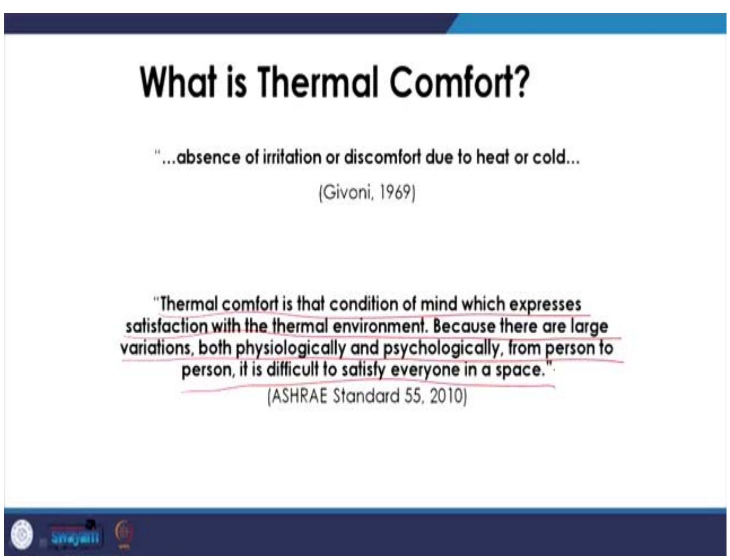

So, through this lecture let us look at the fundamentals of thermal comfort. Now, as defined by ASHRAE Standard 55 thermal comfort is that condition of mind which expresses satisfaction with the thermal environment because there are large variations both psychologically and physically from person to person it is difficult to satisfy everyone in a space. Yet thermal comfort is defined as a state in which a person experiences or expresses satisfaction with the thermal environment.

Very simply this thing was put by Givoni long back before ASHRAE Standard 55 define thermal comfort as absence of irritation or discomfort due to heat or cold. So, when we are at peace, when we are comfortable with the thermal environment that is what thermal. comfort is. Now, how do we define whether we are at thermal comfort or not, whether we are thermally comfortable or not.

So, the entire discussion and the research around thermal comfort was on defining thermal comfort and quantifying it.

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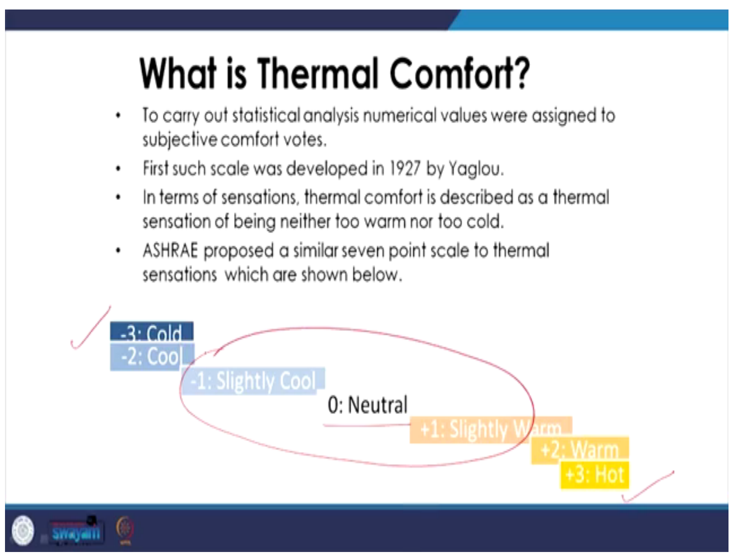

So, what are the factors and parameters which determine thermal comfort? How these parameters interact with each other so that a condition is generated which can be called as a condition of thermal comfort. So, a scale was supposed to be defined developed and the first attempt at it was in 1927 by Yaglou where he tried to assign numerical values to different comfort votes.

So, 0 in almost all thermal comfort scales is taken to be the neutral which is the thermally comfortable state and it was a 7 point scale which was proposed by ASHRAE not by Yaglou the first attempt was not a 7 point scale like which we used today which is proposed by ASHRAE which is from minus 3 which is extremely cold to plus 3 which is extremely hot and this comes minus 1 to plus 1 comes to be a relatively comfortable state.

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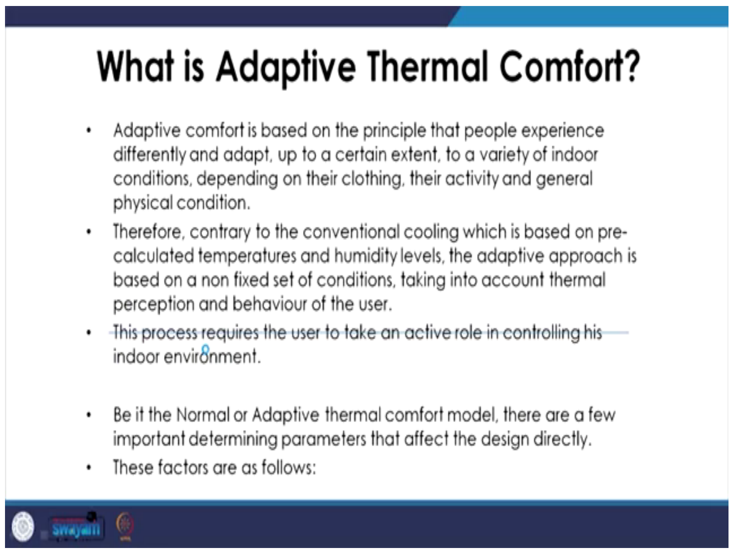

Now, as ASHRAE defines thermal comfort they define a range of various parameters within which thermal comfort can be experienced. However, a new discussion which is recent not very recent, but a recent discussion around thermal comfort is also there which is adaptive thermal comfort. An adaptive thermal comfort is based on the principle that people experience and behave differently, their bodies behave differently.

So, people who are used to living in warm climates they are comfortable at higher temperatures while people who are used to living in extremely cold climates are comfortable even at much lower temperature. So, if you look at our own country people coming from the extreme southern part of the country which does not experience any winter months extreme winter months are comfortable at very high temperatures while if you go to the extreme north where we are talking about Ladakh and Kashmir where the temperatures are significantly low throughout the year the people are quite comfortable at temperatures which are probably very cold for the people coming from extreme south of our own country.

So, there is a great variation. So, thermal comfort cannot be defined as one limited range it is adaptive and it also changes from season to season. So, that is what was the concept of adaptive thermal comfort.

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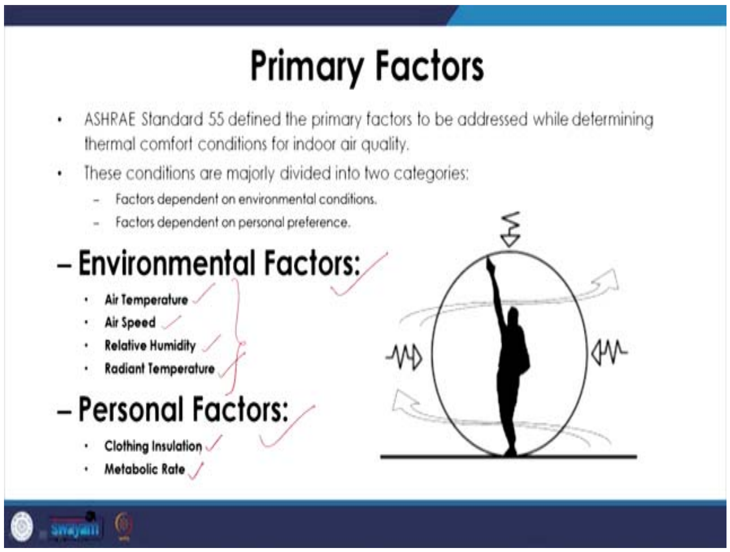

Now, whether it be a fixed defined thermal comfort or it be adaptive thermal comfort there are some factors which help us assess whether the given condition is thermally comfortable or not. Now, there are some primary factors which determine comfort thermal comfort and they can be clubbed in two distinct categories. One is environmental factors and the other one is personal factors.

Now, there are four factors with an environmental factor, air temperature, air speed, relative humidity and radiant temperature while in addition to these environmental factors which are the more predominant ones, we also have clothing insulation and metabolic rate. So, together these six parameters interact together to determine whether a person will be experiencing thermal comfort or not.

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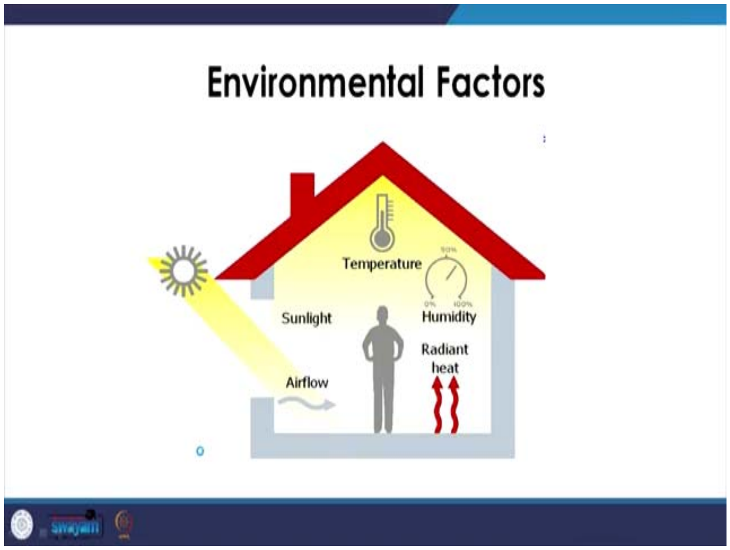

Now, let us look at each of these primary factors individually.

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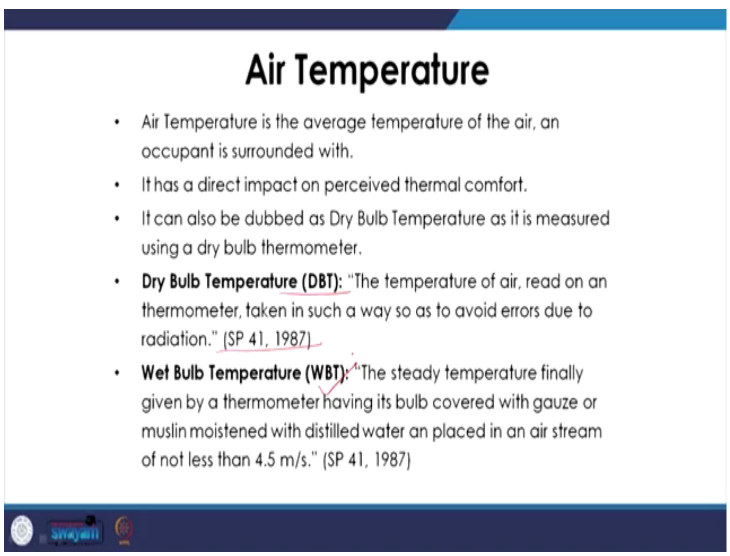

So, air temperature is the average temperature of the air ambient air with which the occupant is surrounded with and it has a direct impact on perceived thermal comfort. So, we very clearly know that when the summers come and the air temperature increases to 40 – 42 degree directly we start experiencing heat as the temperatures go on increasing. Now, this air temperature is of two types you might have already studied it, but let us quickly brush it up.

One is dry bulb temperature which is the temperature taken in such a manner and this is taken by the regular thermometer in such a manner so as to avoid errors due to radiation this is defined as what SP 41 of India SP 41 is a code prevalent in our country India. The other is WBT which is Wet Bulb Temperature which is the temperature which takes into account the impact of humidity in the air. So, dry bulb temperature does not take into account the humidity while WBT wet bulb temperature takes into account the humidity which is present in the air.

Now, what does the humidity do? So, humidity helps us release some heat from our body evaporate. So, take away some heat and makes us feel comfortable. So, wet bulb temperature takes into account that.

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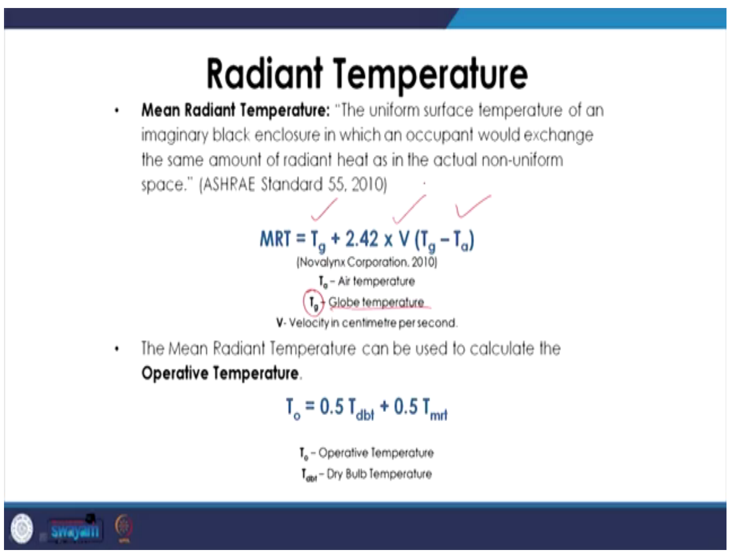

Now, another thing is radiant temperature which there are several different terminologies which we use when we are talking about radiant temperature the most common one being MRT or mean radiant temperature. Now, mean radiant temperature takes into account the radiation effect of these surrounding surfaces the surfaces which are surrounding the occupant.

Now, that is taken into account with the help of a term with the help of a quantity called globe temperature. Now, what is globe temperature? Globe temperature is the temperature of the air only, but it takes into account the radiation which is received from the surfaces which are surrounding anybody, a blackbody. So, what is done to note this globe temperature in a globe thermometer is used. So, we cover a thermometer, regular thermometer surrounded by a black globe and then place it in any space.

So, the heat which is the radiation which is absorbed by this black globe which is surrounding this thermometer and the radiation which is passed on to the thermometer is accounted for through the globe temperature reading. So, with the help of and also the MRT takes into account the air velocity, velocity of the air in meter per second centimeter per second; the globe temperature which is taking into account the radiate radiant temperature radiation the temperature of the air and velocity.

The mean radiant temperature is further used to calculate operative temperature. Now, operative temperature is also a terminology which takes into account the impact of radiation as well as the air and giving us a condition, which is equivalent to a given surface condition with at different temperatures and also the air which is surrounding. So, together both these two quantities are taken together.

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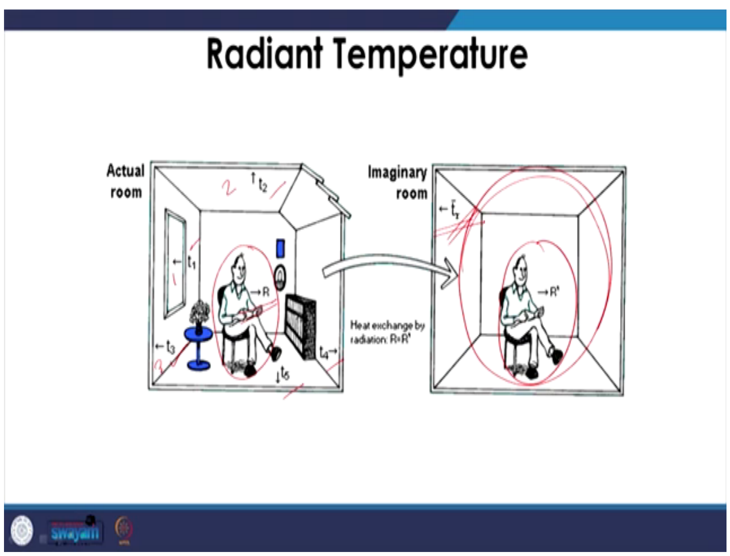

Now, if we have to explain the radiant temperature very simply through this image. We can see assume that the occupant is surrounded by different surfaces say surface 1 which is this at a different temperature; surface 2 which is at a different temperature; surface 3 which is as at a different temperature and so on.

So, what is the experience of this occupant who is receiving radiations, who is experiencing surfaces on all the sides. So, this has to be clubbed together. So, the experience remains the same where the experience of this person here with so many different surfaces is the same if all these surfaces were made of one material and at one particular temperature. This is the radiant temperature we are talking about.

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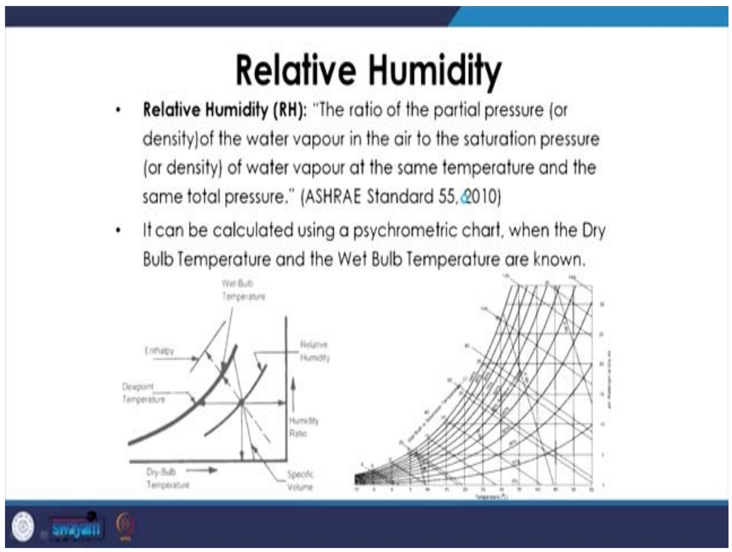

Now, second quantity is relative humidity. Now, relative humidity is the ratio of partial pressure or density of the water vapor in the air to the saturation pressure of water vapor at the same temperature. So, we very clearly know as the temperature of the air increases it can hold more water it can hold more moisture.

So, what percentage of that saturation pressure or density is present at a given point of time is what relative humidity is and it is a very common terminology which is used to define the environmental factors of a given place in a given time. So, rains happen when it is 100 percent relative humidity. So, the air is saturated with moisture maximum that it can contain.

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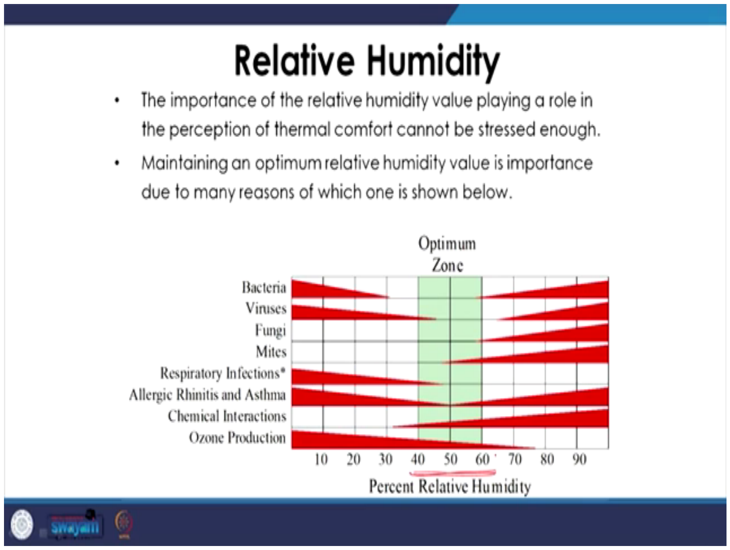

So, relative humidity has to be maintained at optimum level between 40 to 60 percent from not just thermal comfort point of view, but also from the point of view of growth and development of different kind of bacteria and viruses in the environment. So, and fortunately apparently 40 to 60 percent is also the range where human beings feel thermally comfortable, of course, along with the given conditions of temperatures.

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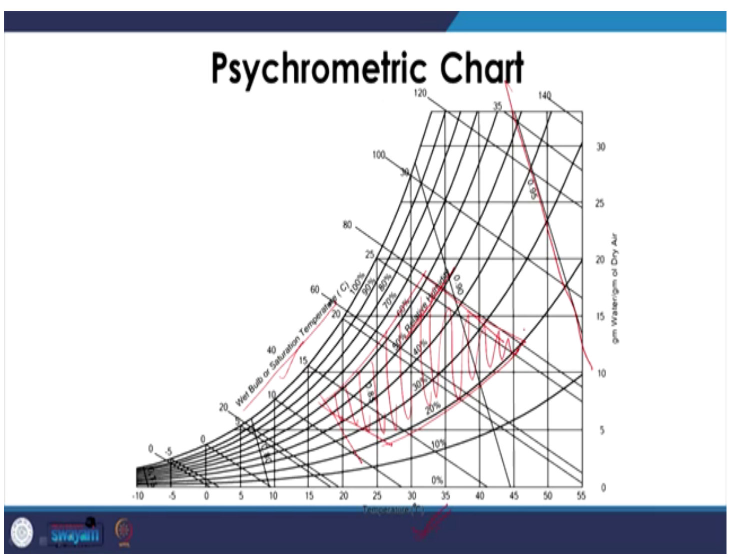

Now, these three quantities one is of a temperature which is dry bulb temperature, the wet bulb temperature which takes into account the humidity, but if we do not have that then we have this humidity relative humidity percentages which are going and if we know the temperature if dry bulb temperature if we know the relative humidity we can automatically calculate the wet bulb temperature through psychometric chart. This also takes into account or it also has the lines for the air velocity within the psychometric chart.

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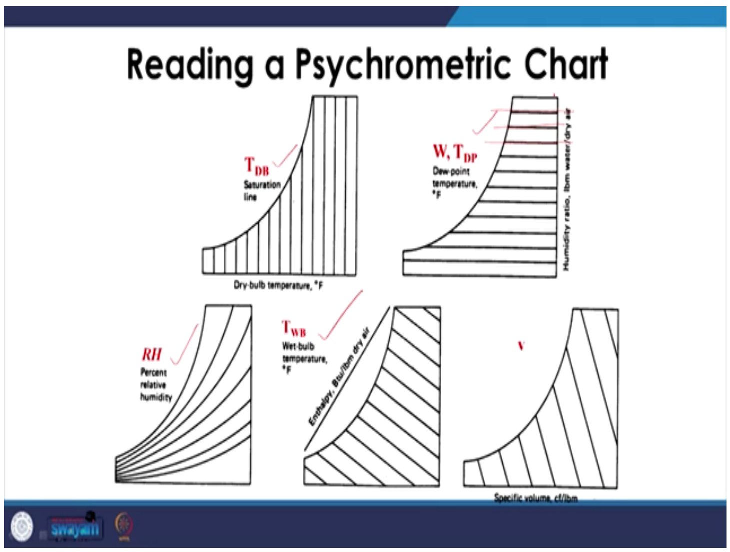

So, if we have to understand the psychometric chart. So, we have the dry bulb temperature DB we have WBT which is wet bulb temperature we have relative humidity through these curved lines and we have dew point temperature which is this. So, we would know the dew point temperature, if we know the temperature of a place at a given point of time if we know the relative humidity, we can also calculate the dew point temperature.

This along with that we can also calculate the specific volume. Now, here if we look at the psychometric chart again the psycho through the psychometric chart very clearly the comfort range can be defined, we can define the comfort range which is experienced thermal comfort range which is experienced by the human beings.

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So, psychometric chart was a good way of demonstrating experimenting and also defining the thermal comfort, but not in a very comprehensive manner as other parameters for example, the air velocity and the personal factors could not be taken into account.

Another measure is air speed. So, air speed is the speed average wind speed which is present in the environment surrounding the occupant the user and it is usually measured with the help of anemometer. Now, if we understand if you want to understand the impact of air speed on thermal comfort, we can very clearly relate with our common day everyday experiences. So, at the same temperature suppose you start or turn on a fan you suddenly start to feel comfortable while the temperature and the relative humidity have remained the same.

So, the temperature is the same, say 32 degrees, the relative humidity is around say 50 percent at that temperature when a person occupant a subject was feeling relatively hot slightly warm at the same temperature with wind speed rain coming in the same subject would feel relatively less hot slightly more towards thermal comfort.

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So, there are different devices which are used for measuring these environmental parameters. We have data loggers which help us measure relative humidity as well as temperature, we have anemometers for air speeds, we have surface temperatures which are measured using the data loggers and thermometer surface thermometers.

We have the thermometers which are specifically used for measuring the wet bulb temperature where the thermometer is covered with the wick and which is moist which is wet and then it is rotated. So, it takes into account the rate of evaporation and hence the impact of humidity presence of humidity on the temperatures which is wet bulb temperature and then we have relative humidity which is measured.

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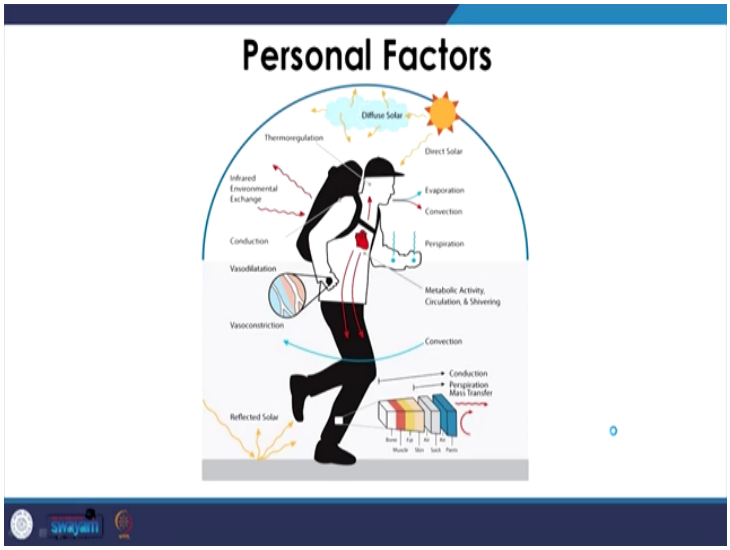

Now, we come on to personal factors. Now, personal factors are two – one is clothing and the other one is metabolic rate.

So, if we are properly clad when in woolen clothing winter clothing at the same temperature, we would feel comfortable because our clothing is heavy our Clothing value is high the second factor personal factor is metabolic rate. So, suppose I am in a given space and I am standing still or I am just sitting comfortably, I would have a metabolic rate which is low because I am not very active as compared to that and I am likely to be comfortable at lower temperatures while if I am say working out in a gymnasium my metabolic rate is very high.

So, when my body itself is producing heat I am likely to be more comfortable thermally comfortable at temperatures which are lower when I am at a sedentary when I am not working out much.

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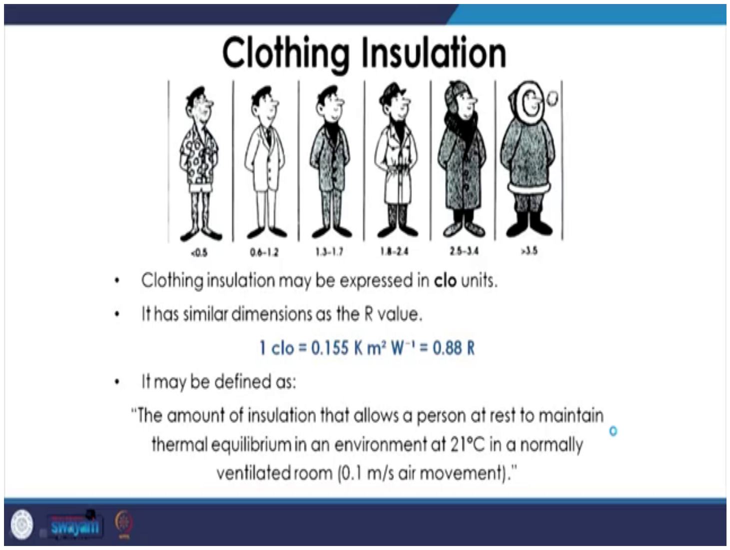

So, the first factor which we have is clothing insulation and it is expressed in Clothing value this it has a similar dimension as the R value or resistance. So, it is Kelvin meter square per watt which is the resistance offered by the clothing for the exchange of heat.

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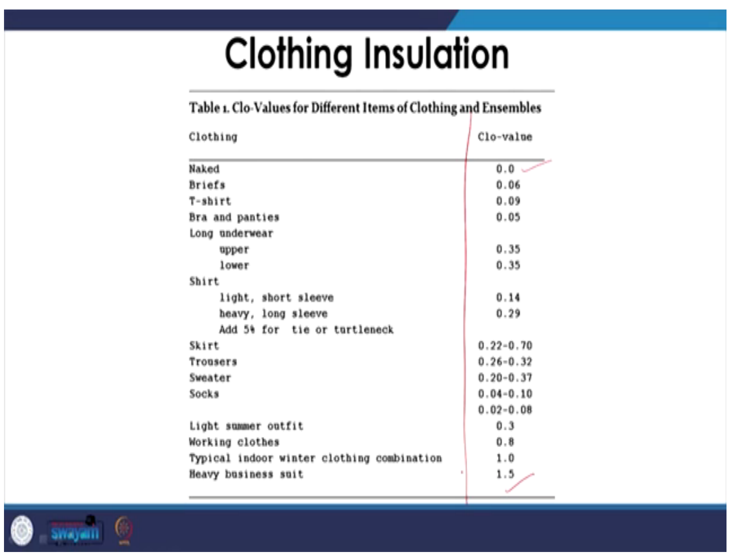

So, there are defined Clothing values, insulation values for different kinds of clothing patterns clothing types starting from 0 when the subject is not clothed at all to a very heavy business suit which may go as high as 1.5. So, by varying the Clothing values, we our clothing patterns we can feel comfortable for the given same set of environmental parameters.

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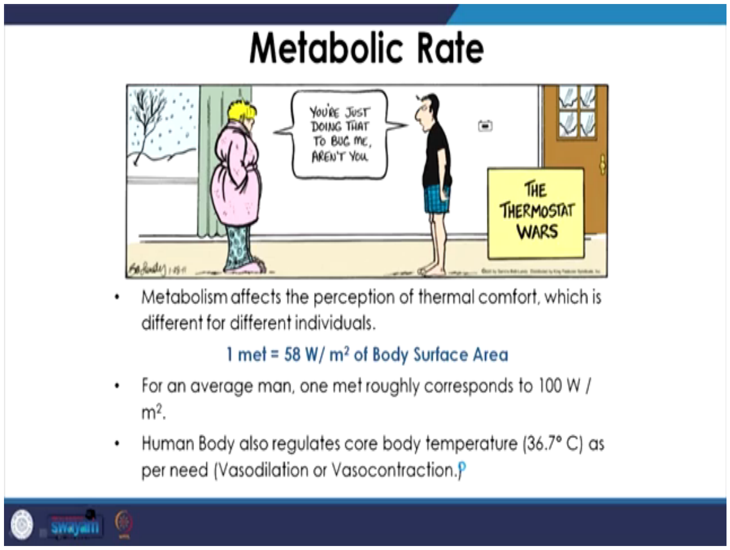

The next is metabolic rate. Now, metabolic rate varies from people to people from communities to communities from subjects to subjects and that is why the adaptive thermal comfort varies because from subjects to subjects and that is why different countries when they are developing their own energy conservation code, energy codes they take into account objects in those specific regions to define what is the adaptive thermal comforts.

If you look at India the world’s developed countries for example, US they already have their adaptive thermal comforts in place. India, in our country, we have also tried to develop an adaptive thermal comfort scale which is called IMAC where we have tried to understand at what temperatures are people comfortable the Indian subjects, tropical subjects. So, this is by virtue of the climate that the people are exposed to.

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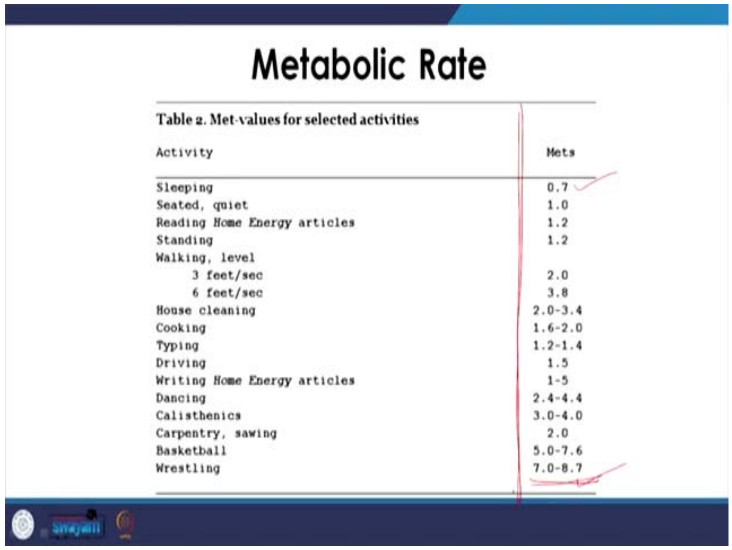

Table 2. Met-values for selected activities

Activity	Mets
Sleeping	0.7
Seated, quiet	1.0
Reading *Home Energy* articles	1.2
Standing	1.2
Walking, level	
3 feet/sec	2.0
6 feet/sec	3.8
House cleaning	2.0-3.4
Cooking	1.6-2.0
Typing	1.2-1.4
Driving	1.5
Writing *Home Energy* articles	1-5
Dancing	2.4-4.4
Calisthenics	3.0-4.0
Carpentry, sawing	2.0
Basketball	5.0-7.6
Wrestling	7.0-8.7

So, for different types of activities we are not talking about the subjectivity which is coming in because of the chosen subjects, but we are talking about the metabolic rate variation because of the different types of activities which are there. So, from sleeping which is the lowest of metabolic rate which is 0.7 Mets to an intensive activity sports activity; for example, wrestling where the metabolic rate is very high if a person is involved. So, based upon this we also have the metabolic rate.

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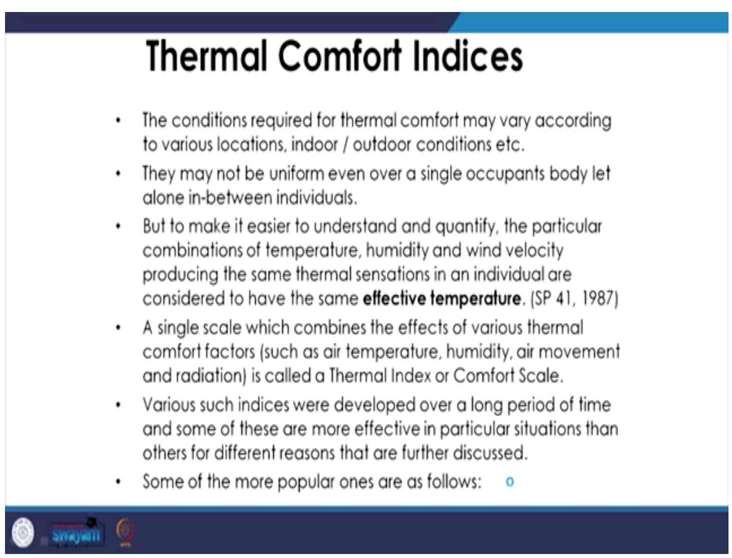

Now, all these six parameters which we have seen so far come together to give us a perception of thermal comfort. So, suppose the air temperature is high the relative humidity is low the radiation is also high, the air speed is also high the metabolic rate is low and Clothing value is also low.

Now, what is the combined effect of all these? How do we know that how do these parameters what is the weightage of each one of this whether a temperature is more important? So, usually we understand that oh it is very hot today, it is 42 degree centigrade. So, it is going to be very hot today, but we may not perceive it as that hot or maybe say 35 degree on some days with a very low humidity and a good wind speed will not be the same as 35 degrees with a high humidity. In a very humid place, the same temperature might be resulting in an environment which is absolutely uncomfortable, it is discomfort.

So, the attempt was made to understand how these different parameters interact together to give us a perception to give us a feeling of what thermal comfort is or whether it is comfortable or not. Now, this was called thermal comfort index. So, several attempts to develop thermal comfort index they have been happening across the world and different thermal comfort indices have been developed.

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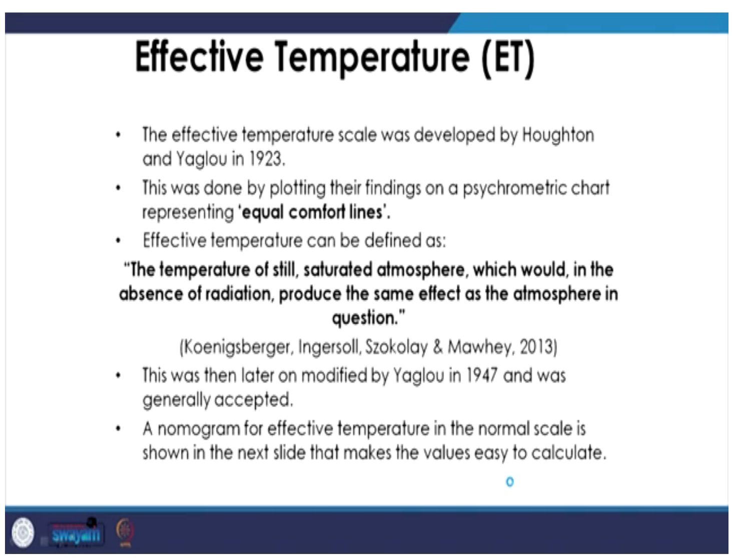

The first one was developed by Houghton and Yaglou in 1923 which was called effective temperature.

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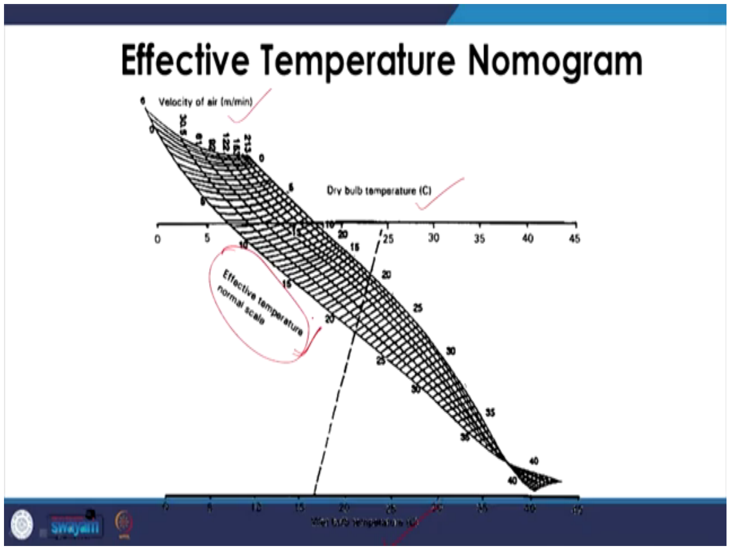

Now, effective temperature brought together three quantities three parameters – one is dry bulb temperature, the other one is velocity of the air and third one is humidity which is taken into account by wet bulb temperature. So, wet bulb temperature is always lower than the dry bulb temperature by virtue of the humidity which is present in the air. So, it combined these three quantities together and resulted in a quantity called effective temperature.

So, if we knew these three quantities, we would know the effective temperature and we would know whether at what range of the effective temperature would people feel comfortable. So, this was one quantity which put together three parameters, but this was not enough and more and more research started to happen starting from 1923.

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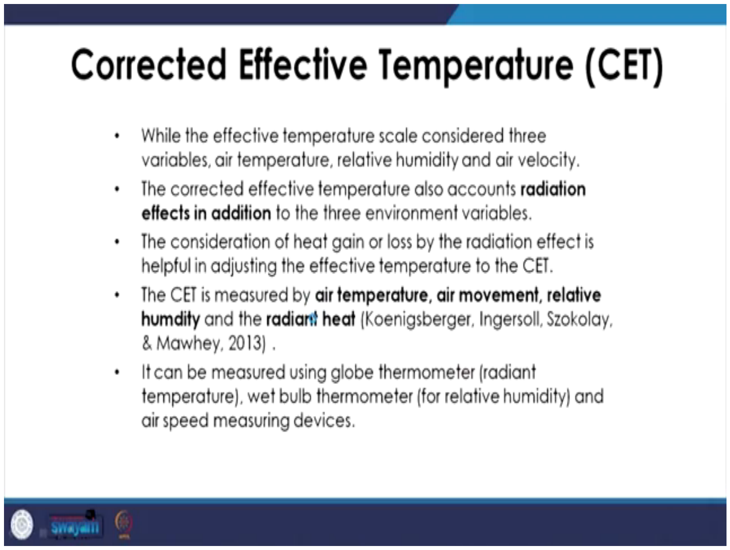

So, the next index which was developed was corrected effective temperature CET.

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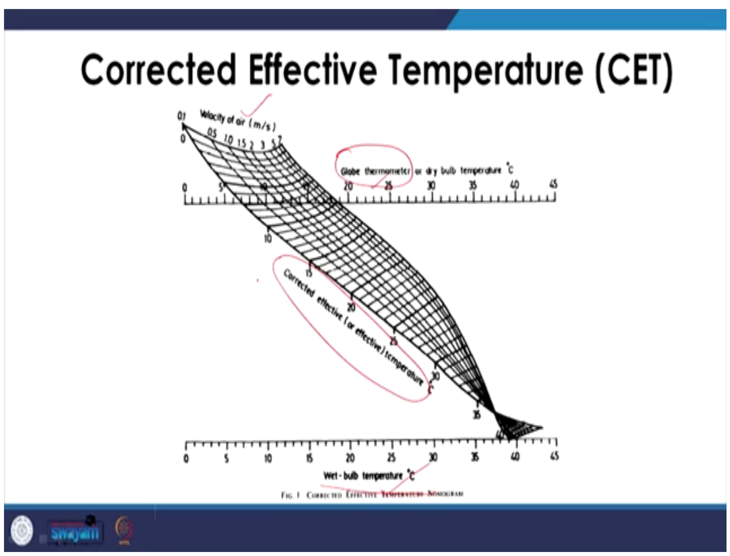

And, in CET the additional quantity which was added was the radiation the radiant temperature which was taken into account by replacing the dry bulb temperature with the globe temperature. The velocity of air remained the same and the wet bulb remained the same which was taking into account the relative humidity and the graph looks very similar the nomogram looks very similar, but it is it is not and the index now was called corrected effective temperature which took into account all the four environmental parameters.

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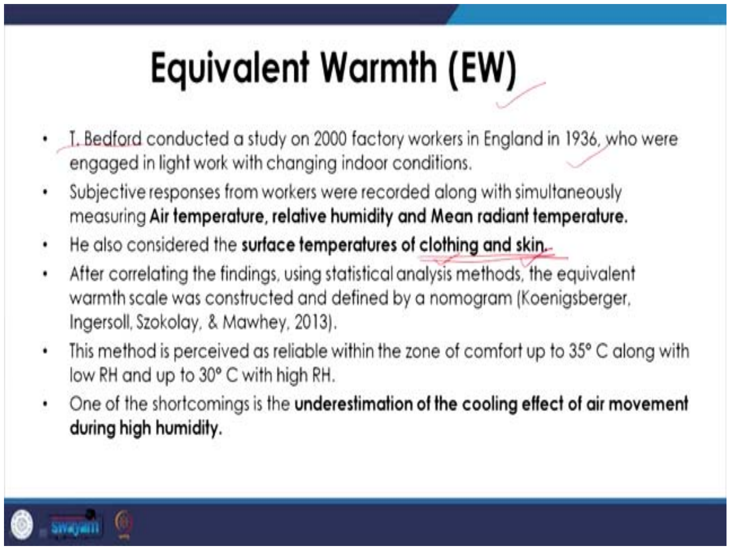

Now, more research was happening and new and new indices were coming into place. So, equivalent warmth was brought into was developed which was developed by T. Bedford in England in 1936.

Now, here for the first time he considered the surface temperatures of clothing and skin. So, in some way the clothing and metabolic rate was brought in, but it was not the units which we currently understand. It was only the surface temperatures of clothing and skin which were brought together. So, almost all the parameters including environmental parameter and the personal parameters were brought in.

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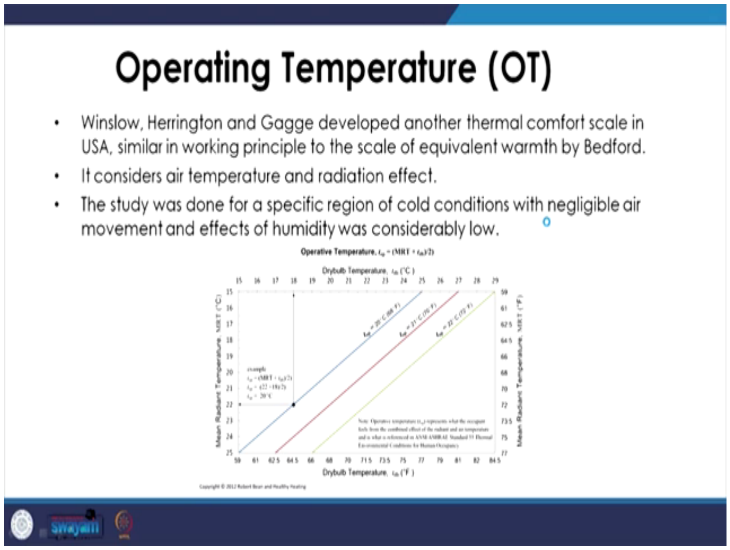

Very similar to the equivalent warmth another thermal comfort index was created in USA which was operative temperature and this particular study was actually done for the specific region of cold conditions with negligible air movement.

So, both in equivalent warmth and in operating temperature the air movement was considered to be almost negligible.

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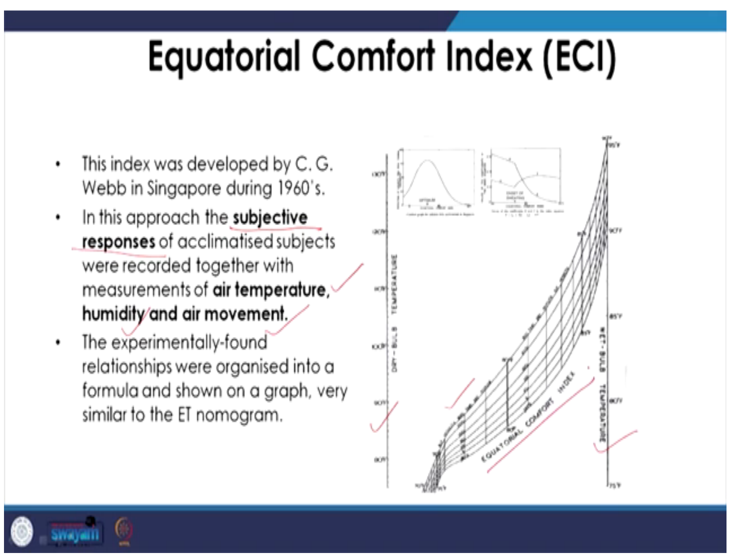

Another thermal comfort index was developed in 1960s which was called equatorial comfort index and it was developed in Singapore by C.G Webb and here the subjective responses and these responses were acclimatized. So, this equatorial comfort index was based upon these equatorial tropical subjects and they took into account the air, temperature, humidity, air movement and then recorded the subjective responses and this was organized. So, this was very similar to the effective temperature nomogram where we have dry bulb temperature what wet bulb temperature and humidity and air movement put together and the resulting in an equatorial comfort index.

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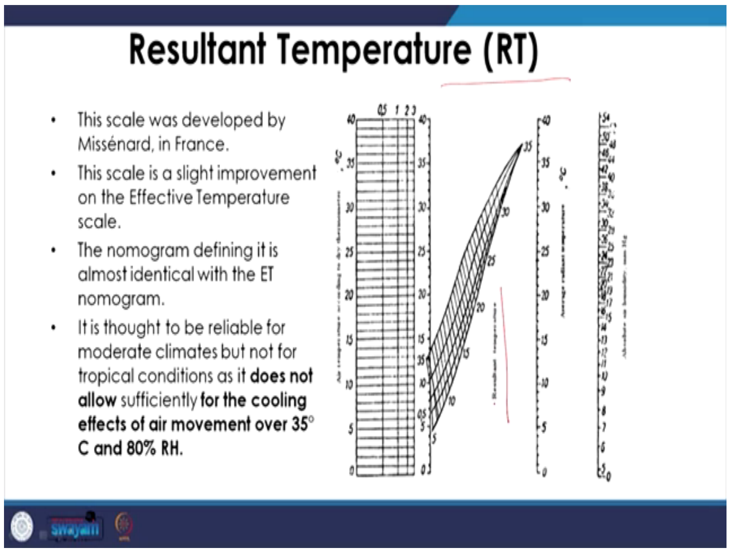

Many such indices were developed another one being resultant temperature which was also very similar to the effective temperature scale very close to that also. Again, taking into account the dry bulb temperature, the wet bulb temperature the air velocity and the resultant temperature again came out to be very similar to the effective temperature nomogram.

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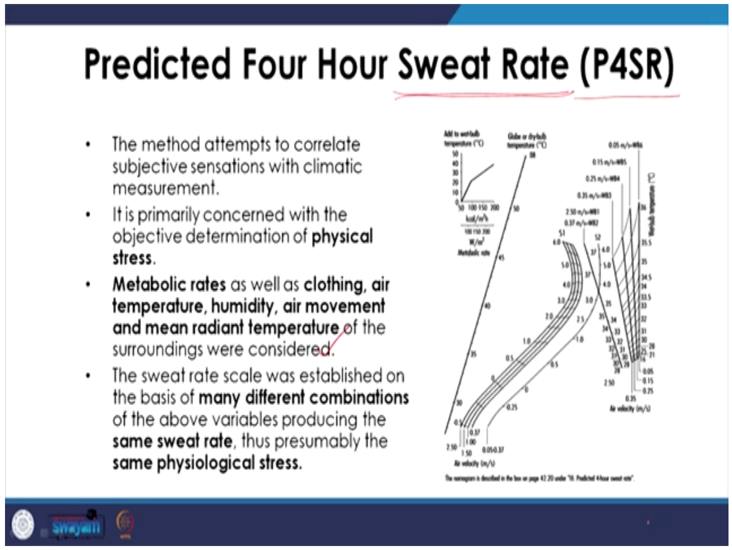

Another index which was slightly different from the all previous ones that we have discussed is the P4SR which is predicted for our sweat rate. Here the metabolic rate as well as clothing, air temperature, humidity, air movement and mean radiant temperature of the surrounding was considered for the first time in the same state as we understand today.

So, all these six parameters were put together and the index actually looked at the sweat rate, the 4 hour sweat rate to identify and to index the given circumstance to give to understand the given environmental condition and understand the thermal comfort implication of it whether it will be thermally comfortable based upon the predicted sweat rate.

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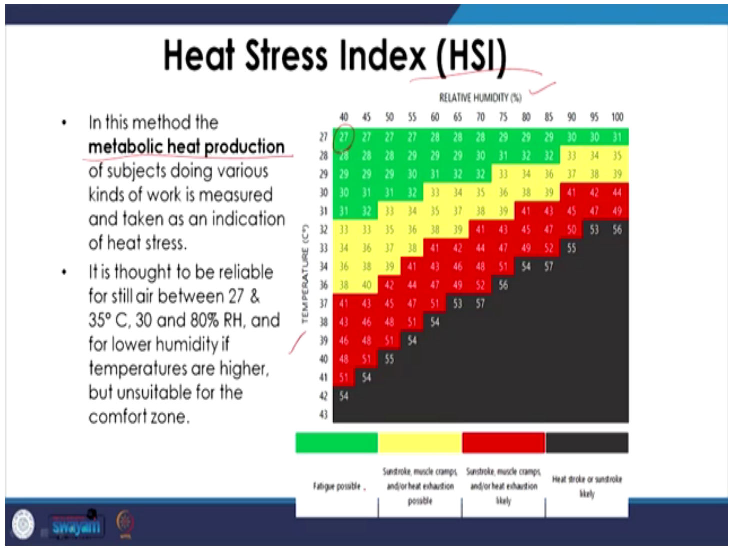

So, this was a new and an interesting concept another one was heat stress index. So, we have seen that gradually from the initial thermal comfort indices where only the environmental parameters were clubbed together gradually, we started moving on to indices which had metabolic rate and clothing values integrated with the environmental parameters.

So, this one heat stress index talks about the metabolic heat production of subject which would which was doing different kinds of works and it was actually talking about the stress heat stress on the human body based upon the temperature and relative humidity and the resulting heat stress which would lead to the different kinds of impacts on human body.

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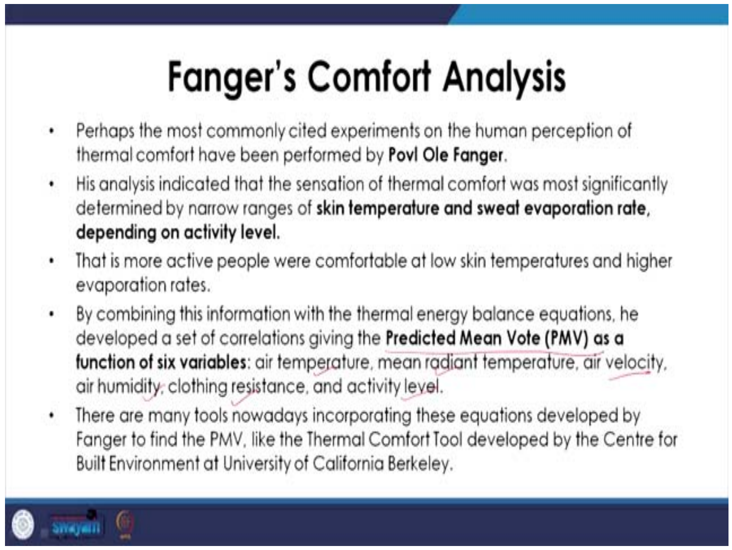

After all these the most commonly used the most popular comfort index which is used is Fanger's comfort analysis which was performed by P.O Fanger and it has become one of the most common popular tools for understanding thermal comfort. So, it was determined and it took into account all the six variables which were established by that time through P4SR and the previous ones. So, all the six air temperature mean radiant temperature, air velocity, air humidity, clothing and activity level were all took into account to develop the correlation to develop a set of correlation which gave the predicted mean vote.

So, whether for the given same set of parameters the environmental as well as personal parameters what would be the predicted mean vote as neutral which is 0 to thermally to hot or cold. So, what would the subject be voting this particular set of conditions as which was PMV was developed by Fanger's comfort analysis and that became a very common method of indexing in a very simple manner the environmental conditions.

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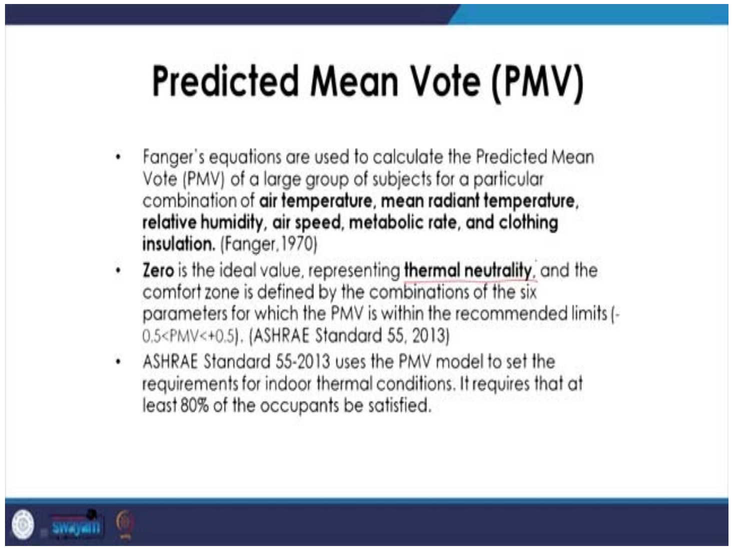

So, ASHRAE 55 which is the standard which we commonly use for understanding the thermal comfort use the same scale PMV to define thermal comfort and 0 was taken which was what we were seeing in the first initial slide of this presentation where a 0 expressed thermal neutrality and it would vary both sides besides 0 from minus 5 to plus 0.5.

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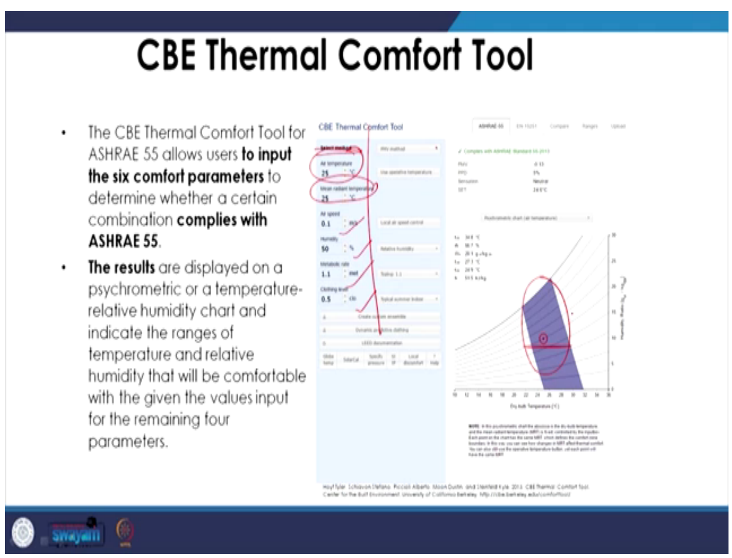

The CBE thermal comfort tool used the same data of ASHRAE 55 and the PMV the same method to understand from the user's perspective and give it on the basis of ASHRAE 55 whether the given set of condition is going to be comfortable or not.

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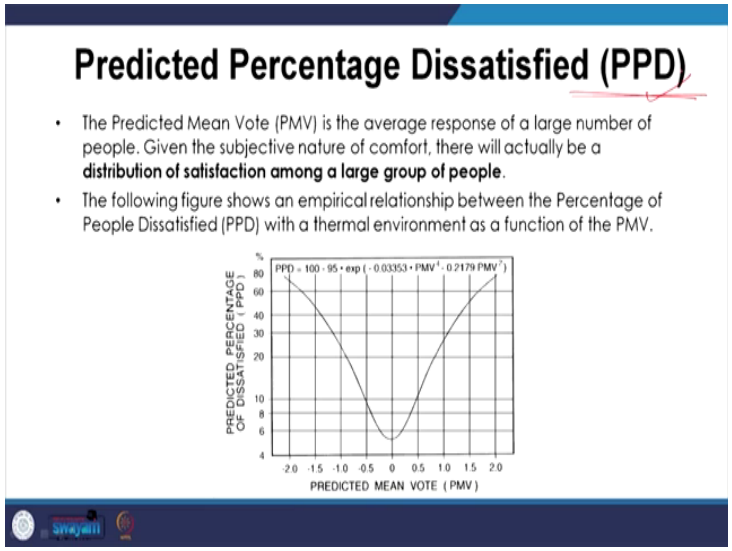

Now, this could be done on the basis of PMV method or adaptive comfort method where the user inputs the air temperature, the MRT, air speed, humidity, metabolic rate or clothing level and bringing all six of them together to give you a condition which as per PMV the fixed thermal comfort mode whether it will give you a condition which is comfortable or not. If it was the adaptive comfort method which we could select from here, we could also see from adaptive thermal comfort point of view whether the given set of condition is thermally comfortable or not.

The inverse of PMV was understood as PPD. So, if there are there is a predicted mean vote where more people would say that I am comfortable, there is also a percentage of people who are predicted to be dissatisfied. So, there was a relationship between PMV and PPD, and PPD also became the measure of understanding how many people in a group will remain dissatisfied at the given environmental conditions set. So, this was also used.

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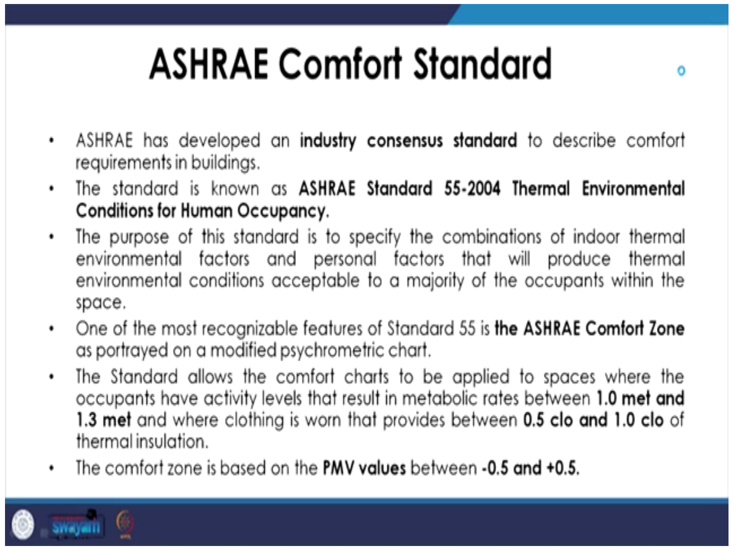

Now, ASHRAE comfort standard which is ASHRAE 55 which was developed in 2004 defined all these six parameters to define a range of conditions which will be perceived as thermally comfortable. Now, this is not adaptive thermal comfort this is based on PMV values between minus 0.5 to plus 0.5 and it defines that within this range of minus 0.5 to plus 0.5 people are going to remain comfortable. They are most likely to feel comfortable.

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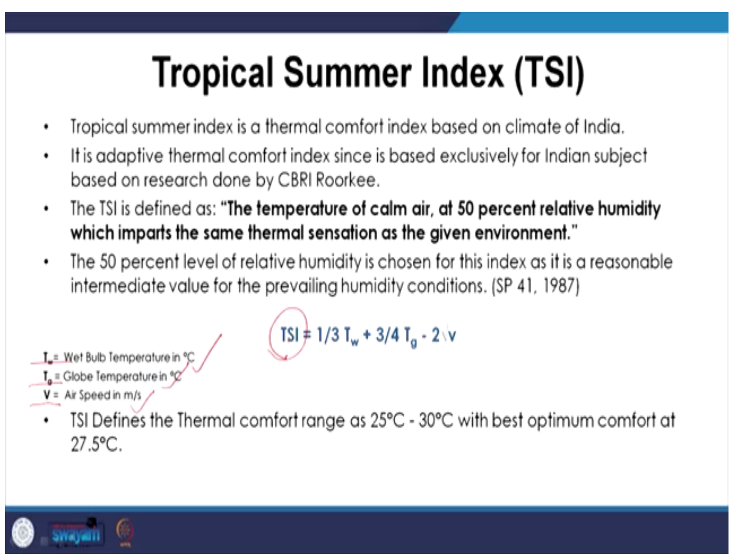

The thermal comfort index which was developed for India by scientists from CBRI Central Building Research Institute at Roorkee they developed an adaptive thermal comfort index because it was exclusively based on the study of Indian subjects human beings within the tropical climate of India and it took into account the wet bulb temperature, the globe temperature and air speed. So, we are taking into account the radiation, the dry bulb temperature, humidity and air speed.

So, all four environmental parameters were taken into account and the subjects were tropical subjects. So, we were taking in through this we are taking into account the adaptive thermal comfort. However, no specific consideration for the clothing value and the metabolic rate has been taken through the tropical summer index. Yet because tropical summer index is based on the study of Indian subjects it is very close to the experience of tropical Indian subjects as far as thermal comfort is concerned.

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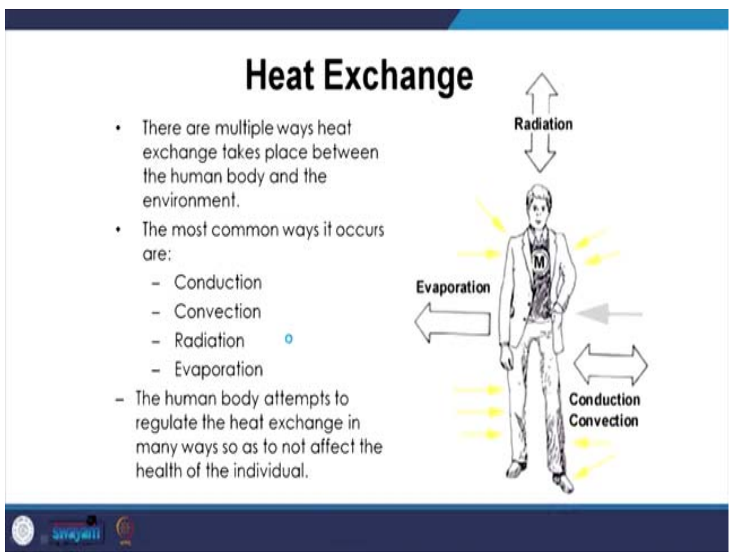

Now, once we have understood that these six parameters are responsible for defining the thermal comfort, we have to quickly revise the ways in which heat exchange takes place between different bodies.

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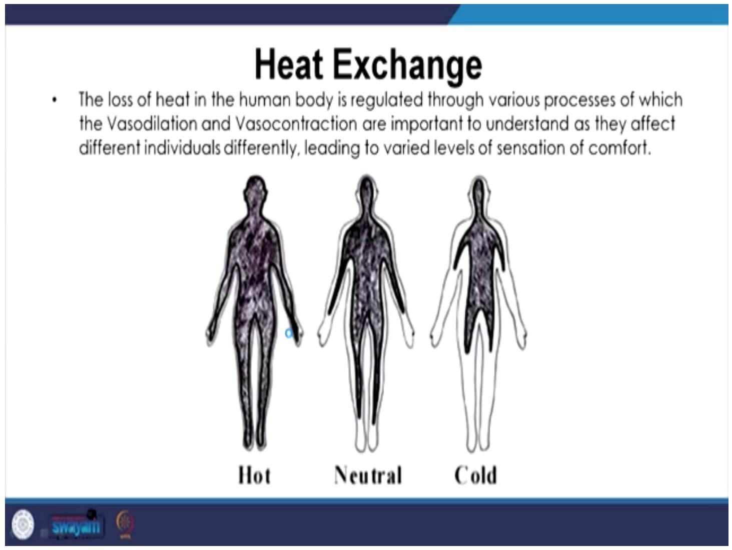

So, let us quickly go over this.

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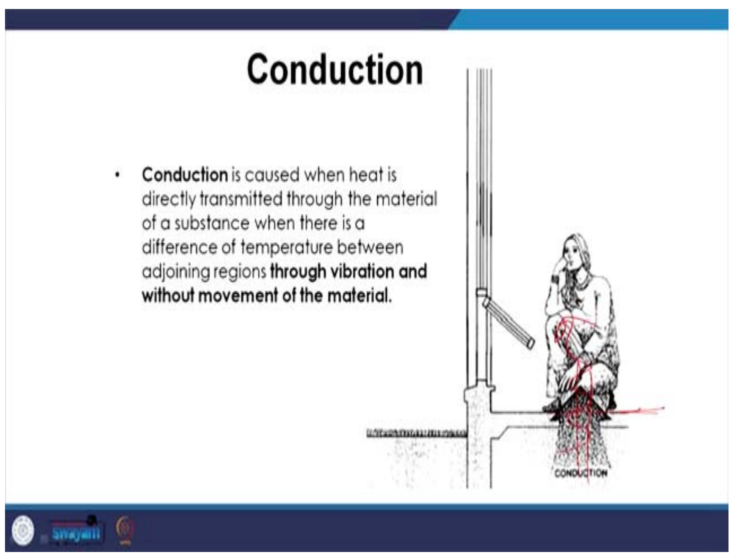

So, one first is through conduction where the heat transfer is happening through the material of a substance when there is a temperature difference between adjoining regions and it is through vibration and without movement of that material. All of us very clearly understand that when we are in direct touch with a surface with a body that is when without movement of a material the heat transfer heat exchange takes place which is conduction.

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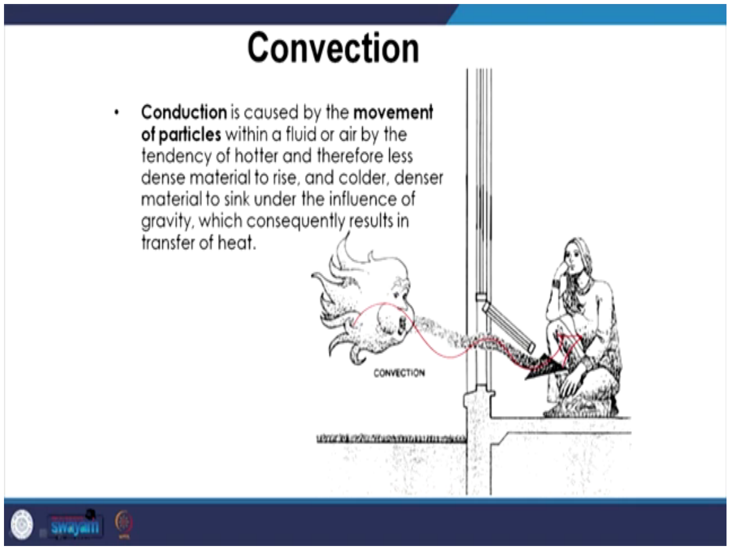

Convection is which is the heat transfer is caused by the movement of particles. So, through the movement of air, this is convection.

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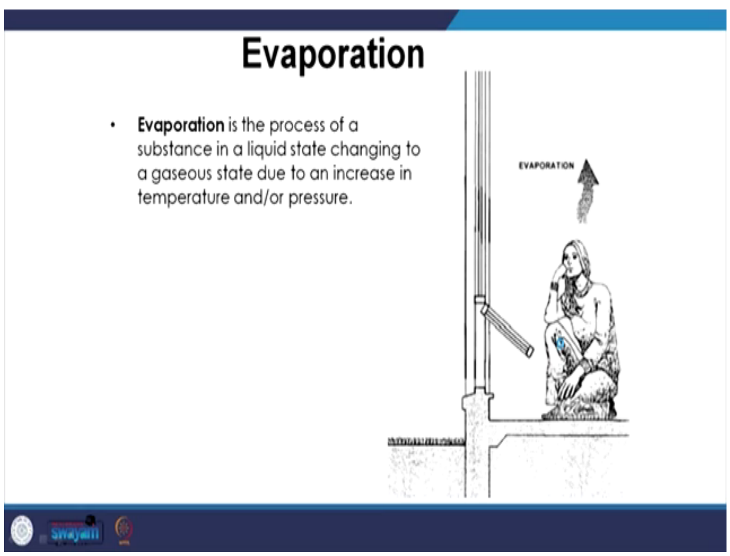

Then, we have evaporation which is the process of change of state from liquid to vapor to gaseous state. So, the process of evaporation is also a way of heat exchange.

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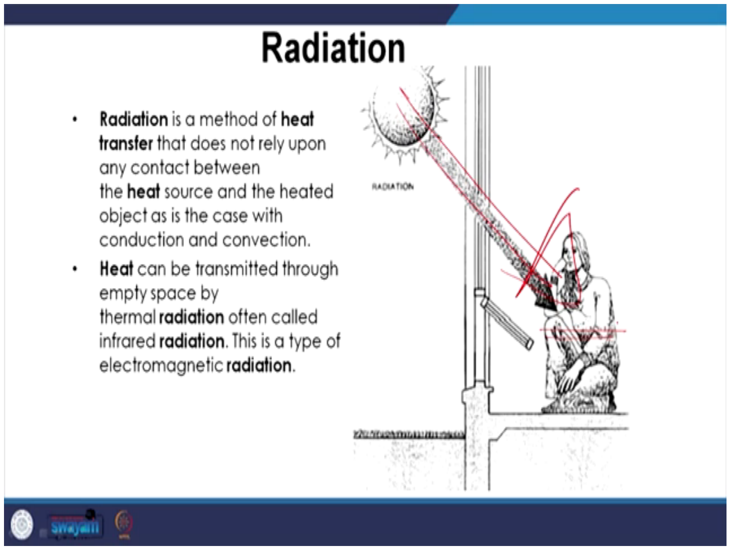

Then is radiation which is the method of heat transfer where there is no direct contact between the source and the sink and the radiation is directly taking place without a medium and the direct radiation is reaching the sink the body that is radiation.

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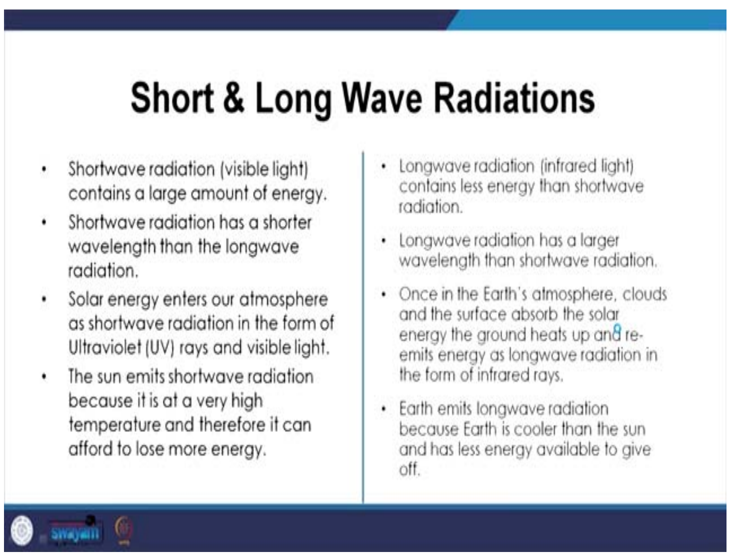

So, all these four ways of heat transfer are responsible for causing the heat exchange into a building. So, a building both receives heat and it loses heat through either of the four mechanisms conduction, convection, evaporation or radiation. Evaporation is added here because the buildings because it is very important for designing the buildings and understanding the physics behind performance of buildings.

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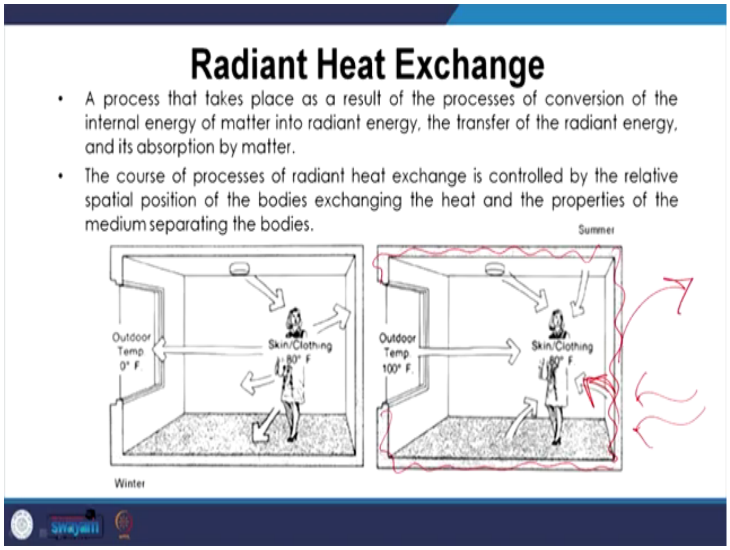

So, we have radiant heat exchange where these surfaces the surfaces of the building absorb the heat during winters and then they transmit the heat inside and they re-radiate the heat to outside as well.

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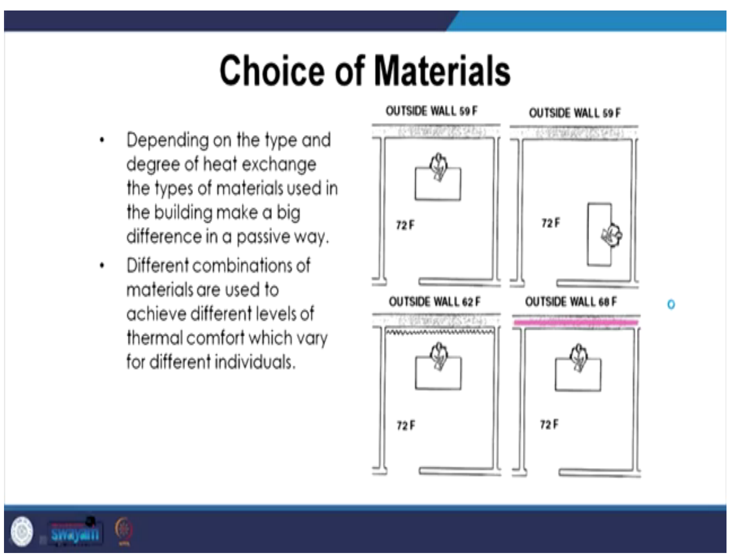

Once we understand that how this heat is going to be transferred it may be from outdoor to indoor or indoor to outdoor depending upon the climate of the place and depending upon the season, we have to choose our design features carefully, we have to choose our materials very carefully. So, for example, we are in an extremely hot dry climate where the outdoor temperatures are very high. So, and there is very strong radiation which is present.

Now, the heat exchange will happen take place from outdoors to indoors through one is conduction. So, the heat which is absorbed by the walls of the building will conduct that heat to indoors; second is through conduction. So, the hot air from outside will be traveling to indoors and that is by way of conduction there is radiation when the sun direct sun is entering the building the indoors. So, that is by radiation. Now, these three have to be controlled by through design.

So, through conduction if we have to control, we make the mass thick. So, thicker the world lesser is the heat which is conducted because more will be absorbed within it. Convection, so we use feature such as Jalli. So, the hot air because it will be passing through these small holes, pores will lose out it is heat and cool down by the time it is transferred to indoors. For radiation we provide the shading devices we provide Jharokas, we provide Chajjas, we provide over overhangs, so that the direct radiation is cut off.

So, these fundamentals of heat exchange are important to understand because then we can design the buildings appropriately for the given climate and for the given context in which we are working. So, that is all for this lecture today.

Thank you very much and see you in the next lecture.