The hostel building shown above is a facility forming part of The School of Advanced Studies of TERI at Vasant Kunj in New Delhi. It is comfort cooled with an EAT system working in tandem with a Direct Evaporative Cooling plant

EAT and Comfort Cooling (and Heating)

Part 1 of 2

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Abstract

The Earth Air Tunnel (EAT) provides cooling in summer and heating in winter by exchange of heat between the air and the soil. This exchange of heat occurs because the temperature of the soil at a depth of 4-5 m from the ground- surface will be approximately constant, close to the average dry bulb temperature of the ambient. This article covers the fundamentals, design, principles of working, description of the EAT system, and the basis of design and calculations of the tunnel performance.

The design as well as the performance of EAT has been carried out by using computer simulation. The article includes several graphics obtained from the simulation program.

The article explains how the EAT systems can be seamlessly extended to the design of building cooling and heating systems. The significance of EAT systems for HVAC in the form of providing pre-cooling, pre-heating - and also, as a part of Mixed Mode Systems, is brought out in the article. But the focus remains essentially on Whole Building Cooling (WBC).

The article introduces the concepts of the Adaptive Model for comfort in which the comfort temperature selected for the built-in space will vary over a relatively large range. The worked example presented shows how to arrive at the comfort temperature for given ambient dry bulb temperature. Also included in the example worked are calculations for sizing air cooling (evaporative) plant down stream of the EAT.

There are a few EAT systems working

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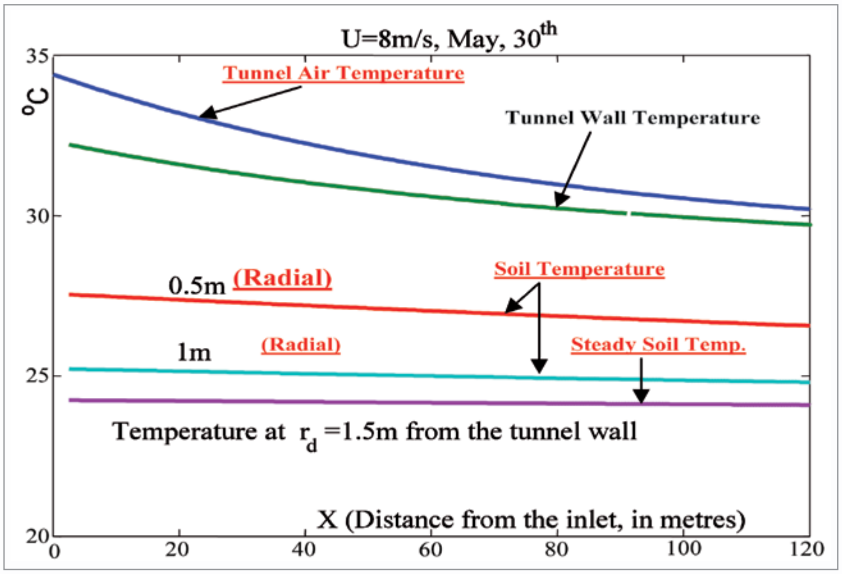

Figure 1: Tunnel, Soil and Air Temperatures (May 30th)

in the country. Apart from the obvious attraction of low energy consumption, its unique feature is that it is also effective in winter heating. The importance of the EAT systems in today's scenario is that they achieve both cooling and heating without resorting to either mechanical cooling or external heating. In the event the temperature of air leaving the tunnel does not meet the requirement of the project, the additional cooling or heating required can be supplemented by external sources, but the quantum of total energy supplied for heating is reduced spectacularly.

EATs have the potential to become one of the major players in the category of "Passive Cooling Systems (Natural Cooling Systems)", which help meet challenges to Sustainability. A large number of EAT Systems have been installed for cooling and heating of buildings in several countries - Europe, US and elsewhere. Though a considerable amount of spadework has been done in our country, there is still a long way to go. However, there is vast potential for EAT systems waiting to be tapped.

The Concept

The EAT leverages on the fact that the soil temperature at a depth of 4.5 to 5 m below the surface remains steady throughout the year even though the ambient temperature varies a great deal.

EAT consists essentially of a network of concrete pipes (commonly called Hume pipes) which cool / heat the outside air for delivery to the controlled space. Once heating or cooling has been achieved, the air is transported and distributed thereafter to the space served, by fans, ducting and such other familiar elements of an air distribution system. The system could also include elements like Air Washers, Cooling Coils and Heaters, if required and desired.

Conventionally, EAT is applied in HVAC plants for pre-cooling / pre-heating ventilation (outside air). In this article however, focus is on application of the EAT system for total cooling / heating of buildings with emphasis on cooling rather than on heating.

The Way EAT Works

Air is drawn in from the ambient, and is cooled or heated as it passes through the EAT. For clarity, consider the case of operation during summer when the soil is cooler than the ambient and the air is going to be cooled. The heat is transferred from the:

1. air to the pipe walls by convection
2. pipe walls into the soil by conduction.

Thus, with time the soil gets warmer as the summer season progresses and its 'Cooling Capacity' reduces.

Pipe length (L), pipe diameter (d), pipe spacing (lateral distance between pipes), velocity of the air (U) in the pipe are the main design variables. The soil properties like thermal conductivity, thermal diffusivity and density also affect the tunnel performance.

Tunnel Performance – New Delhi

Tunnel, Soil and Air Temperatures at U=8 m/s & X=120 m (Summer)

Most of the discussion will be related to a case study done for Delhi climate. *Figure 1* shows - as a function of distance from the tunnel inlet - the air temperature, the tunnel wall temperature, and the soil temperatures at several radial distances from the pipe wall. Two points may be noted - 1) the soil temperature at a distance of about 1.5 m from the tunnel wall is around 24°C, the annual average dry bulb temperature in Delhi.

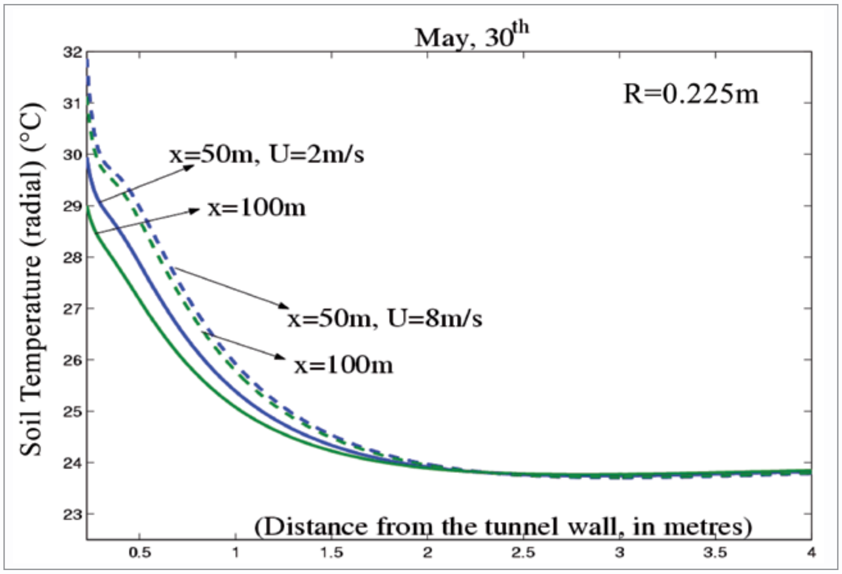

Figure 2: Soil Temperatures v/s 'R' at U = 2 & 8 m/s and x = 50 & 100 m (May 30th)

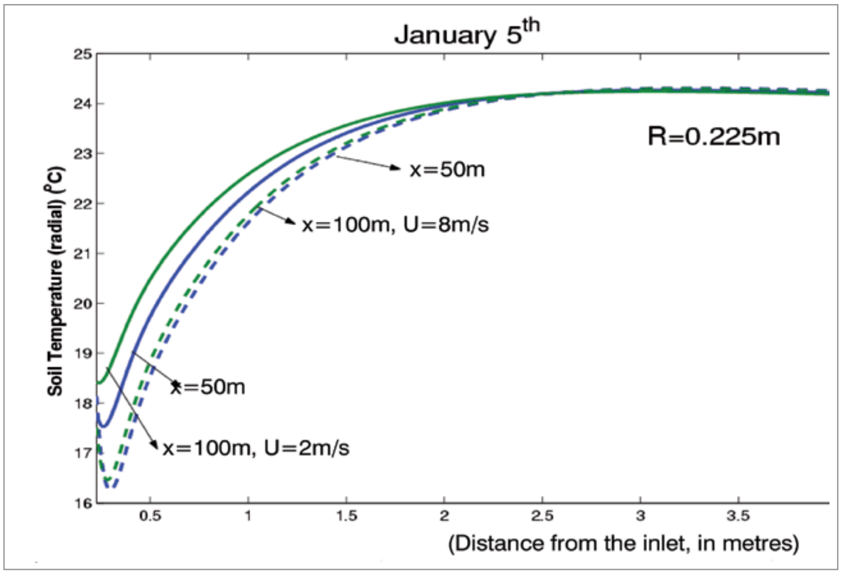

Figure 3: Soil Temperatures v/s 'R' at U = 2 & 8 m/s and x = 50 & 100 m (January 5th)

2) the air temperature reduces from the ambient value of 34°C to about 30°C at distance of 120 m. The significance of this is that it is unnecessary to go for a longer tunnel. At this distance the tunnel air temperature and pipe wall temperature are nearly the same. The data are for U=8 m/s on May 30, and are obtained from computer simulation of transient heat conduction in the soil and convection in the pipe.

Air and Soil Temperatures at U=2 m/s & 8 m/s and X=50 m & 100 m

Figure 2 shows the radial variation of soil temperature on May 30 at two air velocities (2 m/s and 8 m/s) and at two axial locations (50 m and 100 m). As noted above, the soil temperature at distance of 1.5 m from pipe is 24°C. It may be noted that at the higher velocity of 8 m/s though the outlet temperature is higher, the distance at which the soil temperature reaches 24°C is same as that for V=2 m/s. This distance roughly gives the required lateral spacing between pipes. The variation of temperature in the soil is due to both the conduction and the thermal storage effects. The soil is gradually heated (by the air) from the starting of summer.

Tunnel, Soil and Air Temperatures at U=8 m/s & X=120 m (Winter)

In the winter months, the reverse occurs: the air gets heated as it passes through the tunnel. *Figure 3* shows the radial variations soil temperature for January 5. In contrast to the summer months (*Figure 2*), the soil is warmer than the ambient, but still at 24°C at 1.5 m from the pipe surface.

3-Year Performance :

Figure 4 summarizes the performance of an EAT in Delhi over a period of three years.

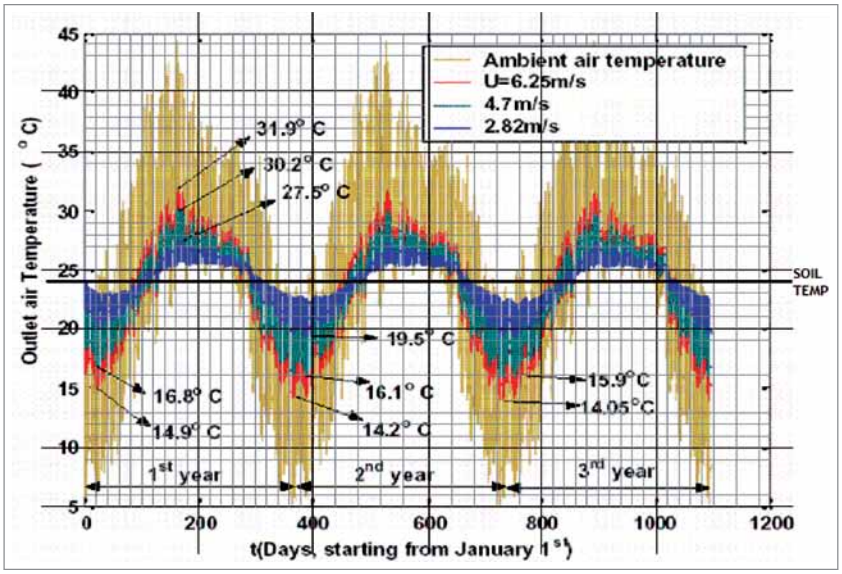

Figure 4: Tunnel Performance over a 3-year period (New Delhi)

The temperature of the air leaving the tunnel depends on air velocity; the 'performance' is better – lower peak temperatures in summer and higher lows in winter – for the lower velocities. However, if further conditioning is required – reduction of temperature, for example, other elements like DEC, IDEC+DEC (Direct Evaporative Cooling & In Direct Evaporative Cooling) cooling coils, heating coils... as described may be used for this purpose.

Layout of EAT Pipe Grid

The layout of the pipe grid is shown in *Figure 5a* & *5b*. For pipe length required see *Figure 1*. Spacing information is available in *Figures 2 & 3*.

The spacing of pipes – both the rows and the columns - is determined by the computer simulation outputs. See *Figures 2* & *3*.

Daily Usage Pattern

Simulation results shown (*Figures 1, 2* & *3*) are for a tunnel operating 24 hours a day and throughout the year. However, optimization is possible for any desired working pattern Fox example, for an office building working only during daytime, the tunnel may be 'rested' at night times. This aspect is discussed later in the article. Further, double staging of pipes (using two EAT systems in series) may be employed to improve the performance. The decision to employ double staging will be based on economic considerations – performance enhancement vs extra cost incurred.

Value of Steady Soil Temperature

While the ambient (air) temperature varies through out the year, there is little variation in the soil temperature. This steady temperature will occur at a depth of 4 - 5 m. The soil temperature (which is close to ambient temperature

continued on page 54

continued from page 50

at the surface) falls gradually - during summer; it is the other way round in winter. The "steady" temperature of soil is approximately equal to the average air temperature over a period of the year (this is about 24°C for Delhi).

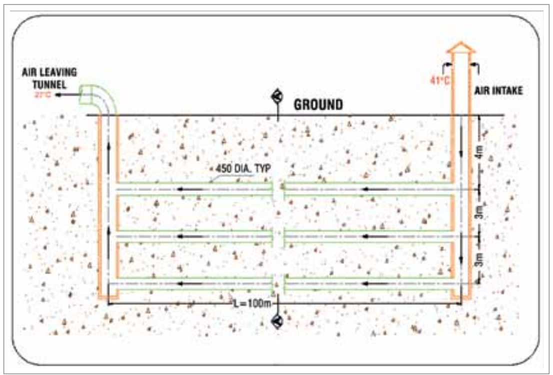

Figure 5a: EAT diagram - longitudinal section

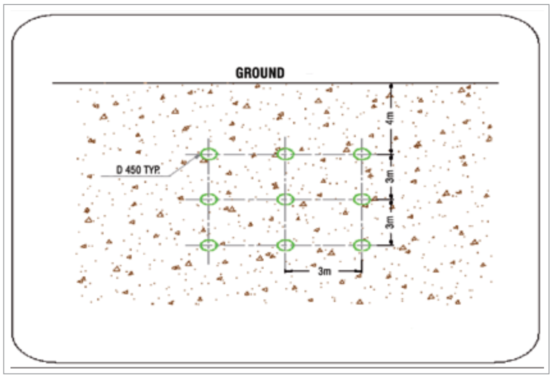

Figure 5b: EAT diagram - transverse section

Potential and Limitations in Performance

The process that the air undergoes in an EAT system is essentially a constant dew-point process. (Cooling occurs without addition of any moisture). The lowest tunnel leaving temperature that can be attained theoretically is the steady temperature of the soil (which in turn, is the average ambient dry bulb temperature). This may be contrasted with the EC (Evaporative Cooling) system, which is essentially an adiabatic (constant wet bulb) process – involved in evaporation of moisture (to saturation) into the air. In practice, the closest that the leaving air temperature can approach the steady temperature of the soil, depends on efficiency of the tunnel.

Resting the Tunnel

At the end of the cooling period (in summer) - say 6 PM in the evening every day, the tunnel or the soil around it will become warm due to absorption of heat from air through out the day. Some recovery of the tunnel soil temperature is possible and also the loading on the tunnel is reduced, during night hours, but such recovery may not be adequate for providing necessary cooling the next day. This situation can be tackled by totally shutting off the tunnel during the night, and using a duplicate tunnel, which has not been used earlier during the day.

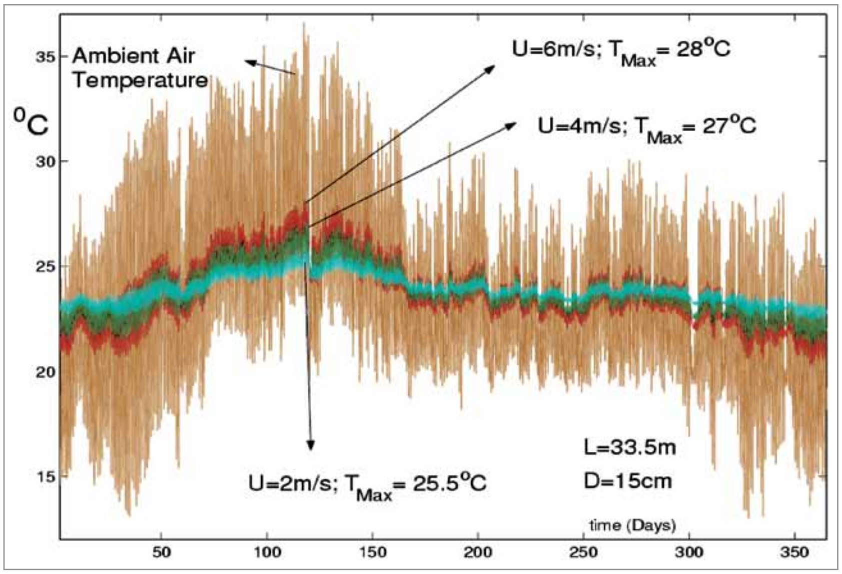

Figure 6: Tunnel Performance over a 12-month period (Bangalore)

Winter Performance

In winter, the tunnel air leaving temperature will be around 16 - 17°C. With this temperature the room can be maintained at about 20°C. Higher temperatures, if they are desired, can be obtained by supplementary heating. It should be noted in this context that in Delhi, the heat losses in winter will be relatively low – compared to summer heat gains. Accordingly, for the same airflow rate as in summer, the difference between room temperature and supply air temperature can be kept around 2 to 3°C to meet the heat losses or alternatively the airflow rate can be reduced. In other words, the required output of the tunnels in winter will be substantially less than the output called for in summer. The supplementary heating by external sources may be provided by solar heating also.

Monsoon Performance

In monsoon, the tunnel is not as effective as in summer and winter, but performs better than the Direct Evaporative Cooling (EC or DEC) system. Conditions can be improved if desired, by adding mechanical refrigeration (chilled

continued on page 56

continued from page 54

water coil). This needs to work only in the monsoon season. Usually, this requirement does not call for any additional cooling capacity, because the air conditioning plant selected to meet summer cooling requirements will have surplus capacity in monsoon season.

Tunnel Performance for Moderate Climate (Bangalore)

EATs may be used in a moderate climate like that obtained in Bangalore. Smaller sized tunnels will suffice. *Figure 6* shows the simulated performance of an EAT for Bangalore. Except for some periods in summer when the temperature exceeds 27°C for velocities of 4 m/s and 6 m/s, the temperatures of the air from the tunnel are comfortable. Alternately, the velocities can be lowered to achieve lower air leaving temperatures.

Favourable Factors for Application of EAT

Factors which favour application of EAT systems are a) adequate land space, b) a site free from rocks, boulders etc., c) a low water table, d) possibilities of excavation from a depth of 5m and below, e) high soil density, f) high soil thermal conductivity and g) low thermal diffusivity. And conversely, the absence of these requirements will constitute adverse factors for application of EAT systems.

EAT can be used for either whole building cooling or heating or for providing pre-cooling and pre-heating for buildings with air conditioning plants. This represents an advantage over IDEC+AW (Air Washer) systems from which pre-cooling (of OA) cannot be obtained since the cooling obtained is from a constant WB process.

It is particularly interesting to note that EAT is especially suitable for rural applications. Public buildings like community halls, taluk offices and district offices. Farm houses and bungalows could also benefit from EAT systems. This is because land is likely to be readily available in rural areas at affordable costs. A large part of EAT system work involves burying pipes underground - with associated excavation and back-filling requirements. Labour costs are likely to be lower in rural areas. Thus the potential for EAT systems appears to be high in rural areas.

Not all areas in big projects (software parks, malls, hospitals, resorts...) require air conditioning everywhere. Typically, dining halls, recreation areas and assembly areas for functions, come under this category. Potential exists for EAT or EAT+EC installations in such facilities.

BMS system, which can control the speed of fans and pumps – to minimize energy consumption at part loads will help boost energy saving. Providing a BMS will also offer all other facilities (including data acquisition) that a BMS system is expected to provide. Operating strategy for a plant should be carefully planned and meticulously implemented to exploit the low energy characteristic of the EAT system.

All things considered, the most important characteristic of the EAT system is the low energy consumption. Note the COP arrived at in the worked example. At 28.57 (*Table 4*), it represents a spectacularly high value compared with all existing HVAC systems.

Comfort Conditions

Referring back to *Figure 4,* it will be seen that the outlet temperature (which is same as DB temperature of air leaving the equipment) is available for all inlet temperatures experienced (in New Delhi) during the entire year (reference: WeDCo). Such data helps to determine the conditions achievable in the built space under various ambient conditions. The next paragraphs present a discussion on built-space comfort conditions.

The Fixed Temperature Approach/Standard

Comfort conditions, as most amongst us understand is the 23°C Standard or 23°C Paradigm. This is based on ASHRAE Standard 55. Ranges and tolerances for DB, RH and air movement have been stipulated but they are narrow being - ±1°C, ±5% RH, 0.2 to 0.5 m/s air movement. No doubt, summer and winter design conditions are differentiated, but that has not improved the acceptable comfort range significantly **(Range in the Fixed Temperature Standard being 8.4°C while the corresponding value is 14.6°C in the Adaptive Model)**. Also this effort has elicited the comment from an eminent worker in this field, that it is based "on crude assumptions for clothing and metabolic rate". This gives rise to another name for this Standard viz., The Fixed Temperature Standard.

Standard 55 duly takes environmental factors (DB, RH and air movement) and physiological factors (skin temperature and metabolism) into consideration. However, adaptive capabilities inherent in people are not factored in adequately.

Buildings built to Fixed Temperature Standard have often given rise to buildings which are too cold in summer or too warm in winter with the result being that the energy consumption due to HVAC is seen to be high.

Above all, it does not allow any significant increase in summer comfort temperature for non-ventilated buildings.

The need to exercise the option of going for higher comfort temperature during summer for NV (Non Ventilated) buildings and semi-air-conditioned buildings, especially in tropical regions has lead to an earnest search for a variable temperature model or guidelines or standard. Achieving success in such a search

continued on page 58

continued from page 56

will go a long way to legitimize the exercise of option for higher comfort temperature. In what follows therefore, we shall concentrate essentially on a Variable Temperature Model (which features the adaptive principles) to select the Comfort Temperature; references and comparisons will be made to the Fixed Temperature Model, but mainly to help gain an understanding of the Variable Temperature Model more readily.

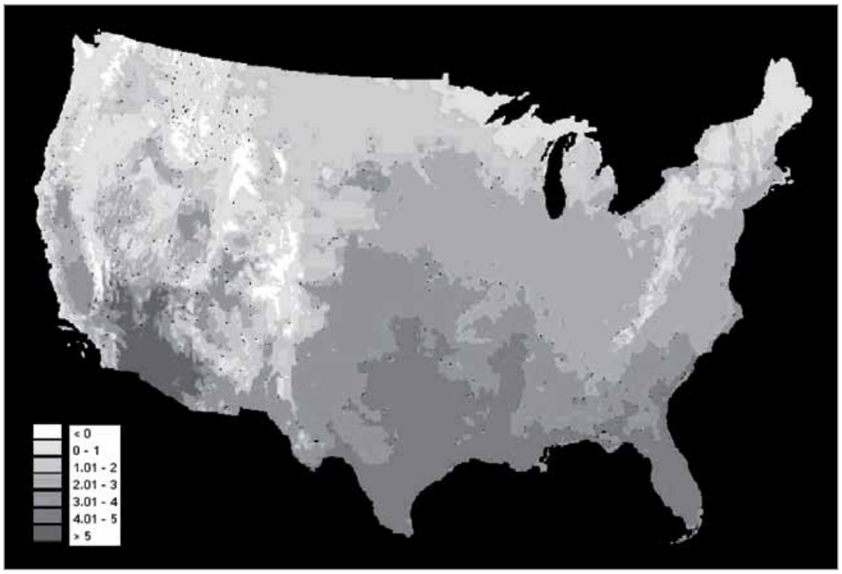

Figure 8: Comparison of recommended indoor comfort temperatures, upper limits of ACS Vs. ASHRAE Std., 55. Darker areas indicate larger differences between setpoint temperatures and therefore larger energy savings

Note that near maximum savings corresponding to a difference (5°C) between ACS and fixed temperature standards and savings when the difference declines to 4°C are in the areas likes Texas, Arizona and New Mexico. They correspond to warm areas. Large areas in our country would fit in to these categories. Application of ACS to such areas would therefore result in huge energy savings.

Variable Temperature Approach - The Adaptive Approach/Standard

The Variable Temperature Model is also known as the Adaptive Comfort, Adaptive Approach and Adaptive Approach Model; the currently applicable Standard based on Adaptive principles is known as The Adaptive Comfort Standard (ACS).

The Adaptive Principle is – if a **change** occurs such as to produce discomfort; people react in ways which tend to restore their comfort. By linking the subject's perception of comfort to the change and reaction, the Adaptive Principle introduces **context** as a factor in comfort.

The **prime contextual variable** is the **climate.** Climate has an overarching influence on the culture and thermal attitudes of any group of people and on the design of the building they inhabit. The heat exchanges between the body and the environment may not change with climate but there are a number of detailed ways in which people are influenced by the climate they live in and these play a cumulative role in their response to the indoor environment.

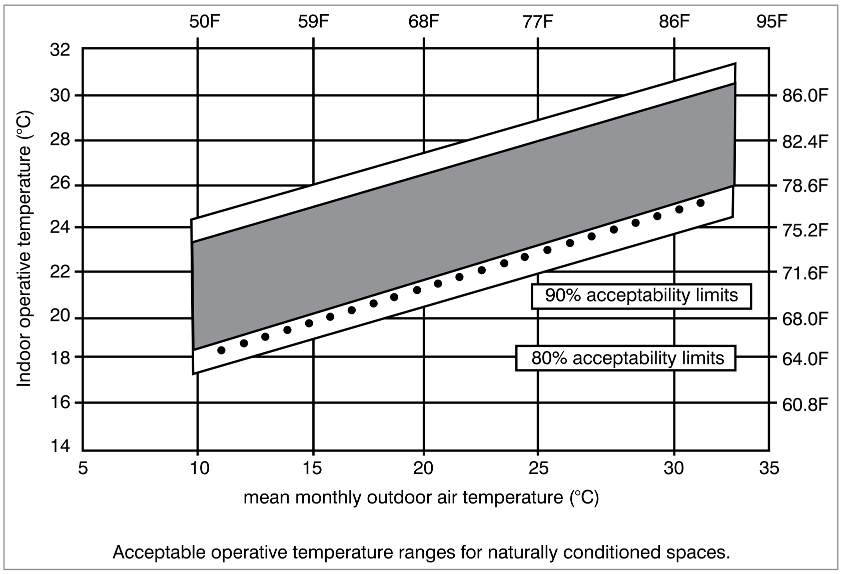

Figure 7: Acceptable Operative Temperature Ranges for Naturally Conditioned Spaces

Recognizing that climate - especially, the ambient temperature is a major influence on the sensation of comfort, the Figure above shows the Indoor Operative temperature against mean monthly outdoor temperature. Note that the Operative temperature is determined from the temperature of Thermal Neutrality. The PMV and PPD (Predicted Mean Vote and Predicted Percentage Dissatisfied - see explanation at the end of this Part 1) procedures have been applied to arrive at 90% and 80% acceptability.

The **second major context** is the nature of the **building**.

The third context is **time**. The activities of people and their responses take place in a time frame. This leads to a continuously changing comfort temperature. The rate at which these changes occur has an important bearing on comfort. The comfort temperature is thus a result of interaction between the subjects and the building. One writer has observed – "Actual adaptive behavior is an amalgam of these two types of actions-changing the conditions to accord with comfort and changing the comfort temperature to accord with prevailing conditions". In the fixed temperature approach, climate and building are not factored in comfort considerations and therefore they do not have the opportunity to respond and adapt to arrive at a comfort temperature in the larger range i.e., like 20°C to 30°C as compared to 22°C to 24°C.

In the Fixed Temperature Approach, the

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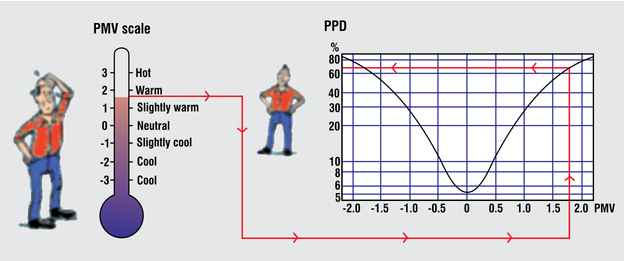
PMV and PPD



PMV-index (Predicted Mean Vote) predicts the subjective ratings of the environment in a group of people.

PPD-index predicts the number of dissatisfied people.

Figure 9: PMV and PPD explained

subjects are not aware of either the climate or the building and therefore they have no opportunity to adapt themselves and arrive at a comfort temperature in a larger range. In Adaptive Approach, the larger range is achieved by the freedom they have to adapt and by adjusting their responses. Incorporating adjustable desk fans, openable windows, provision of blinds and curtains, making changes to their dress and moving their positions, constitute some of the responses - all of which or those feasible amongst them will be adopted. People have a natural tendency to adapt to changing conditions in their environment. This natural tendency is factored in the Adaptive Approach.

In the Adaptive Approach, "comfort vote" by occupants is not based on a climate chamber as in a built-in environment. The basis is voting in **actual built environment**. This will naturally comprise varieties of buildings, differing mix of people, varieties of location. Also, conditions in the environment are left to vary as they will and subjects to dress and behave as they would normally do.

Proposed ACS In ASHRAE Std. 55 NV Bldgs

There is in fact an "Optional Method" provided in ASHRAE Standard 55-2004 which incorporates the Adaptive Approach – clause 5.3 in Standard 55.

Energy Savings Due to Application of Adaptive Model

Figure 8 represents energy savings possible due to use of ACS. It begins with July climate data for the U.S., and then compares the upper 80% acceptability limit of the ACS to the upper limit of the ASHRAE Std. 55 comfort zone (based on 0.5 clo* and 50% RH) which is 26°C.

The map shows the regions of the country where the difference in comfort temperatures using these two methods ranges from 0-5°C. Energy savings would be proportional to the difference in these set points. This is actually a conservative estimate, and savings are likely to be much higher than indicated since it is more common to operate buildings at the center of the ASRHAE Std. 55 comfort zone (approximately 23°C), rather than at the upper end of 26°C.

It should be emphasized that this is a preliminary application of applying GIS (Geographical Information System) technology to thermal comfort analysis and is based on coarse data. However, the picture is still indicative of the large potential for saving energy by using natural ventilation instead of air-conditioning (assuming that people have direct control of the operable windows, and are also free to adapt their clothing). The map is also being shown as an example of combining thermal comfort prediction methods with GIS technology to expand our analysis to a regional scale.

Uses of ACS

There are several ways in which ACS can be used:

a) It can be applied as a (optional) design standard with 80% to 90% acceptability for whole building cooling.
b) ACS can be employed as a simulation tool to check whether thermal conditions achievable are acceptable. If not, design modifications can be tried, the process being repeated as required.
c) For Mixed Mode buildings, ACS can be applied as an operating guideline. Benefits could be down sizing the plant, first cost reduction and energy saving.
d) ACS will be handy for working on Task/Ambient Conditioning (TAC) systems. Building's ambient can be allowed to float within border limits of ACS with individual controls to elevate local comfort levels and finally it can be used for identifying feasibility of using natural ventilation using Passive Cooling/Natural Cooling/Alternates to Air Conditioning systems.

Constraints to ACS

Constraints applicable for ACS as listed in clause 5.3 of ASHRAE Standard 55 are:

a) Spaces where occupants regulate thermal conditions through opening and closing of windows. They must be easy to access and operate.
b) If heating is provided, the method (Adaptive Control) does not apply when it is in operation.
c) There should be no mechanical cooling system examples: Refrigerated Air Conditioning, Radiating Cooling, Desiccant Cooling.
d) Mechanical ventilation (unconditioned air) is acceptable but primary control will be through operable windows.
e) Activity levels to be within 1 to 1.3 met (met is a unit of measurement of Metabolism. One met = 58.1 w/sqm. Office work like typing = 70 w/sqm or 1.2 mets). Occupants must be able to freely adapt their clothing to indoor /or outdoor thermal conditions.

Adaptive Approach Recommended

Considering all the points discussed on this topic, the Adaptive Approach has been followed in arriving at acceptable comfort temperatures in this article. The explanations that follow in Part 2 will warrant this recommendation.

*clo units represent clothing insulation values or thermal resistance. 0.5 clo represents the kind of clothes we wear in Mumbai, Chennai and Bangalore.