DEVELOPMENT OF A HYBRID VENTILATION SYSTEM USING NATURAL NIGHT TIME VENTILATION FOR CLEVELAND, OHIO

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1. Abstract

This paper presents the development of a hybrid system involving both conventional HVAC systems and natural ventilation as a viable solution to energy consumption issues. Whereas conventional systems are more energy consuming, the fact remains that control of indoor conditions cannot be exercised by simply opening and shutting of windows and other openings. The considerations to be made towards the needs of the building users suggest that a single system, i.e., mechanical or natural, cannot remedy all the issues. A theoretical framework of the hybrid HVAC system with natural night ventilation serving as the natural component of the system is developed in this study. A model for calculation of indoor temperature after night cooling has been formulated. This is done with the aim of using internal room temperature as an index of thermal comfort of the occupants. Accordingly, a model is developed for the final temperature by incorporating the heat gains/ losses observed in a building unit. The model requires extensive time consuming calculations for solar radiance, and consequently, the resulting heat gain components. The model is applied to develop night cooling times on a monthly basis for Cleveland, Ohio.

2. Introduction

Ventilation of buildings is a significant and complicated process influenced by various parameters. Though the natural ventilation system saves lot of energy; most of the factors are dependent on nature. On the other hand, though the artificial ventilation systems have much more control on those parameters, the energy consumption is very high. It is not feasible to rely totally upon the natural ventilation. Moreover, the artificial ventilation is very costly.

Surveys performed in 1993 have shown that the energy cost of air-conditioned buildings is 40 % more than for non-air-conditioned buildings. As much as 25 % reductions in cooling energy are possible for lightweight structures (Jones and West, 2001). Natural ventilation can result in improved environmental quality and occupant satisfaction (Kolokotroni, 2001). A majority of occupants prefer provision of good daylight and ventilation by openings in walls. So today, entire malls are being designed using natural ventilation principles (Fordham, 2000 and Jones and West, 2001).

In spite of having all the arguments in favor of natural ventilation, all occupant needs that pertain to indoor comfort cannot be fulfilled by only natural ventilation. Certain rooms like Intensive Care Units in hospitals require controlled ventilation where the mechanical ventilation is necessary. Hence, channeling the advantages of both the disparate systems into a hybrid system will give flexibility for use of the system under varying situations (Elovitz, 2002, Fordham, 2000, Kosik, 2001 and Wright, 2000).

HVAC system can be designed using the night time ventilation as the natural component of it. This possibility is explored in this study. The paper also makes an effort to fix times of night cooling for a building by using indoor temperature as an index of thermal comfort. In doing so, it is ensured that the occupant comfort is not sacrificed while the concepts of energy efficiency are implemented.

This paper presents an analysis of suitable combinations of natural and conventional ventilation systems. It also makes an attempt to quantify the effects of the factors affecting natural ventilation and developing cooling times using the information derived.

3. Model Development

3.1 Derivation

This section deals with the derivation of a relation between the indoor temperature after night cooling for certain duration with the components of a building and other factors such as weather, climate etc. While calculating the heat gains, heat gains through walls, roof, windows, heat transfer to furnishing in a building, load due to cooling by natural ventilation are taken into account.

The heat gain through the walls is given by following equation (ASHRAE, 2001):

$$Q_w = \Sigma(F_w * U_w) * [T_{sa}(t) - T_i(t)] \quad (1)$$

where,

F_w is the area of the walls and roof

U_w is the thermal conductivity of walls/roof

$T_{sa}(t)$ is the sol-air temperature at time t

$T_i(t)$ is the internal temperature of the room at time t

Heat gain through a window is to be computed in two parts. The first part Q_1 is the simple heat transfer due to the difference in temperature between internal and external temperatures and is given as follows:

$$Q_1 = U_g * F_g [T_o(t) - T_i(t)] \quad (2)$$

where,

U_g is the thermal conductivity of window

F_g is the area of window

$T_o(t)$ is the outdoor temperature at time t

The second part, Q_2 is the heat transfer due to solar heat gains given as:

$$Q_2 = q_b + q_d \quad (3)$$

Both parts of Q_2 are explained below.

The first part is the direct beam solar heat gain q_b given as:

$$q_b = SHGC_\theta * F_g * E_D \quad (4)$$

where,

$SHGC_\theta$ is the solar heat gain coefficient for incidence angle θ

E_D is the surface direct irradiance.

The second part is the diffuse solar heat gain q_d, is given as:

$$q_d = SHGC_D * F_g * (E_r + E_d) \quad (5)$$

where,

$SHGC_D$ is the diffuse solar heat gain coefficient

E_r is the ground reflected irradiance

E_d is the diffuse irradiance

The total heat transfer through all the windows, Q_g will be the sum of Q_1 and Q_2.

$$Q_g = \Sigma\{U_g * F_g [T_o(t) - T_i(t)] + Q_2\} \tag{6}$$

While calculating the heat transfer due to furnishing, it is assumed that the furniture is an isothermal mass with high thermal conductivity and great surface to the furnishing. So it can be assumed that temperature of the furniture is same as indoor temperature at that time. Heat transfer to furnishing Q_f, may be given as:

$$Q_f = \sum M_f * C_f * (dT_i/dt) \tag{7}$$

where,

M_f is the mass of furniture

C_f is the coefficient of heat transfer for the internal mass

T_i is the indoor temperature

Load due to cooling by natural ventilation is given by:

$$Q_v = M_a * C_a * n_a * (T_i(t) - T_o(t)) \tag{8}$$

where,

n_a is number of air changes per hour

M_a is air mass inside the building, which is the product of volume of air inside the building unit and the density of air

C_a is the coefficient of heat transfer of air

The indoor temperature in the building exposed to natural ventilation will depend on outdoor temperature and heat transfer characteristics of the outer covering of the building. In the simplest form, the relation appears as:

$M_aC_a(dT_i/dt)$ = Sum of heating and cooling loads in the building (9)

where,

dT_i/dt is the rate of change of temperature with respect to time

Sum of heating and cooling loads in the building is given by combining (1), (6), (7), and (8) with appropriate signs.

In order to obtain the indoor temperature after night cooling for duration of t hours, the equation (9) is integrated as follows:

$$\int_{T_1}^{T_2} \frac{dTi}{Ti-(Y/Z)} = \int_{t_1}^{t_2} -\frac{Z}{X}dt \qquad (10)$$

where,

$Y = (\Sigma(F_w * U_w)\, T_{sa}(t)) + (\Sigma\, \alpha * \tau_g * I(t) * F_g) + (\Sigma\, U_g * F_g * T_o(t)) + M_a * C_a * n_a * T_o(t))$

$X = M_aC_a + \sum M_f * C_f$

$Z = (\Sigma(F_w * U_w)) + (\Sigma\, U_g * F_g) + (M_a * C_a * n_a)$

where,

T_2 is the indoor air temperature after cooling has taken place

T_1 is the indoor air temperature before the advent of cooling

F_g is the area of fenestration

α is absorptance of surface for solar radiation

$\Sigma \alpha * \tau_g * I(t)$ is the heat gain due to solar radiation incident on the fenestration

The equation (10) may also be written as:

$\log (T_2 - (Y/Z)) - \log (T_1 - (Y/Z)) = (-Z/X) * (t_2 - t_1)$

After solving for T_2 we get,

$$\mathbf{T_2 = (Y/Z) + (T_1 - (Y/Z)) * e^{(-Z/X) * (\Delta t)}} \qquad (11)$$

where,

Δt is the duration of the cooling process

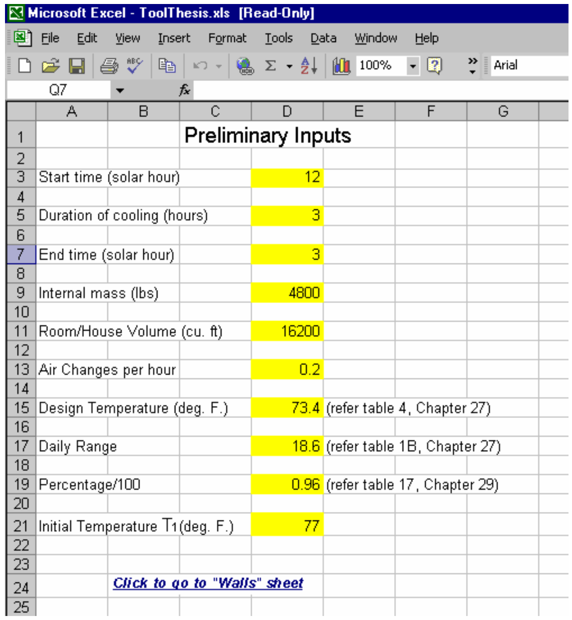
3.2 Design of the Spreadsheet tool

The equations in the previous section require lengthy calculations for various factors such as the sol-air temperature, incident radiation etc. All the calculations are based on the methodology described in the ASHRAE Handbook of Fundamentals, 2001.

The tool is a MS Excel workbook, which is divided into three worksheets.

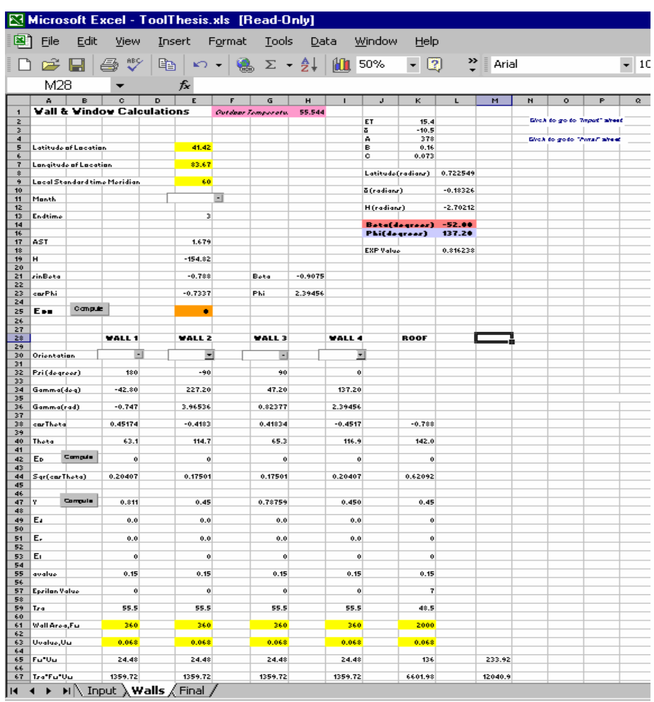
The first worksheet (see figure 1) is used to enter the data relating to the internal mass, internal volume of the building, start and end times in terms of solar hours, the duration, initial temperature, and air change rate.

Figure 1: Screenshot of sheet 1



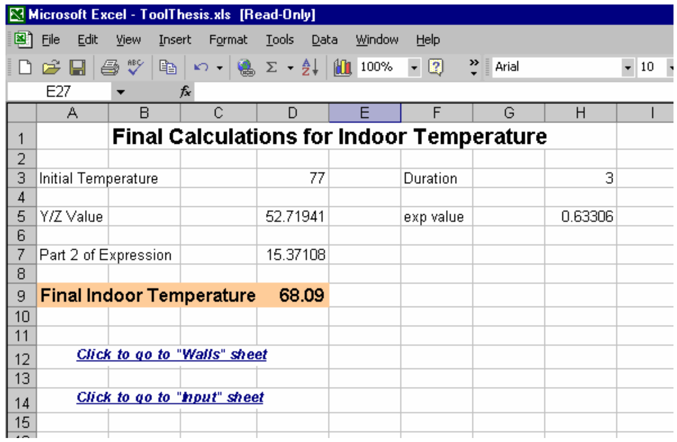
The second sheet (see figure 2) is used to calculate data relating to the walls and fenestrations.

Figure 2: Screenshot of sheet 2



The third sheet (see figure 3) showcases the various components of the main equation and the final result, which is the indoor temperature T_2 after the cooling process.

Figure 3: Screenshot of sheet 3



4. Results and Discussion

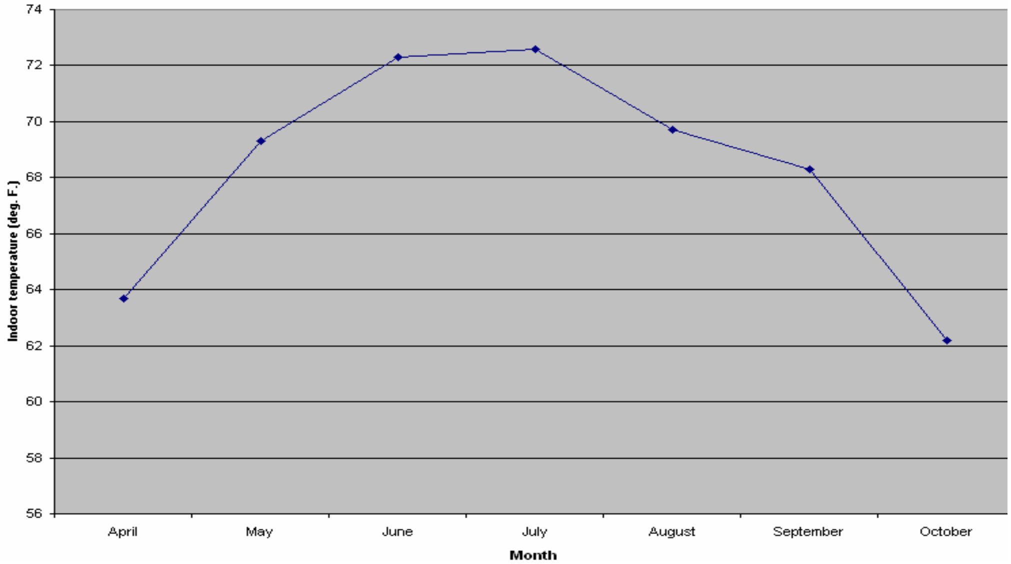
4.1 Role of the various factors in computing indoor temperature

The variation of indoor temperature with respect to internal mass, air changes per hour, duration, start and end times were studied on a monthly basis. Some of the results from the study for Cleveland, Ohio are shown below in figures 4 to 9.

Case 1

The variation of indoor air temperature for a cooling time of 6 hours between 12 midnight and 6 a.m. was studied for different months (see figure 4). The calculations for sol-air temperature, surface irradiance, equivalent outdoor temperature, solar intensity and such other factors were performed on a monthly basis for certain months. The air change rate was assumed at 5 air changes per hour and the internal mass was assumed at 4800 lbs.

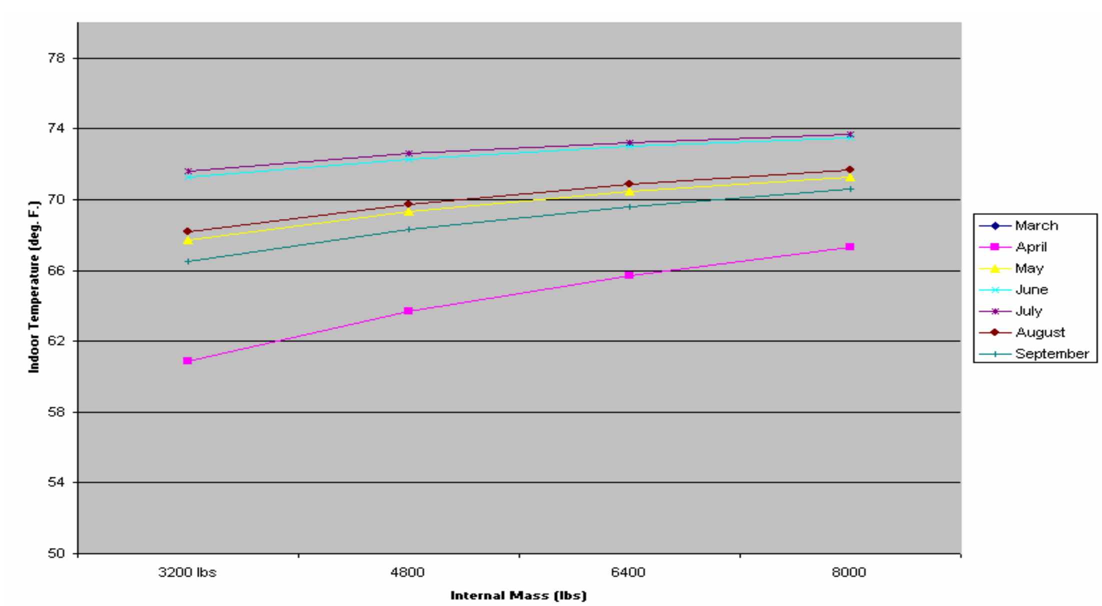
Figure 4: Indoor Temperature Variation



Case 2

The variations of indoor temperature were studied with respect to internal mass (broadly described as furniture). The figure 5 shows the variation for the furniture mass values are 3200, 4800, 6400 and 8000 lbs.

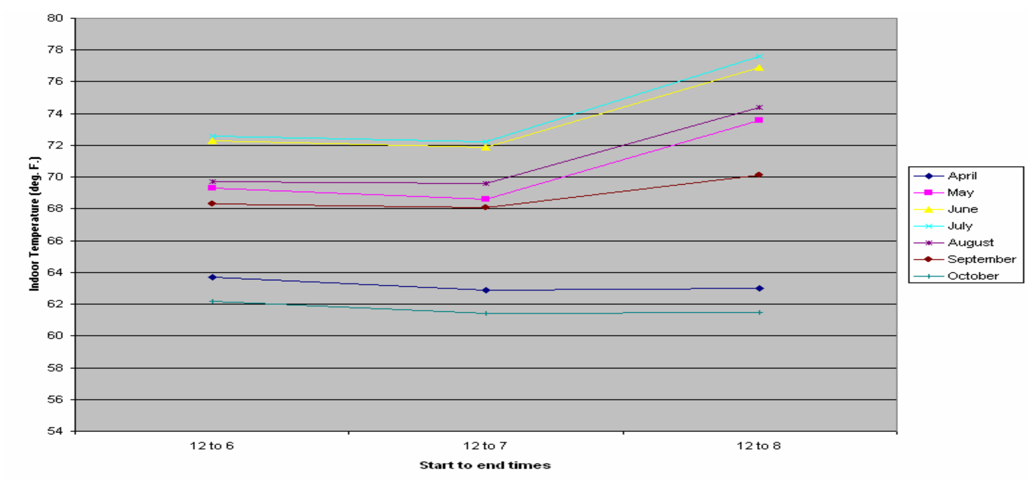
Figure 5: Variation of indoor temperature with respect to internal mass



Case 3

Temperature variation due to varying end times but start times constant was computed. The various durations considered were 12 midnight to 6 a.m., 12 midnight to 7 a.m. and 12 midnight to 8 a.m. (see figure 6).

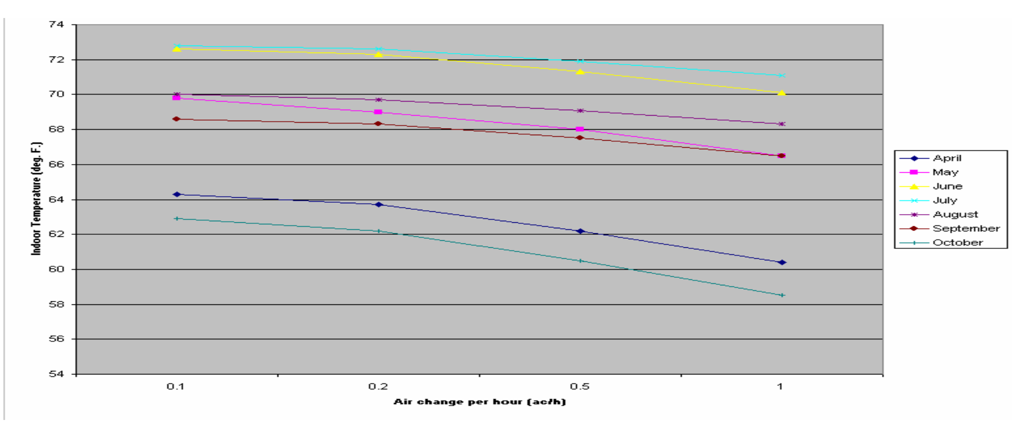
Figure 6: Variation of indoor temperature with respect to duration (start times fixed and end times varying)



Case 4

This case considers the variation of indoor temperature with respect to the natural ventilation rate. The air changes per hour were 0.1, 0.2, 0.5, and 1 (see figure 7).

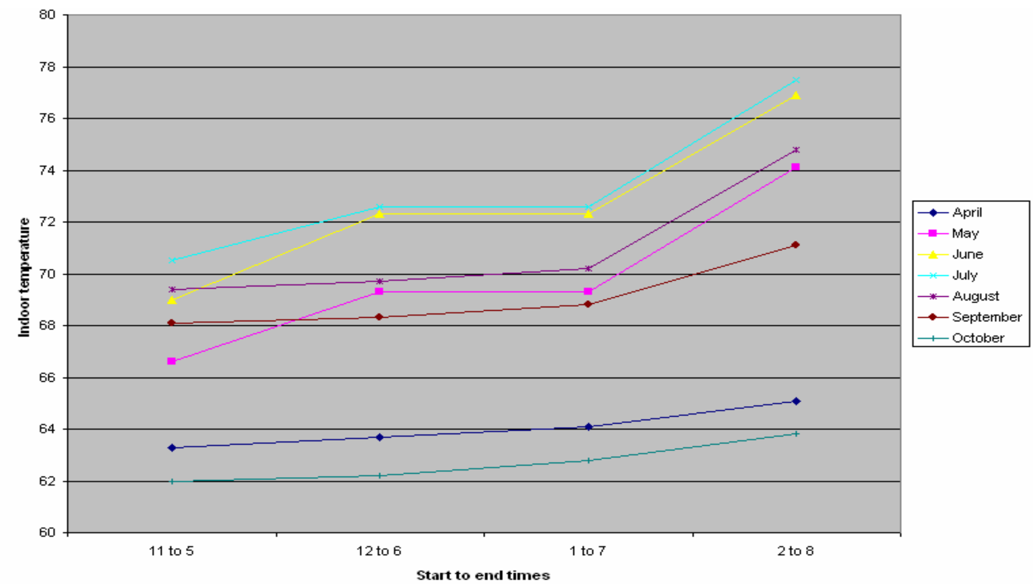
Figure 7: Variation of temperature with respect to ventilation rate



Case 5

Temperature variation due to varying start and end times but at the same time, keeping duration of 6 hours constant, was computed. The various durations considered were 11 p.m. to 5 a.m., 12 midnight to 6 a.m., 1 a.m. to 7 a.m. and 2 am to 8 a.m. (see figure 8).

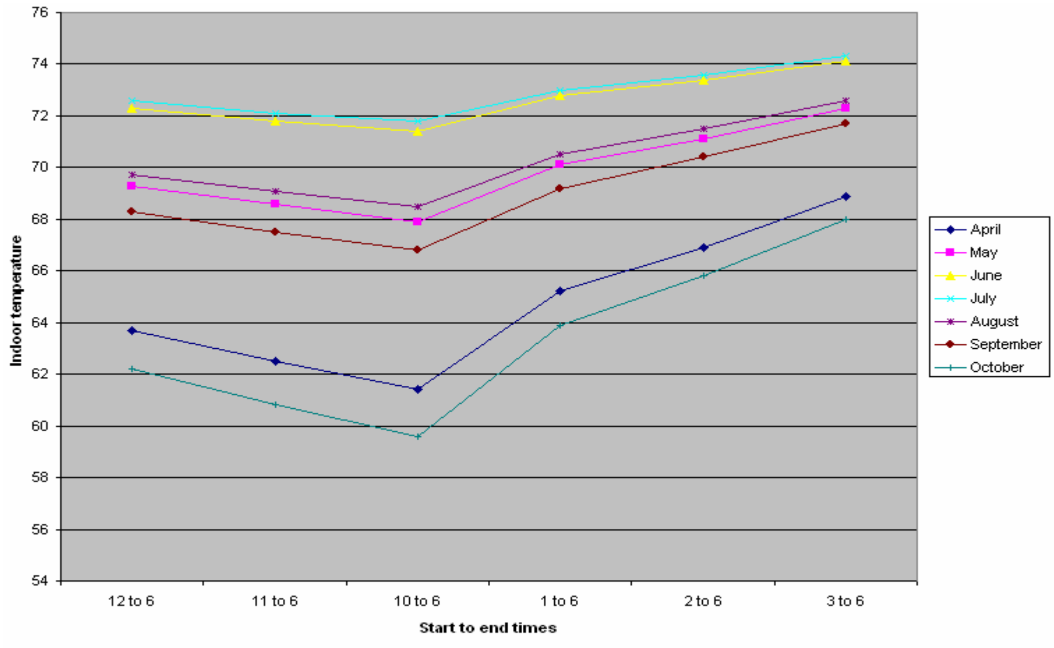
Figure 8: Indoor Temperature Variations with respect to Fixed Durations and Varying Start and End Times



Case 6

In this case, the variation is studied with respect to varying duration of the night ventilation, but at the same time keeping the end time constant. The study was done for the period between 12 to 6, 11 to 6, 10 to 6, 1 to 6, 2 to 6 and 3 to 6. (see figure 9).

Figure 9: Indoor Temperature Variations with respect to Varying Durations and Fixed End Times



Night cooling cannot be carried for months in which the temperature indoors falls below the comfort ranges recommended by Brager and Dear (2000). From the case studies mentioned above, a few general observations were noted.

1. By variation of cooling times and ventilation rates, internal temperature variation can be controlled to suit thermal comfort requirements.
2. The variation of duration must be accompanied by optimal end time adjustments to ensure optimum derivation of desired decrease or increase in indoor air temperature.
3. To design an effective mixed mode system, detailed study of all the input parameters must be made. Each case will have its own peculiarities and consequently its own specific natural ventilation opportunities.

4.2 Determination of Cooling Times

The model presented in this paper is applied to develop night cooling times on a monthly basis for Cleveland, Ohio. The following sets of input data were prepared to calculate night cooling times:

Set 1: Conservative settings. These settings are for occupants with low tolerance for temperature fluctuations.

1. Average monthly outdoor temperatures for Cleveland, Ohio are first obtained (NOAA Website). (Refer table I).

Table I: Monthly Outdoor Temperature and Indoor Comfort Ranges for Cleveland, Ohio.

Month	Average Monthly Temperature (^oF)	Ranges (^oF)
April	47.8	64 – 74
May	58.3	65 – 75
June	67.5	69.5 – 79.5
July	71.9	72 – 81
August	70.3	71 – 80
September	63.9	69 – 79
October	52.8	65 - 75

2. Based on the outdoor temperature, acceptable ranges of indoor temperature are obtained (Brager and Dear, 2000).
3. Indoor temperature variations are studied for different settings, similar to the ones documented in case studies.

4. Cooling times wherein the resultant temperature falls within the comfort range for the particular month are selected, with preference being given for the indoor temperature that falls in the middle of the comfort range.
5. In case of more than one result for a particular month(s), the cooling time with the higher indoor temperature is selected.

Set 2: Non-conservative/speculative settings. These set of recommendations are for occupants with higher levels of tolerance of temperature fluctuations.

1. Average monthly outdoor temperatures for Cleveland, Ohio are obtained (NOAA Website). (Refer table I).
2. Based on the outdoor temperature, acceptable ranges of indoor temperature are obtained (Brager and Dear, 2000).
3. For this type of recommendation, trend patterns are studied from the variation charts from the conservative recommendations.
4. Based on the observed trends, cooling times are recommended which are longer in duration than the first set of recommendations, making sure that the resultant temperature is always within the comfort range.
5. In case of more than one result, a cooling time resulting in lower indoor temperature is chosen.

The results are given in following table (see Table II).

Table II: Recommendations for night cooling times for Cleveland, OH.

Month(s)	Recommendations	
	Conservative	**Non-Conservative**
April, August and September	2 a.m. to 8 a.m.	12 midnight to 8 a.m.
May, June and July	12 midnight to 7 a.m.	8 p.m. to 8 a.m.
October	3 hour period beginning at midnight or ending at 6 a.m.	3 hour period beginning at midnight or ending at 6 a.m.

Recommendations given in Table I may be used to reduce the energy requirement for ventilating a typical building from April to October in Cleveland, Ohio. The table shows that night cooling can be a very viable option for the months of April, May, June, July, August, and September, when indoor temperatures are well within comfort ranges. However, for the month of October, reduction of duration and increase in air changes could bring the resulting indoor temperatures within the comfort ranges. Again this would be largely depending on the preferences of the occupants.

5. Conclusion

Using, indoor temperature as an index, a suitable night cooling time schedule can be drawn up as a part of a hybrid ventilation system. This study presents results for Cleveland (Ohio). The employment of natural night ventilation will result in energy savings and lowered peak demand for the conventional systems during daytime.

6. References

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