EFFECT OF VENTILATION OF SPACE BETWEEN ROOF AND FALSE CEILING ON AIR-CONDITIONING LOAD

V. Charan
Mechanical and Industrial Engineering Department
University of Roorkee, Roorkee-247 667, India
R.K. Agarwal
Mechanical Engineering Department
Regional Engineering College, Jaipur, India

ABSTRACT

This paper presents the results of a theoretical investigation on energy conservation in an air-conditioned building, if the space between roof and false ceiling is ventilated by outside air. It outlines the procedure for determining the reduction in roof heat load over a conventional system where no such air is flown. The percent saving is determined at different times of the day between 10 am to 5 pm. The other parameters taken are viz. air velocities of 1,2 and 3 m/s; roof length in the direction of flow as 10, 20 and 30 m; inclination of roof at 0°, 30° and 45° at a location of 29.85°N latitude. The effect of these parameters are studied and their optimum combination is found at 2 m/s, 20 m length and 30° angle of inclination which gives an average reduction of 17.4 percent for roof load between 10 am to 5 pm.

INTRODUCTION

Solar radiation on roof in an air-conditioned building constitutes one of the main source of cooling load on air-conditioning plant. An airconditioned building is usually provided with false ceiling. If the space between roof and false ceiling is ventilated by outside air, a certain portion of the roof load Q_1 may be carried away by this air due to convective heat transfer from the inside surface of the roof. This paper outlines the procedure which may be adopted for determining this heat transfer Q_2 to the flowing air and thus the roof load (Q_1-Q_2) passing to the conditioned space. This when subtracted from the roof load Q without flowing any air as above gives the net saving Q' which may expressed as a percent of the former. This model under investigation is shown in figure (1).

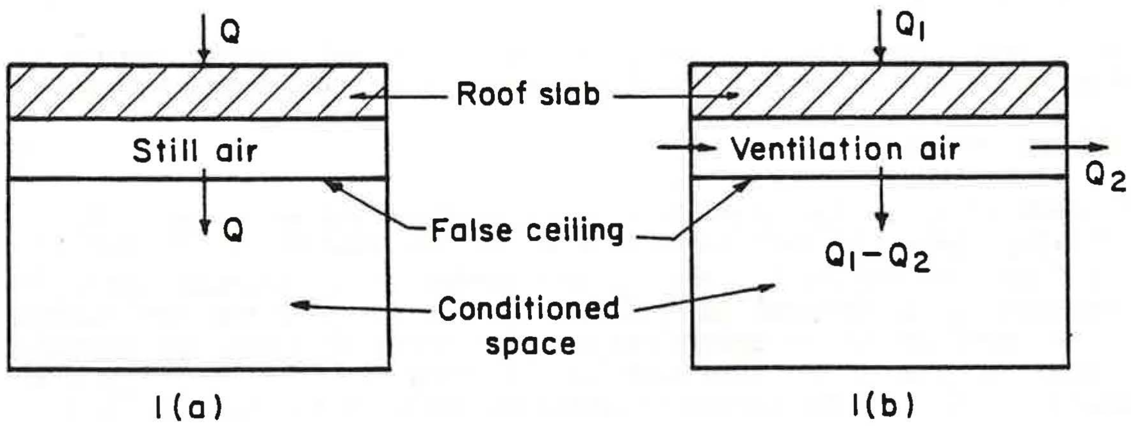

FIGURE 1. Model under investigation

The results of a case study for a chosen location have been presented to show the effect of the time of the day, air velocity V, angle of inclination of roof S^o with the horizontal and length of the roof in the direction of flow as x, on the percent reduction of heat load. Such an investigation is useful to develop an energy conservation technique for airconditioned buildings.

MATHEMATICAL FORMULATION

Intensity of Solar Radiation (I)

The relevant relations obtained from reference (1) are given by equations (1 to 10).

$$d = 23.45 \sin [360(284+n)/365] \quad (1)$$

where, n is the day of the year (n=172 for June 21).

For horizontal surface, $\theta = \theta_z$ and thus

$$\cos \theta_z = \sin d. \sin L + \cos d. \cos L. \cos w \quad (2)$$

For tilted surface facing north,

$$\cos \theta_T = \sin d. \sin (L+S) + \cos d. \cos (L+S) . \cos w \quad (3)$$

For tilted surface facing south,

$$\cos \theta_T = \sin d. \sin (L-S) + \cos d. \cos w. \cos(L-S) \quad (4)$$

$$I_n = 1082 \exp (-0.182 m) \quad (5)$$

where, $m = 1/\cos \theta_z$ (6)

$$I_d = R_b . I_n . \cos \theta_z \quad (7)$$

where, $R_b = \cos \theta_T/\cos \theta_z$ (8)

$$I_D = C.I_n . (1+\cos S)/2 \quad (9)$$

where, the sky diffusion coefficient C depends upon the day of the month (C = 0.134 for June 21)

$$I = I_d + I_D \quad (10)$$

Roof Load

The effect of radiation is taken into account by considering the roof exposed to sol-air temperature t_e, given by equation (11)

$$t_e = t_o + a.I/f_o \quad (11)$$

Since t_o and I vary over a period of 24 hours, the heat transfer through the roof is determined by the solution of one-dimensional heat transfer equation(12)

$$\partial t/\partial \tau = \alpha . \partial^2 t/\partial y^2 \quad (12)$$

The values of t_o can be taken from meteorological data and t_i as t_o for the air flowing below the roof surface. Now for the solution of equation (12), the surface temperature t_{so} and t_{si} are needed at a particular time. The temperature t_{si} is different for still and moving air below the roof surface. These temperatures can be determined by using fininte difference approximation technique, as given in the literature (2). Referring to figure (2), the relevant relations to determine the surface temperatures are given by equations (13 & 14).

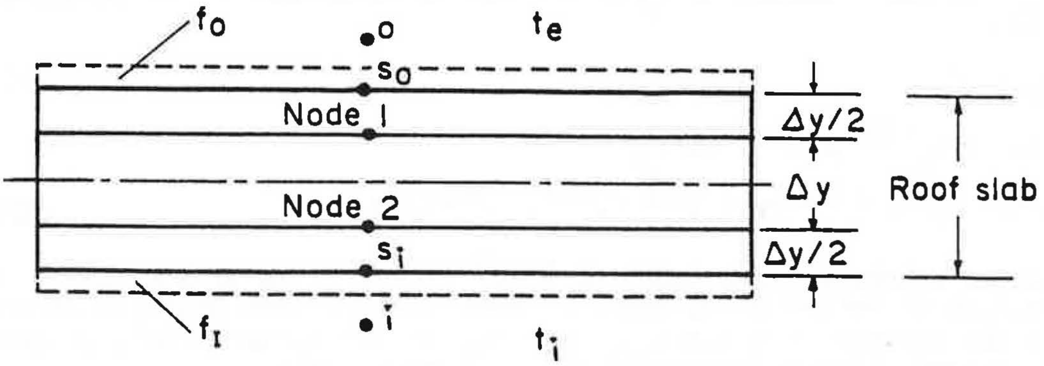

FIGURE 2. Nodal points in roof for finite difference approximation

$$t_{so} = (Bi_o . t_e + 2t_1)/(Bi_o + 2) \quad (13)$$

$$t_{si} = Bi_i . t_i + 2t_2)/(Bi_i + 2) \quad (14)$$

After time $\Delta\tau$, the temperatures t_1 and t_2 at nodes 1 and 2 change to temperatures t'_1 and t'_2 as given by equations (15 and 16)

$$t'_1 = [(2\, t_{so} + t_2) + (M-3)t_1]/M \quad (15)$$

$$t'_2 = [(2\, t_{si} + t_1) + (M-3)\, t_2]/M \quad (16)$$

$$\text{where, } M = (\Delta y)^2/\alpha(\Delta\tau) \quad (17)$$

The values of t_{siN} for still and t_{siM} for moving air are determined using corresponding values of Bi (=f.Δy/k) in equation (14). These values are then used in equation (16) to determine t'_2 for the two cases. In order to use the relations given by equations (13 and 15) it is first necessary to evaluate the value of t_e at a particular time. This value is then imposed as the outside boundary condition. In addition, an approximate temperature distribution through the roof at a certain time $\tau = 0$ is to be assumed as a starting condition. The calculations are made to determine the temperature distribution at various nodes at time interval $\Delta\tau$, 2 $(\Delta\tau)$ etc. until the total time of 24 hours. The calculations are stopped, if at the end of 24 hours the same values as assumed are obtained, otherwise calculations are repeated with newly determined temperature distribution. The iteration is carried out until the two values are in agreement. Thus inside surface temperature of the roof is finally obtained. It is pointed out that for stability of equations (15 and 16) and accuracy of results M should be taken as $M \geq 3$. Therefore, a time interval $\Delta\tau$ is so chosen that this condition is satisfied. In the present investigation $\Delta\tau$ is taken as one hour. The heat load from the roof is then given by equations (18 and 19).

$$Q = A.\, f_{iN}\, (t_{siN} - t_i) \quad (18)$$

$$Q_1 = A.\, f_{iM}\, (t_{siM} - t_i) \quad (19)$$

Heat Load Carried Away by Moving Air and Saving in Roof Load

First the length of roof upto which the flow is laminar is determined by equation (20) and then the heat transfer coefficient for the laminar portion

x_1 and the turbulent portion $(x-x_1)$ of the roof is determined (3) by equations (21 and 22).

$$x_1 = (Re_1)\,\nu / V \tag{20}$$

$$h_1 = 0.664\,(Re_1)^{1/2}\,(Pr)^{1/3}\,(k/x_1) \tag{21}$$

$$h_t = 0.037\,(k)\,(Pr)^{1/3}\,(V/\nu)^{0.8}\,(x^{0.8} - x_1^{0.8})/(x-x_1) \tag{22}$$

In the above relations Re_1 is taken as 5×10^5 applicable for a flat plate and the properties of the air in the space between roof and false ceiling is determined at the average of t_i and t_{siM}. Now Q_2, Q' and percent saving of roof heat load are calculated by equations (23 to 25), respectively.

$$Q_2 = (h_1 A_1 + h_t A_t)\,(t_{siM} - t_i) \tag{23}$$

$$Q' = Q - (Q_1 - Q_2) \tag{24}$$

$$\text{percent saving} = (Q'/Q) \times 100 \tag{25}$$

CASE STUDY

The following particulars were chosen for the case study:

Place : Roorkee, India (latitude 29.85°N)
Month and Date : June 21
Roof particulars : Thickness 25 cm; width 1 m; made of concrete having $\alpha = 5\times10^{-7}$ m^2/s, k = 1.279 W/mK, a = 0.9
Parameters : V = 1, 1.5 and 2 m/s; x = 10, 20 and 30 m; S = 0°, 30° and 45° (inclined roof facing north-south); time = 10 am to 5 pm at interval of 1 hour.
Assumptions: f_o = 23 W/m^{2}K (at V=12 km/h); f_i=7,11,13 and 15 W/m^{2}K (at V = 0, 1,1.5 and 2 m/s);
Note: For inclined roofs, the north and south facing portions of the roof are considered separately and then their total effect is taken in determining Q, Q_1, Q_2 and percent saving.

In view of lengthy calculations help of a computer was taken to determine the percent saving in roof load by the proposed scheme. In general, it varied from 1 to 22 percent. The effect of various parameters under study are now discussed under results.

RESULTS

Effect of Air Velocity:

Figure (3) shows the variation of percent saving on load with time for an angle of inclination of 0° (flat roof) and length 10 m at velocities 1,1.5 and 2 m/s. The saving first rises from 10 am to 11 am and then decreases. Throughout the day this saving is largest at the higher air velocity of 2 m/s. This is due to the reason that for a fixed x, as V increases, the length of laminar flow part decreases and that of turbulent part increases. Since the heat transfer coefficient in the turbulent part is more than the laminar part, an increase in turbulent length enhances the total heat flow to the moving

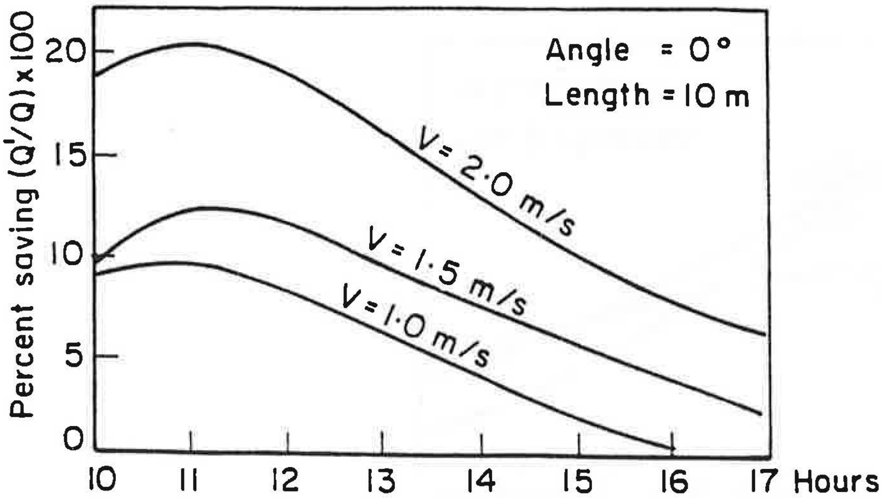

FIGURE 3. Showing effect of air velocity

air. Similar pattern was observed for other cases of varying roof length and at other angles of inclination of roof.

Effect of Length

Figure (4) shows the variation of percent saving in load with time for an angle of inclination 0° and air velocity of 2 m/s with varying length of 10,20 & 30 m. Again the percent saving first increases from 10 am to 11 am and then decreases. It is also seen that as the length of roof increases, the percent saving first increases by about 2 percent at 20 m length and then this increase is 1 percent at 30 m length, both in comparison to that at 10 m length. At a given velocity the laminar flow length and its heat transfer to flowing air is fixed. The heat transfer to air from the turbulent portion of the roof length depends upon the value of $V^{0.8}$ $(x^{0.8} - x_1^{0.8})$. With increase in x,this increases and thus the total heat transfer Q_2 increases. At the same time Q also increases in proportion to x. The net result is that upto some value of length x, the ratio Q_2/Q first increases and then starts falling but the subsequent reduction is not appreciable. Thus an increase in length beyond some value may not be of great advantage.

Effect of Angle of Inclination:

Figure (5) shows the variation of percent saving in load with time for varying angle of inclination as 0°,30° and 45° keeping air velocity of 2 m/s and roof

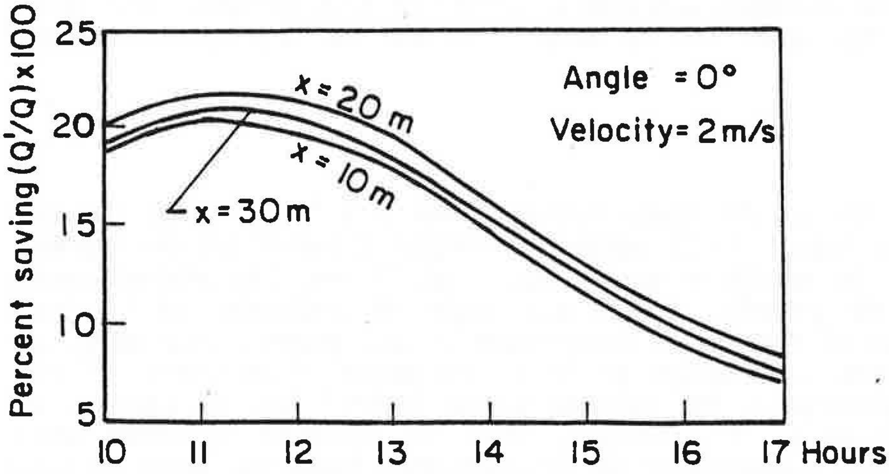

FIGURE 4. Showing the effect of roof length

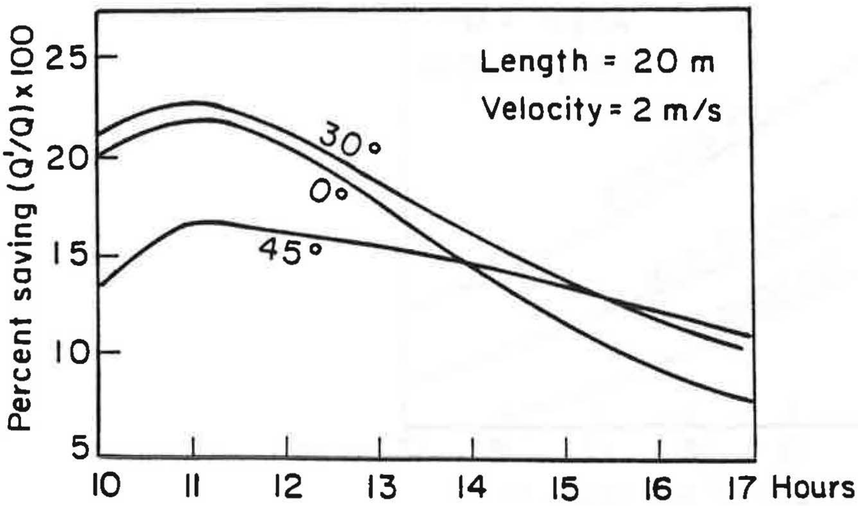

FIGURE 5. Showing effect of angle inclination of roof.

length of 20 m as fixed for this study since these two had given maximum load saving. Here again the load saving first increases at 11 am and then decreases.

It is also observed from the calculated results that the values of Q, Q_1 and Q_2 increase at higher angles as compared to those at 0°. An examination of the data shows that at 30° the increase in Q is more than the corresponding increase in (Q_1-Q_2). Therefore,the ratio $(Q_1-Q_2)/Q$ decreases which results in an increased percent saving of the roof load. At 45° the increase in Q is relatively less than the corresponding increase in (Q_1-Q_2) which results in an increase in the ratio of $(Q_1-Q_2)/Q$ and hence a decrease in percent saving of the roof load. Thus from Figure (5) it is seen that out of the three angles considered 30° inclination of the roof gave maximum saving.

Optimum Average Saving During the Day

An examination of the load saving with the help of expression $V^{0.8}(x^{0.8} - x_1^{0.8})/x$ shows that the maxima would occur at smaller values of x for higher air velocities. For the highest velocity of 2 m/s under investigation,the maximum saving is found at 20 m length. Thus the optimum parameters for the percent saving are obtained as air velocity 2 m/s, roof length 20 m and angle of inclin-ation of the roof as 30°. For this case the percent saving in load between 10 am to 5 pm were averaged and this amounted to 17.4 percent. Thus saving upto this order in roof load may be obtained during the day by the proposed scheme.

CONCLUSION

By flowing outside air in the space between roof and false ceiling the roof load reduction varies from 1 to 22 percent at various times of the day between 10 am and 5 pm. The maximum saving occurs at 11 am. The percent saving depends upon the air velocity, length and angle of inclination of the roof. The optimum values of the above parameters in the present case study are air velocity as 2 m/s, roof length as 20 m and angle of inclination of roof as 30°. For this combination the average saving in roof load between 10 am and 5 pm is found to be 17.4 percent. Thus the proposed technique shows a potential for energy conservation in airconditioned buildings. More research need be carried out on this aspect.

NOMENCLATURE

A	area of roof
a	absorptivity of surface
d	declination angle
f	surface heat transfer coefficient
h	convective heat transfer coefficient
k	thermal conductivity
L	latitude of place
m	air mass
t	temperature
w	hour angle
α	thermal diffusivity
ν	kinematic viscosity
Δ	small increment
θ	angle of incidence of solar radiation
θ_z	zenith angle
τ	time
Bi	Biot number
Pr	Prandtl number
Re	Reynolds number

Suffix

s	surface
T	tilted surface
o,i	outside, inside
l,t	laminar, turbulent flow
n,d,D	normal, direct, diffuse radiations

REFERENCES

1. Duffie, J.A. and Beckman, W.A., 'Solar Engineering of Thermal Processes', John Wiley, New York, (1980)

2. Arora, C.P., 'Refrigeration and Airconditioning', Tata McGraw Hill, New Delhi, (1984).

3. Domkundwar, S., 'A Course in Heat and Mass Transfer', Dhanpat Rai and Sons, New Delhi, (1974).