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out a Ceiling

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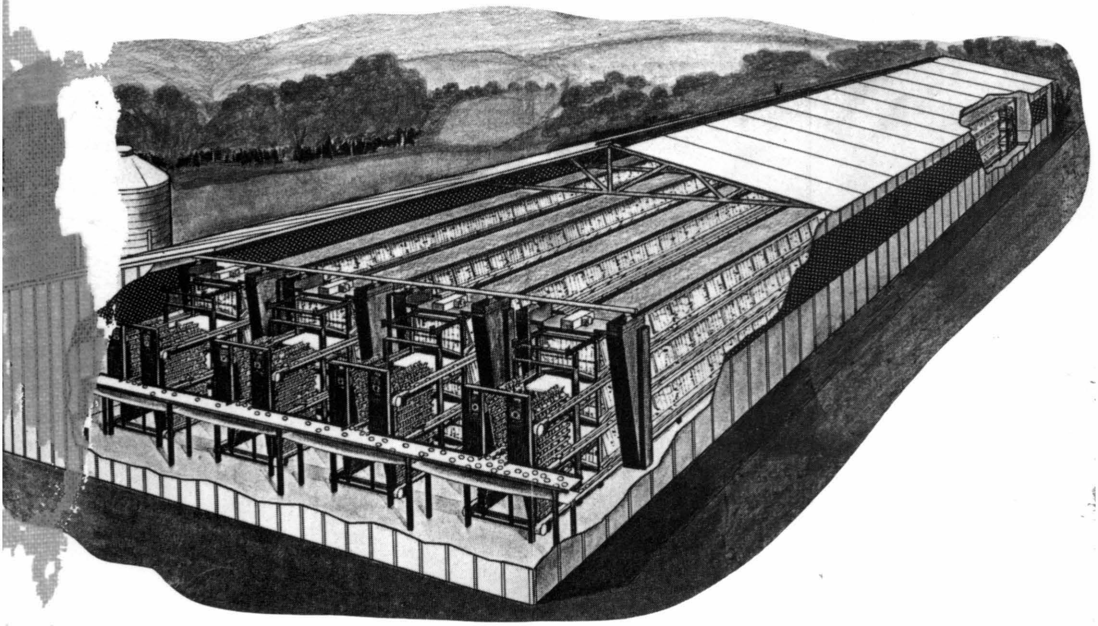

James R. Nichols, Dean and Director
College of Agriculture and Life Sciences
Virginia Agricultural Experiment Station
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061

The Virginia Agricultural and Mechanical College came into being in 1872 upon acceptance by the Commonwealth of the provisions of the Morrill Act of 1862 "to promote the liberal and practical education of the industrial classes in the several pursuits and professions of life." Research and investigations were first authorized at Virginia's land-grant college when the Virginia Agricultural Experiment Station was established by the Virginia General Assembly in 1886.

The Virginia Agricultural Experiment Station received its first allotment upon passage of the Hatch Act by the United States Congress in 1887. Other related Acts followed, and all were consolidated in 1955 under the Amended Hatch Act which states "It shall be the object and duty of the State agricultural experiment stations . . . to conduct original and other researches, investigations and experiments bearing directly on and contributing to the establishment and maintenance of a permanent and effective agricultural industry of the United States, including the researches basic to the problems of agriculture and its broadest aspects and such investigations as have for their purpose the development and improvement of the rural home and rural life and the maximum contributions by agriculture to the welfare of the consumer . . . "

In 1962, Congress passed the McIntire-Stennis Cooperative Forestry Research Act to encourage and assist the states in carrying on a program of forestry research, including reforestation, land management, watershed management, rangeland management, wildlife habitat improvement, outdoor recreation, harvesting and marketing of forest products, and "such other studies as may be necessary to obtain the fullest and most effective use of forest resources."

In 1966, the Virginia General Assembly "established within the Virginia Polytechnic Institute a division to be known as the Research Division . . . which shall encompass the now existing Virginia Agricultural Experiment Station . . . "

CALCULATION OF SUMMER VENTILATION FOR A LAYER HOUSE WITHOUT A CEILING

Wu Jinkang and Harold A. Hughes

Department of Agricultural Engineering
Virginia Polytechnic Institute and State University
Blacksburg, Virginia

Virginia Agricultural Experiment Station
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FOR A LAYER HOUSE WITHOUT A CEILING

Abstract

The required ventilation rate for a poultry layer house with sidewall openings (e.g. curtain walls) and without a ceiling was calculated. The sensible heat balance equation was used as the basis for the process. Other factors which were considered included: 1) heat production by the birds, 2) solar radiation, including direct radiation, sky-diffuse radiation, radiation reflected from the ground, and radiation through openings in the building, 3) weather information, and 4) design of the building and the thermal characteristics of building components.

It was observed, through analysis of worked examples, that some sources of heat gain, including heat gain through the side-walls, were quite small. At night, the building will lose heat through the walls. The walls have little effect on the required ventilation rate. The roof structure, however, is very important in the estimation of summer ventilation. Adequate thermal resistance in the roof is necessary to reduce the required ventilation rate in the summer.

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INTRODUCTION

Modern egg production units are large and concentrated. Up to 100,000 hens are housed in wire cages in a single layer house which can be up to 20 m wide and 200 m long. Feeding, watering, and egg gathering are performed by automatic mechanical systems. Waste is either removed from the building by a mechanical system or stored temporarily in a pit beneath the cages. A modern egg production system is complex, complicated, and expensive to develop and operate.

Proper ventilation is critical for successful operation of a layer house. The air rapidly becomes stagnant in an improperly or inadequately ventilated house, growing both warmer and more humid, and there often is a high concentration of dust and other particulate matter, ammonia and other gases, and any pathogenic micro-organisms that are present on the birds or in the environment. The stress which results may cause the birds to exhibit a lack of appetite, poor productivity, and an increased susceptibility to disease.

A critical step in the process of designing a ventilation system for a layer house is to predict the ventilation rate that will be needed under certain conditions. The proper airflow rate depends on a variety of factors, including time of year, building design, ambient temperature and other weather parameters, building location, building orientation, etc.

Estimation of the ventilation rate required for a layer house is a straight-forward process, utilizing conventional heat balance equations, when the effects of solar radiation are neglected. However, the calculation procedure becomes considerably more complicated when solar effects are included to improve the accuracy of the prediction. The external thermal environment, including temperature and incidence of solar radiation, changes constantly, so it is obvious that steady-state heat transmission seldom occurs in a structure. Actually, the heat gain or loss in a layer house, like any other building, is variable and lags behind changes in the outside environment.

This bulletin presents and discusses a procedure which has been developed and used to predict ventilation requirements for a layer house under summer conditions, with solar effects included. Winter rate prediction will be discussed in a companion publication. The procedure involves two major steps:

(1) Calculation of the total heat gain at particular solar times, including solar radiation heat gain through roof, walls, and other openings.

(2) Calculation of the ventilation rates required for the specified solar times, using the outside and inside air dry-bulb temperatures, the relative humidity inside the house, and parameters which describe the structure and the location.

The following assumptions were made to simplify the analysis and presentation of results.

(1) Wind velocity was assumed to be constant at 6.7 m/s. (i.e. The effects of wind on the convection and radiation heat transfer coefficients for the surfaces of the walls and the roof were not considered.)

(2) The ambient temperature and other environmental variables were assumed to be periodic with respect to solar time.

(3) The building was assumed to not have a ceiling (i.e. insulation was in the roof.)

(4) The inside temperature and relative humidity were considered to be constants.

(5) Natural ventilation was assumed to be used.

SENSIBLE HEAT BALANCE

Proper ventilation rates depend on the amount of heat, moisture, and odor that must be removed to set up a comfortable environment for the layers. Two equations, separately describing the heat and moisture balances, are usually needed. In the winter, the proper ventilation rate is determined by the requirement to balance and control moisture in the air. The maximum ventilation rate required in summer is determined by the heat balance equation.

Figure 1 is a representation of the cross-section of a naturally ventilated layer house with long openings (curtain walls) in both sidewalls. The sensible heat balance for this house may be written as shown in Equation 1. Sensible heat is a measure of the energy that produces a temperature change.

$$Q_v = Q_a + Q_s + Q_r + Q_e + Q_{sup} \qquad \ldots(1)$$

where

Q_v = sensible heat loss in ventilation air, Kj/hr.

Q_a = sensible heat gain from layers, Kj/hr.

Q_s = solar radiation heat through roof and walls, Kj/hr.

Q_r = solar radiation heat through openings, Kj/hr.

Q_e = heat gain produced by equipment, Kj/hr.

Q_{sup} = supplemental heat supplied to maintain the specified (minimum) inside temperature, Kj/hr.

In Equation 1, the heat produced by equipment was neglected because it was small in comparison with the other heat gains. Also, supplemental heat is typically not provided in summer. Therefore, only four parameters were considered in the study, and the heat balance was simplified to a shorter form, including only those terms shown in Equation 1a.

$$Q_v = Q_a + Q_s + Q_r \qquad \ldots(1a)$$

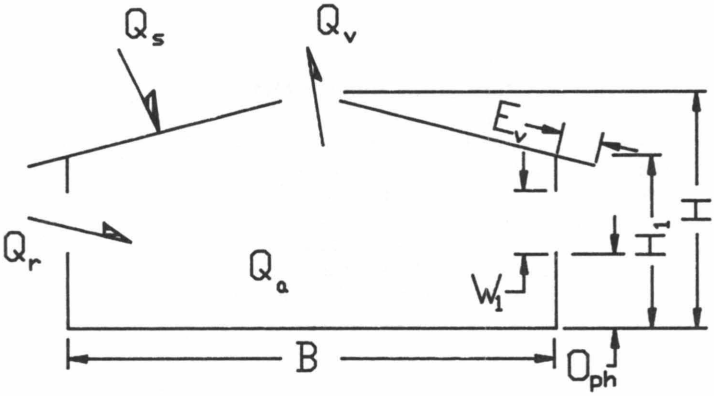


Figure 1: Schematic cross-section of a layer house showing variables considered for estimation of sensible heat gain and loss. Sensible heat is a measure of the energy that accompanies a temperature change.

SENSIBLE HEAT GAIN FROM LAYERS--Q_a

The most popular breed of laying chickens is the Leghorn. Roller and Dale (1963) found that the sensible heat loss of Leghorn chickens depends on dry-bulb temperature, mean bird weight, feed consumption, and dew-point temperature, as shown in Equation 2.

$$Q_a = m*Y_s*(17.48 - 0.71*t_i + 1.14*W_t + 13.7*X_c + 0.565*t_{dew}) \quad ...(2)$$

where

m = the number of layers in the house being studied.

Y_s = the fraction of total heat dissipated as sensible heat.

t_i = the air temperature to be maintained inside the layer house, ^{o}C.

W_t = the mean weight of the layers, N.

X_c = feed consumption, N/day-bird.

t_{dew} = dew-point temperature of the air inside the house, ^{o}C.

$$Y_s = 1.530 - 0.0284*t_i - 0.0119*W_t + 0.0143*t_{dew} \qquad \ldots(3)$$

$$t_{dew} = 6.983 + 14.38*\alpha_1 + 1.079*\alpha_1^2 \qquad \ldots(4)$$

where

$$\alpha_1 = \ln(P_w) = \ln(R_{hi}*P_{ws}) = \ln(R_{hi})+\ln(P_{ws}) \qquad \ldots(5)$$

P_w = water vapor pressure, KPa.

P_{ws} = water vapor pressure at saturation, KPa.

R_{hi} = relative humidity of air inside layer house.

$$\ln(P_{ws}) = -7511.52/T_i + 89.63121 + 0.02399*T_i - 1.16545*10^{-5}*T_i^2 - 1.28103*10^{-8}*T_i^3 + 2.09984*10^{-11}*T_i^4 - 12.151*\ln(T_i) \qquad \ldots(6)$$

T_i, the absolute temperature in K, of the air inside the house can be calculated from the Celsius temperature as shown in Equation 7.

$$T_i = 273.16 + t_i \qquad \ldots(7)$$

The feed consumption of a bird depends on body weight and egg production. It can be estimated by using Figure 2 or Equation 8.

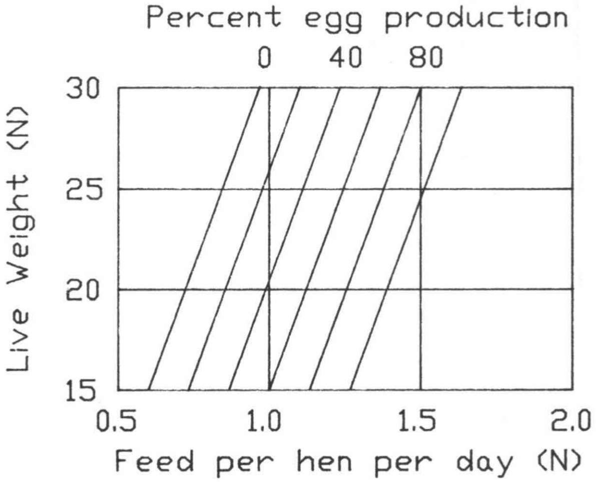


Figure 2: Feed consumption per day per bird (Longhouse et al., 1960).

$$X_c = 0.25 + 1.03*Egg + 0.022*(W_t - 15) \qquad ...(8)$$

where

Egg = egg production factor (i.e. 0.75 if 75 percent of chickens in the house lay eggs on a given day).

SOLAR RADIATION HEAT GAIN THROUGH OPENINGS--Q_r

Curtain walls and other openings are usually fully open in summer to maximize ventilation air flow. Energy may be transmitted into the building through these openings because of direct solar radiation, diffuse sky radiation, and solar radiation reflected from surrounding surfaces, particularly hot ground. By assuming there are no openings in the endwalls, we can calculate the total solar radiation through openings at any moment, as shown in Equation 9.

$$Q_r = (I_3 + I_5)*L*\varepsilon_s*W_2 \qquad ...(9)$$

where

I = total incidence of solar radiation on a surface, Kj/hr-m^2. (I_1 and I_2 refer to roof, I_3 and I_5 refer to sidewalls, and I_4 and I_6 refer to endwalls).

L = length of the layer house, m.

ε_s = absorptivity of the building when calculating the solar radiation heat gain through openings.

W_2 = width of the unshaded portion of the sidewall opening, m.

$$I_3 = I_{d3} + I_{dif3} + I_{ref3} \qquad ...(10)$$

$$I_5 = I_{d5} + I_{dif5} + I_{ref5} \qquad ...(11)$$

where

I_d = incidence of direct radiation, Kj/hr-m^2.

I_{dif} = incidence of diffuse sky radiation, Kj/hr-m^2.

I_{ref} = incidence of solar radiation reflected from surrounding surfaces, Kj/hr-m^2.

The whole house performs approximately as a black body (absorptivity ≅ 1.0) when the openings are relatively small and the building absorbs solar radiation only through openings.

Incidence of direct radiation--I_d

The incidence of instantaneous direct solar radiation on a surface can be calculated if the intensity normal to the sun's rays , I_n, is known.

$$I_d = I_n * K_s * \cos(\theta) \qquad \ldots(12)$$

where

I_n = the incidence of direct solar radiation upon a surface normal to the sun's rays, Kj/hr-m^2.

K_s = sky clearness number.

θ = incidence angle of the sun's rays upon a surface, degrees.

I_n, the incidence of direct solar radiation on a surface normal to the sun's rays, can be determined from the charts in Figures 3-6 if the latitude and the day of the year are known. Certain conditions should be satisfied, including a clear sky, a sea-level location, and a dust content similar to that of rural areas of eastern United States. The clearness number, as shown in Figure 7, varies from 0.9 to 1.05.

The incidence angle of the sun's rays upon a surface, θ , can be calculated by Equation 13 (Duffie and Beckman, 1974), if the latitude, tilt angle of the surface to the horizontal, azimuth, and hour angle are given.

$$\begin{aligned}\cos(\theta) = {} & \sin(d)*\sin(l_o)*\cos(s) \\ & - \sin(d)*\cos(l_o)*\sin(s)*\cos(r_1) \\ & + \cos(d)*\cos(l_o)*\cos(h)*\cos(s) \\ & + \cos(d)*\cos(l_o)*\sin(s)*\cos(r_1)*\cos(h) \\ & + \cos(d)*\sin(s)*\sin(r_1)*\sin(h) \qquad \ldots(13)\end{aligned}$$

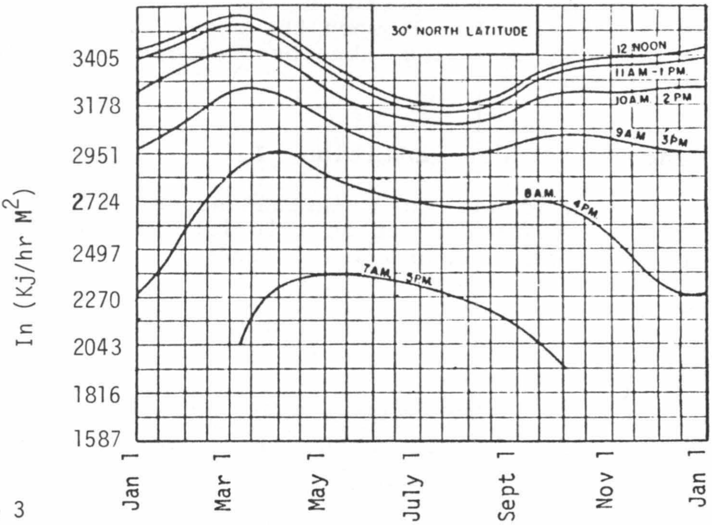


Figure 3

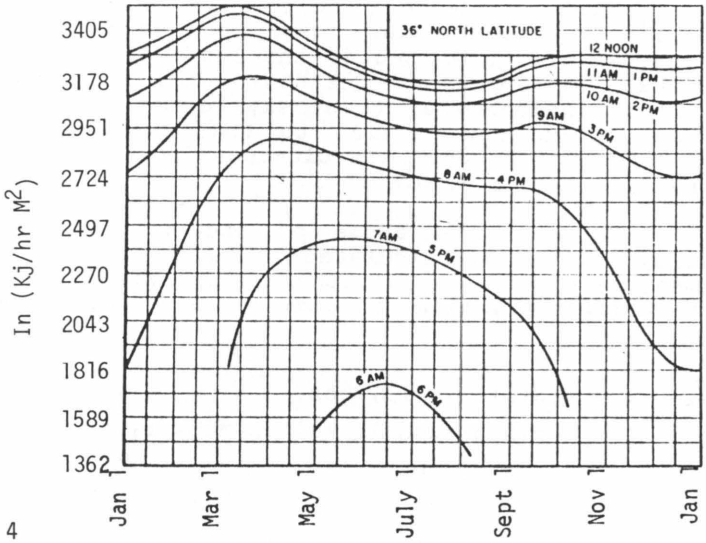


Figure 4

Figures 3-6: Incidence of direct solar radiation normal to the sun's rays at 30, 36,

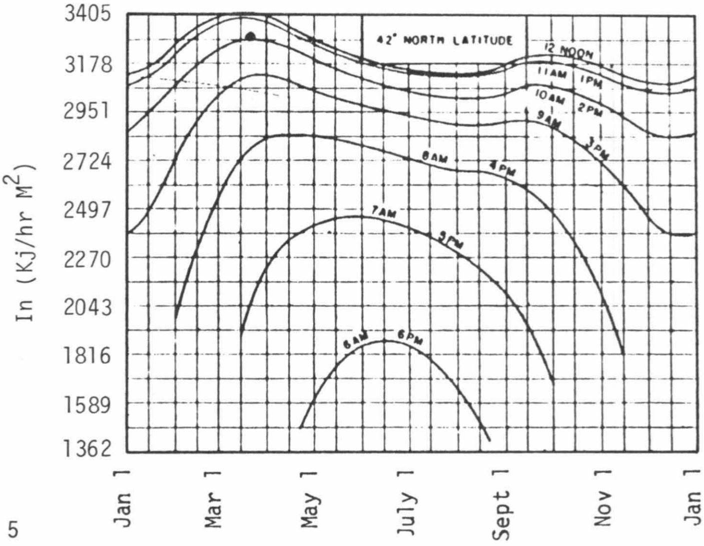


Figure 5

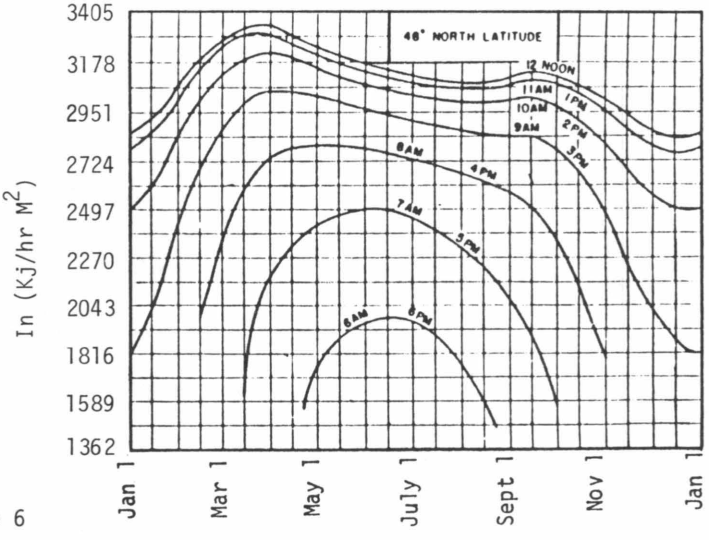


Figure 6

42, and 48 degrees North latitude for an atmospheric clearness number of unity (Nevins and Hall, 1958).

where

d = declination of the sun measured between a line extending from the center of the sun to the center of the earth and the projection of this line upon the earth's equatorial plane, degrees.

l_o = latitude, degrees.

s = angle between a particular surface and a horizontal plane, degrees.

r_1 = azimuth angle of a surface, degrees. (The deviation of the normal to the surface from the local meridian; zero being due south, east positive).

h = hour angle, degrees. (Solar noon is zero and each hour equals 15 degrees of longitude with morning positive, afternoon negative).

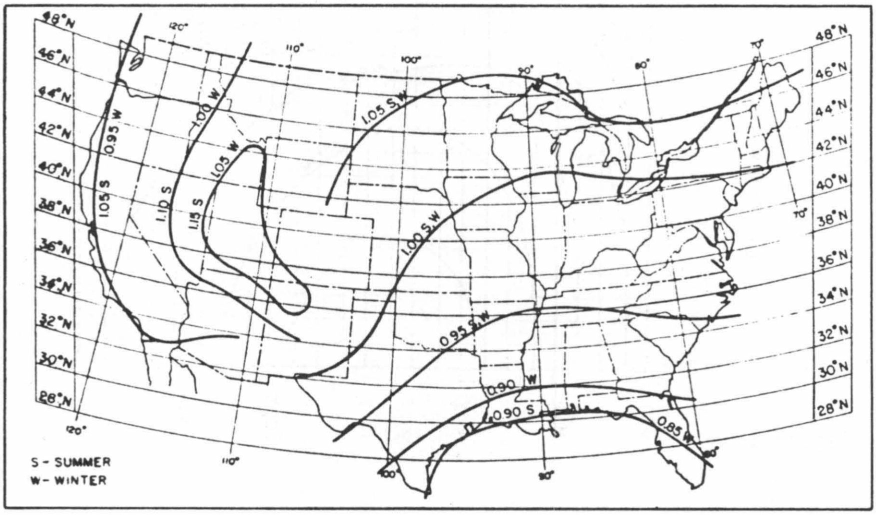


Figure 7: Estimated atmospheric clearness number in the United States for non-industrial localities.

The sign of the latitude, determined by the location of the surface studied, is positive for north and negative for south. The sun's declination varies with the day of the year, as shown in Equation 14.

$$d = 23.45*\sin(360*(284 + n)/365) \qquad ...(14)$$

where
n = the day of the year.

The tilt angle for a roof segment, s_r, is equivalent to the slope, as shown in Equation 15.

$$s_r = \tan^{-1}(2*(H - H_1)/B) \qquad ...(15)$$

where

H = the height of the peak of the layer house, m (see Fig. 1).

H_1 = height of sidewall, m.

L = length of the layer house, m.

B = width of the layer house, m.

For a wall, s_w = 90 degrees.

Solar time is determined by the position of the sun with respect to the location studied, as determined by Equation 16.

$$\Theta_s = \Theta_1 + E + 4*(L_{st} - L_{loc}) \qquad ...(16)$$

where

Θ_1 = local civil time, hr.

E = equation of time, hr. (see Table 1).

Incidence of solar radiation reflected from ground--I_{ref}.

The incidence of solar radiation reflected from the surrounding ground surface is difficult to estimate because both the character and direction are complicated. The best available approach is shown in Equation 17.

$$I_{ref} = (I_{dg} + I_{difg})* \varepsilon_g*F_g \qquad ...(17)$$

TABLE 1: The sun's declination and equation of time

Day	1		8		15		22	
	Dec.	Eq. of time	Dec.	Eq. of time	Dec.	Eq. of time	Dec.	Eq. of time
Month	Deg:Min	Min:Sec	Deg:Min	Min:Sec	Deg:Min	Min:Sec	Deg:Min	Min:Sec
Jan	-(23:08)	-(3:16)	-(22:20)	-(6:26)	-(21:15)	-(9:12)	-(19:50)	-(11:27)
Feb	-(17:18)	-(13:34)	-(15:13)	-(14:14)	-(12:55)	-(14:15)	-(10:27)	-(13:41)
Mar	-(7:51)	-(12:36)	-(5:10)	-(11:04)	-(2:25)	-(9:14)	0:21	-(7:12)
Apr	4:16	-(4:11)	6:56	-(2:07)	9:30	-(0:15)	11:57	1:19
May	14:51	2:50	16:53	3:31	18:41	3:44	20:14	3:30
Jun	21:57	2:25	22:47	1:15	23:17	-(0:09	23:27	-(1:40)
Jul	23:10	-(3:33)	22:34	-(4:48)	21:39	-(5:45)	20:25	-(6:19)
Aug	18:12	-(6:17)	16:21	-(5:40)	14:17	-(4:35)	12:02	-(3:04)
Sept	8:33	-(0:15)	5:58	2:03	3:19	4:29	0:36	6:58
Oct	-(2:45)	10:02	-(5:36)	12:11	-(8:15)	13:59	-(10:48)	15:20
Nov	-(14:12)	16:20	-(16:22)	16:16	-(18:18)	15:29	-(19:59)	14:02
Dec	-(21:41)	11:14	-(22:38)	8:26	-(23:14)	5:13	-(23:27)	1:47

where

ε_g = reflectance of the ground surface (see Table 2).
F_g = angle factor of the ground surface to a roof or wall.

TABLE 2: Reflectance of ground surface--ε_g

type of surface	reflectance
dry, plowed	0.22
moist, 70-90% dark	0.10
concrete	0.40
grassy ground	0.10

According to Lienhard (1981), the angle factor of two surfaces can be calculated by using Equation 18 if the surfaces are normal to each other (Fig. 8).

$$\begin{aligned} F_{12} = {} & (1/(3.14159*A_{11}))*(A_{12}*\tan^{-1}(1/A_{12}) \\ & + A_{11}*\tan^{-1}(1/A_{11}) \\ & - \sqrt{A_{11}^2+A_{12}^2}*\tan^{-1}(1/(\sqrt{A_{11}^2+A_{12}^2})) \\ & + 1/4*\ln\{[(1+A_{11}^2)*(1+A_{12}^2)/(1+A_{11}^2+A_{12}^2)] \\ & * [A_{12}^2*(1+A_{12}^2+A_{11}^2) \\ & / ((1+A_{12}^2)*(A_{11}^2+A_{12}^2))] \\ & ** (A_{12}^2)*[A_{11}^2*(1+A_{11}^2+A_{12}^2) \\ & /((1+A_{11}^2)*(A_{11}^2+A_{12}^2))]**(A_{11}^2)\}) \end{aligned} \qquad \ldots(18)$$

where

$$A_{11} = a_1/c_1$$
$$A_{12} = b_1/c_1 \qquad \ldots(19)$$

For sidewalls and ground,

$$A_{11} = H_1/L$$
$$A_{12} = b_1/L = 15/L \qquad \ldots(20)$$

where

b_1 = the width of the ground, m. For buildings in a

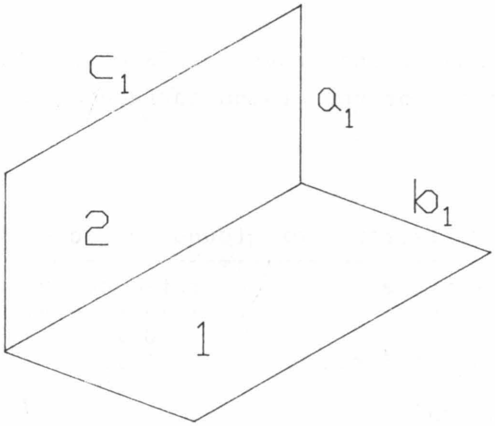


Figure 8: Definition of angle factor

group, it is the distance between adjacent buildings, usually about 15 m. For a single, isolated building, b_1 is infinite, and F_{gw}, the angle factor between the ground and the wall, equals 0.5.

For the endwalls and ground,

$$A_{11} = (H+H_1)/(2*B)$$

$$A_{12} = 15/B \qquad \text{...(21)}$$

F_{gr}, angle factor between the ground and the roof, can be approximated by Equation 22.

$$F_{gr} = (1-\cos(s_r))/2 \qquad \text{...(22)}$$

where

s_r = the slope of the roof, degrees.

Diffuse sky radiation--I_{dif}

A portion of the incoming solar radiation is scattered by air molecules and particles smaller in size than the wavelength of the radiant energy. The downward directed component is called diffuse sky radiation.

The procedure for calculating the intensity of sky radiation during clear sky conditions on a terrestrial surface is shown in Equations 23.

$$I_{difr} = I_n * F_{dif} * F_{sr}$$
$$I_{difw} = I_n * F_{dif} * F_{sw} \qquad \ldots(23)$$

where

I_{difr}, I_{difw} = the diffuse sky radiation received by roof and wall respectively, Kj/hr-m^2.

F_{dif} = the diffuse radiation factor (see Table 3).

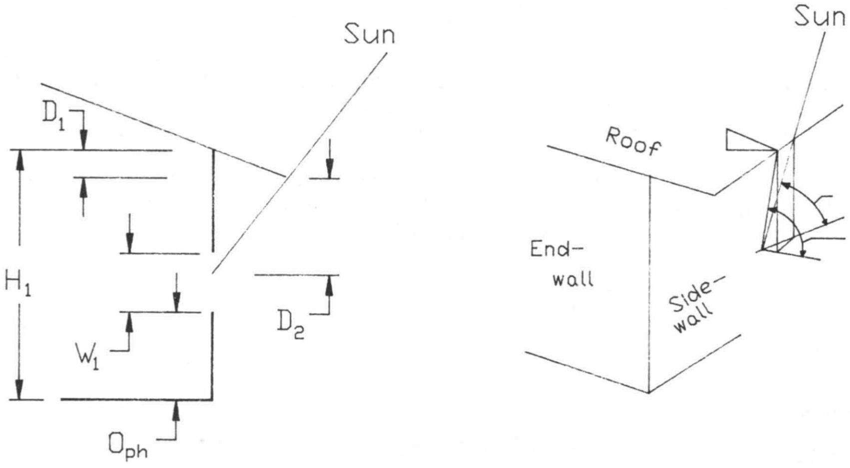
F_s = the sky-surface angle factor. F_{sr} refers to the roof, F_{sw} refers to a wall.

$$F_{sr} = 1 - F_{gr}$$
$$F_{sw} = 1 - F_{gw} \qquad \ldots(24)$$

Table 3: Diffuse radiation factor--F_{dif}
(21st day of month)

Month	Jan.	Feb.	Mar.	April	May	June
F_{dif}	0.058	0.060	0.071	0.097	0.121	0.134
Month	July	Aug.	Sept.	Oct.	Nov.	Dec.
F_{dif}	0.136	0.122	0.092	0.073	0.063	0.057

The sidewall area which is shaded changes, depending on the latitude, day of year, time of day, and length of eaves. The relationship between the variables used to determine the shaded area is illustrated in Figure 9 and explained by Equations 25-29.



Cross-section

Figure 9: The shading of a sidewall

$$\tan(\delta) = \sin(\beta)/\cos(\theta) \quad \ldots(25)$$

$$\sin(\beta) = \cos(l_o)*\cos(h)*\cos(d) + \sin(l_o)*\sin(d) \quad \ldots(26)$$

$$D_1 = E_v*\sin(s_r) \quad \ldots(27)$$

$$D_2 = E_v*\cos(s_r)*\tan(\delta) \quad \ldots(28)$$

$$W_2 = H_1-D_1-D_2-O_{ph} \quad \ldots(29)$$

where

δ = the sun's profile angle, degrees.

β = altitude angle of the sun, degrees.

D_1, D_2 = width of shaded areas, m (see Figure 9).

E_v = the length of eaves, m.

O_{ph} = the distance from the lower edge of the curtain opening to the ground, m.

SOLAR RADIATION HEAT GAIN THROUGH ROOF AND WALLS--Q_s

Heat gain through the portion of the roof and walls facing the sun can be greatly increased because of solar radiation. Mackey and Wright (1944) introduced the term "sol-air temperature" which includes the effect of solar heat on heat transfer through a wall. Sol-air temperature is the temperature at which the heat transfer rate and temperature distribution of a shaded wall are equivalent to the heat transfer rate and temperature distribution of walls which are unshaded and receive solar radiation. The relationship is shown in Equation 30.

$$\begin{aligned} t_e &= t_o + I*\alpha/h_o \\ &= t_o + \alpha*(I_d + I_{dif} + I_{ref})/h_o \end{aligned} \qquad \ldots(30)$$

where

t_e = sol-air temperature, ^oC.
t_o = outside temperature, ^oC.
h_o = combined convection and radiation heat transfer coefficient, Kj/hr-m^2-^oC (see Table 4).
α = solar energy absorptivity (see Table 5).

The outside temperature, which varies with solar time (θ_s), can be approximated by Equation 31.

$$t_o = t_{oa} + (t_{oamax} - t_{oa})*\cos(15*(\theta_s - \phi_a)) \qquad \ldots(31)$$

where

t_{oa} = monthly mean temperature of July, ^oC.
t_{oamax} = the monthly average daily maximum temperature for July, ^oC.
θ_s = solar time, hour. θ_s=1,2,...,24.
ϕ_a = the solar time when t_{oamax} occurs, hr.

It has been observed that t_e varies with I, and that I is a function of solar time at a certain place. Threlkeld (1970) expressed t_e in term of the Fourier series shown in Equation 32.

$$t_e = t_{em} + M_1 * \cos(\omega_1 * \theta_s) + N_1 * \sin(\omega_1 * \theta_s) + M_2 * \cos(\omega_2 * \theta_s) + N_2 * \sin(\omega_2 * \theta_s) + \ldots \qquad \ldots(32)$$

where

$$t_{em} = 1/24 * \int_0^{24} t_e d\theta_s \qquad \ldots(33)$$

$$M_n = 1/12 * \int_0^{24} t_e * \cos(\omega_n * \theta_s) d\theta_s \qquad \ldots(34)$$

$$N_n = 1/12 * \int_0^{24} t_e * \sin(\omega_n * \theta_s) d\theta_s \qquad \ldots(35)$$

$$\omega_n = n * \omega_1 = n * 3.14159/12 \qquad \ldots(36)$$

Table 4: Surface heat transfer coefficient h_i, h_o (Kj/hr.m^2.^oC)

Description of surface	Direction of heat flow	Surface emissivity 0.90	0.20	0.05
Horizontal(still air)	Up	33.3	18.6	15.5
Horizontal(still air)	Down	22.1	7.6	4.5
Sloping,45^o(still air)	Up	32.7	18.0	14.9
Sloping,45^o(still air)	Down	27.0	12.3	9.2
Vertical(still air)	Horizontal	29.8	15.1	12.1
Any position (6.7 M/s)	Any	122.1	/	/
Any position (3.35 M/s)	Any	81.8	/	/

Table 5: Solar energy absorptivity--α (dimensionless)

White paint	0.20
Black paint	0.94-0.98
Felt, roofing, bituminous	0.88
Asbestos cement board, white	0.59
Brick, red	0.55
Wood, planed oak	0.92
Concrete	0.60
Asphalt pavement, dust free	0.93

After applying Equations 32-36, the relationship describing t_e can be written in the form shown in Equation 37.

$$t_e = t_{em} + \sqrt{M_1^2 + N_1^2} *\cos(\omega_1 * \theta_s - \Psi_1) + \sqrt{M_2^2 + N_2^2} *\cos(\omega_2 * \theta_s - \Psi_2) + \ldots$$

$$= t_{em} + t_{e1} *\cos(\omega_1 * \theta_s - \Psi_1) + t_{e2} *\cos(\omega_2 * \theta_s - \Psi_2) + \ldots \qquad \ldots(37)$$

where

$$\tan(\Psi_n) = N_n/M_n \qquad \ldots(38)$$

The quadrant in which Ψ_n lies is dependent on the following rule: the sign of $\sin(\Psi_n)$ is the same as that of N_n, and the sign of $\cos(\Psi_n)$ is the same as M_n.

Two harmonics are generally considered to be adequate to describe the behavior of a horizontal surface. But six or more harmonics may be required for a vertical surface because the variation of t_e is not pure sine-wave behavior.

Alford et al. (1939), in a study of the heat flow through a wall, made the following assumptions to facilitate their analysis.

(1) The wall is of infinite length and height but finite thickness.

(2) The wall is homogeneous.

(3) The indoor and outdoor heat transfer coefficients are constant.

(4) The thermal properties of the structure -- conductivity, specific heat, and density -- are independent of temperature variations.

(5) The variations of outdoor air temperature and solar intensity with time are identical on successive days.

Using these assumptions, they then wrote the differential equation, Equation 39, to describe heat flow at all points in a wall.

$$k_w * \partial^2 t_w / \partial x^2 = \rho_w * C_w * \partial t_w / \partial \theta_s \qquad \ldots(39)$$

where

K_w = thermal conductivity of the materials in a wall, Kj-m/hr-m^2-^{o}C.

t_w = the temperature at any point of wall, ^{o}C.

ρ_w = the density of materials, Kg/m^3.

C_w = specific heat for wall, Kj/Kg-^{o}C.

Equation 39 is subject to the two boundary conditions shown in Equations 40 and 41.

$$q_i = -K_w * (\partial t_w / \partial x)_{x=L_w} = h_i * (t_{wi} - t_i) \qquad \ldots(40)$$

$$q_o = -K_w * (\partial t_w / \partial x)_{x=0} = h_o * (t_e - t_{wo}) \qquad \ldots(41)$$

where

L_w = the thickness of the wall, m.

t_{wo}, t_{wi} = the outside and inside wall temperatures, respectively, ^{o}C.

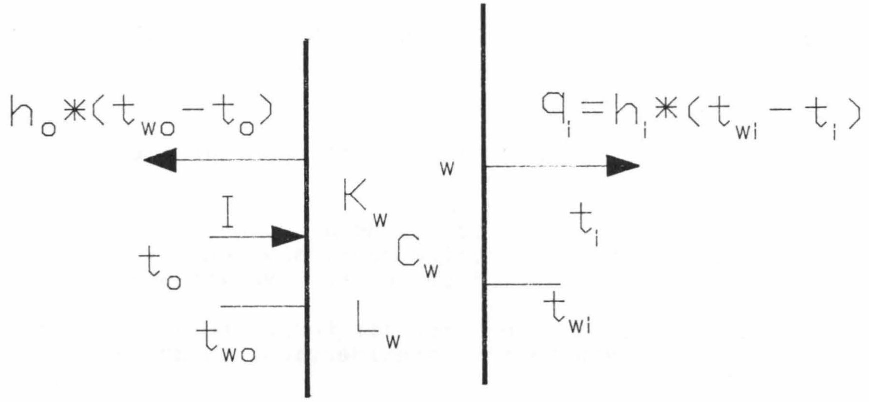


Figure 10: Schematic diagram for periodic heat transfer analysis

The complete solution for Equations 39-41 has been given by Alford et al. (1939). The temperature of the inside-wall surface, t_{wi}, is given in Equation 42.

$$\begin{aligned} t_{wi} &= t_i+1/h_i*(U*(t_{em}-t_i) \\ &\qquad + V_1*t_{e1}*\cos(\omega_1*\theta_s-\Psi_1-\phi_1) \\ &\qquad +V_2*t_{e2}*\cos(\omega_2*\theta_s-\Psi_2-\phi_2)+\ \ldots) \end{aligned} \qquad \ldots(42)$$

where

$$U = 1/(1/h_i+L_w/K_w+1/h_o) \qquad \ldots(43)$$

$$V_n = h_o*h_i/(\sigma_n*K_w*\sqrt{Y_n^2+Z_n^2} \qquad \ldots(44)$$

$$\sigma_n = (1/k_w)*\sqrt{\omega_n*\rho_w*C_w*K_w/2} \qquad \ldots(45)$$

$$K_w*\sigma_n = \sqrt{\omega_n*\rho_w*C_w*K_w/2} \qquad \ldots(46)$$

$$\begin{aligned} Y_n &= (h_o*h_i/(2*\sigma_n^2*K_w^2)+1)*\cos(\sigma_n*L_w)*\sinh(\sigma_n*L_w) \\ &\quad +(h_o*h_i/(2*\sigma_n^2*K_w^2)-1)*\sin(\sigma_n*L_w)*\cosh(\sigma_n*L_w) \\ &\quad +(h_o+h_i)/(\sigma_n*K_w)*\cos(\sigma_n*L_w)*\cosh(\sigma_n*L_w) \end{aligned} \qquad \ldots(47)$$

$$\begin{aligned} Z_n &= (h_o*h_i/(2*\sigma_n^2*K_w^2)+1)*\sin(\sigma_n*L_w)*\cosh(\sigma_n*L_w) \\ &\quad -(h_o*h_i/(2*\sigma_n^2*K_w^2)-1)*\cos(\sigma_n*L_w)*\sinh(\sigma_n*L_w) \\ &\quad +(h_o+h_i)/(\sigma_n*K_w)*\sin(\sigma_n*L_w)*\sinh(\sigma_n*L_w) \end{aligned} \qquad \ldots(48)$$

$$\phi_n = \tan^{-1}(Z_n/Y_n) \qquad \ldots(49)$$

In Equation 49, sin (ϕ_n) has the sign of Z_n and cos (ϕ_n) has the sign of Y_n. The rate of heat transfer to the interior is given by Equation 50.

$$\begin{aligned} q_i &= h_i*(t_{wi}-t_i) \\ &= U*((t_{em}+\lambda_1*t_{e1}*\cos(\omega_1*\theta_s-\Psi_1-\phi_1) \\ &\qquad +\lambda_2*t_{e2}*\cos(\omega_2*\theta_s-\Psi_2-\phi_2)\ +\ldots)\ -\ t_i) \end{aligned} \qquad \ldots(50)$$

where

$$\lambda_n = V_n/U \qquad \ldots(51)$$

$$Q_s = \sum_{i=1}^{6} q_i*F_i \qquad \ldots(52)$$

where

F_i = the area of a wall or a roof, m^2.

Equation 50 is limited by the assumptions stated previously, one of which is that the wall or roof is homogeneous. In fact, most walls are made of multi-layer materials. The parameters used to represent the characteristics of walls are k_w, ρ_w, and C_w. Mackey and Wright (1946) developed a technique to find a homogeneous analog for a multi-layer composite construction. The thermal resistance of the equivalent homogeneous construction is given by Equation 53.

$$L_w/K_w = L_o/K_o + L_{m1}/K_{m1} + \ldots + L_{mn}/K_{mn} + L_i/K_i \qquad \ldots(53)$$

$$L_w = L_o + L_{m1} + \ldots + L_{mn} + L_i \qquad \ldots(54)$$

$$K_w = L_w/(L_o/K_o + L_{m1}/K_{m1} + \ldots + L_{mn}/K_{mn} + L_i/K_i) \qquad \ldots(55)$$

where the subscript o represents the outside layer, i refers to the inside layer, and m refers to interior layers.

The property of $(K_w{*}\,\rho_w{*}C_w)$ of the equivalent homogeneous construction is

$$\begin{aligned}(K_w{*}\rho_w{*}C_w) = {} & (1.1{*}(L_i/K_i){*}(K_i{*}\rho_i{*}C_i) + 1.1{*}(L_{m1}/K_{m1}) \\ & {*}(K_{m1}{*}\rho_{m1}{*}C_{m1}) + \ldots + 1.1{*}(L_{mn}/K_{mn}) \\ & {*}(K_{mn}{*}\rho_{mn}{*}C_{mn}))/(L_w/K_w) \\ & + ((K_o{*}C_o{*}\,\rho_o){*}((L_o/K_o) \\ & - 0.1{*}(L_i/K_i) - 0.1(L_{m1}/K_{m1}) \\ & - \ldots - 0.1{*}(L_{mn}/K_{mn}))/(L_w/K_w) \qquad \ldots(56)\end{aligned}$$

If $((K_o{*}\rho_o{*}C_o){*}((L_o/K_o) - 0.1(L_i/K_i) - 0.1(L_{m1}/K_{m1}) - 0.1(L_{mn}/K_{mn}))/(L_w/K_w) < 0$

then this term is set to equal zero.

The value of $(K_w{*}\,\rho_w{*}C_w)$ for air space may be treated as zero.

SENSIBLE HEAT LOST IN VENTILATING AIR--Q_v

The difference between the outgoing and incoming sensible heat content of air equals the ventilation heat loss from the building, as shown in Equation 57.

$$Q_v = M*C_p*(t_i-t_{oa}) \quad ...(57)$$

where

C_p = the specific heat of dry air, C_p=1.0035 Kj/Kg-^oC

M = air flow mass, Kg/hr.

$$M = Q*\rho_a \quad ...(58)$$

$$\rho_a = (p-p_w)/(R_a*(t_i+273.16))$$
$$= (101.325-R_{hi}*P_{ws})/(0.287055*(t_i+273.16)) \quad ...(59)$$

Using the methods described above, Q_a,Q_s,Q_r can be calculated, and the required ventilation rate can be found, as shown in Equation 60.

$$Q = (Q_a+Q_s+Q_r)/(1.0035*\rho_a*(t_i-t_{oa})) \quad ...(60)$$

DISCUSSION

As described above, the calculation of the required ventilation rate is quite complicated, particularly the estimation of heat gain through the roof and walls. Computer simulation, using Fortran 77 and the P-system, and Basic and DOS on an IBM-PC computer, was used to simplify the process. Details of the computer program will be discussed in another paper. However, this section presents an example to serve as a basis for discussion of some interesting problems.

EXAMPLE

Determine the required summer ventilation rate for a layer house. The types of construction assumed for the roof and walls are shown in Figure 11 and the thermal parameters for the structure are presented in Table 6. For the latitude given, the intensity of solar radiation normal to the sun's rays, I_n, (from Figure 3) is shown in Table 7. Additional data needed to describe the structure, the weather conditions and other factors which affect the ventilation requirement, are given in Table 8.

Table 6: Thermal parameters of the example structure

Layer	Materials	L_i (m)	K_w (Kj-m/hr-m-^oC)	w (Kg/m)	C_w (Kj/Kg-C)
Roof 1	Asphalt felt	0.01	46.38*	1121.3	1.465
Roof 2	Mineral wool	0.075	0.14	48.1	0.67
Roof 3	Wood	0.04	0.57	720.8	2.386
Wall 1	Red brick	0.10	2.59	1922.2	0.837
Wall 2	Concrete	0.02	2.59	1858.1	0.795

* Kj/m^2-hr-^{o}C.

Table 7: Intensity of solar radiation (I_n) at various solar times at the specified latitude (Kj/hr-m^2)

Solar time	1	2	3	4	5	6	7	8	9	10	11	12
I_n	0.	0.	0.	0.	0.	0.	2293.0	2701.0	2940.0	3087.0	3144.0	3178.0

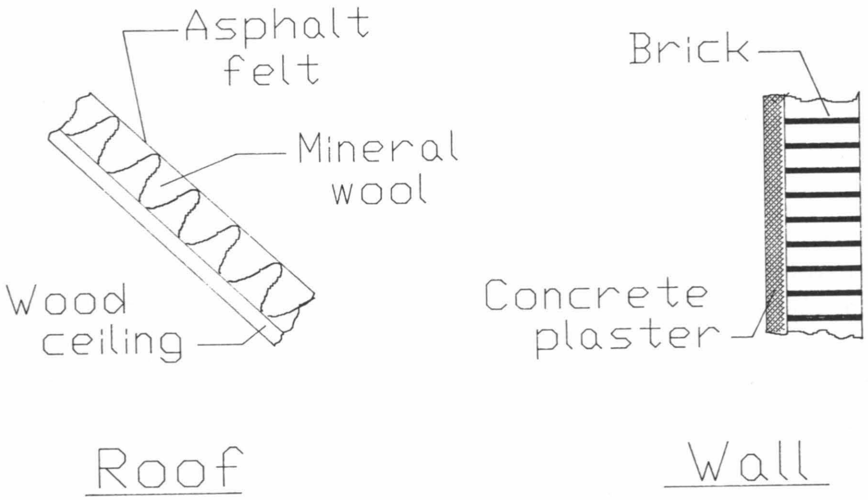


Figure 11: Type of construction assumed for the walls and roof of the example structure

Table 8: House characteristics, weather conditions, and other information for the example problem

Description	Symbol	Data	Unit
Inside temperature	t_i	30.90	°C
Inside relative humidity	R_{hi}	0.55	/
Mean weight of a layer	W_t	17.80	N
Egg production	E_{gg}	0.75	/
Number of layers	M	15000.	/
Length of house	L	100.0	m
Width of house	B	12.0	m
Height of house	H	6.0	m
Height of sidewall	H_1	3.0	m
Width of opening	W_1	1.0	m
Width of eaves	E_v	0.6	m
Distance from lower edge of curtain to ground	O_{ph}	1.0	m
Latitude	l_o	30.0 N	Deg.
Azimuth angle(facing south	r_1	0.0	Deg.
Sky clearness number	K_s	1.0	/
Day number(July 15)	n	196.0	/
Plowed ground reflectance)	ε_g	0.22	/
Diffuse radiation factor	F_{dif}	0.136	/
Absorptivity for house	ε_s	1.0	/
Combined factor of outside surface	H_o	81.8	Kj/hr-m^2-°C
Combined factor of inside surface of roof	H_i	27.0	Kj/hr-m^2-°C
Combined factor of inside surface of walls	H_i	29.8	Kj/hr-m^2-°C
Absorptivity for solar radiation --red brick	α	0.55	/
---asphalt felt	α	0.88	/
Average July temperature	T_{oa}	27.9	°C
Monthly average daily maximum temperature	T_{oamax}	31.9	°C
Time when T_{oamax} occurs	ϕ_a	14.0	hour

RESULTS

As noted above, the analysis was carried out by a computer. The results are summarized in the remainder of this section.

(1) The sensible heat gained from the layers (Q_s) was 467,315.00 Kj/hr.

(2) The rates of solar radiation heat gain through openings (Q_r) at different solar times are shown in Table 9.

(3) The rates of heat transfer through walls and roof (Q_s) are shown in Table 10.

(4) The total rate of heat transfer through wall and roof surfaces is given in Table 11.

(5) The ventilation rates required at different solar times are shown in Table 12.

(6) The maximum ventilation rate, 179,025.20 m^3/hr, occurs at 17:00 (solar time).

Table 9: Rates of solar radiation heat gain through the openings in the sidewalls at different solar times (Kj/hr).

Time	Q_r	Time	Q_r	Time	Q_r
1	0.0	9	47700.5	17	78692.3
2	0.0	10	53914.9	18	0.0
3	0.0	11	57362.1	19	0.0
4	0.0	12	58827.7	20	0.0
5	0.0	13	57362.1	21	0.0
6	0.0	14	53914.9	22	0.0
7	78692.2	15	47700.5	23	0.0
8	39456.3	16	39456.3	24	0.0

Table 10: Rates of heat transfer through walls and roof surfaces (Kj/hr)

Time	Surface Number					
	1	2	3	4	5	6
1	9251.9	9193.1	-8608.8	-2279.4	-8490.8	-1809.3
2	7089.8	7049.0	-10393.7	-2828.9	-10328.1	-2405.1
3	5128.5	5096.1	-11796.9	-3223.0	-11741.7	-2885.3
4	3363.8	3336.6	-12750.1	-3383.4	-12666.9	-3276.8
5	1809.1	1790.3	-13269.9	-3546.0	-13240.8	-3475.0
6	487.6	475.9	-13339.5	-3735.9	-13425.8	-3438.5
7	-620.0	-638.5	-12725.9	-3309.5	-12560.1	-3358.3
8	-1501.5	-1515.0	-11150.0	-1617.8	-10063.1	-2997.6
9	-1955.2	-1874.7	-8647.4	983.5	-6582.2	-2307.9
10	-1628.2	-1330.6	-5505.1	3330.7	-3498.9	-1469.9
11	-274.5	254.3	-1871.4	4614.3	-1213.1	-735.0
12	2076.7	2666.3	2190.4	4897.1	1047.7	-72.2
13	5199.6	5592.9	6208.4	4605.8	3581.7	733.1
14	8791.0	8794.4	9301.9	4066.5	5612.8	1811.2
15	12483.1	12013.9	10886.3	3543.5	6711.8	3248.8
16	15868.2	14939.2	11081.9	3204.9	7539.4	5057.3
17	18593.7	17339.3	10274.6	2922.1	8488.5	6759.7
18	20392.6	19080.0	8625.0	2428.7	8675.1	7385.1
19	21045.2	19958.4	6232.8	1709.6	7139.3	6392.4
20	20453.1	19725.9	3452.6	962.0	4263.4	4389.9
21	18799.3	18378.9	711.3	252.9	1198.9	2486.5
22	16519.4	16280.6	-1835.5	-475.6	-1499.5	1134.6
23	14039.1	13893.4	-4246.4	-1169.1	-3975.4	54.9
24	11587.2	11495.3	-6531.3	-1743.7	-6339.8	-968.4

Table 11: Rates of overall heat transfer through wall and roof surfaces (Kj/hr)

Time	Q_S	Time	Q_S
1	-2743.2	13	25921.5
2	-11816.9	14	38377.7
3	-19422.3	15	48887.3
4	-25376.8	16	57690.9
5	-29932.2	17	64377.9
6	-33021.2	18	66586.4
7	-33212.4	19	62477.7
8	-28845.0	20	53246.9
9	-20384.0	21	41827.9
10	-10102.1	22	30124.0
11	774.5	23	18596.5
12	12806.0	24	7499.4

Table 12: Ventilation rates required at different solar times (m^3/hr)

Time	Q	Time	Q
1	136269.30	13	161494.10
2	133608.70	14	164135.70
3	131378.70	15	165395.10
4	129632.70	16	165559.10
5	128296.90	17	179025.20
6	127391.20	18	156598.10
7	150408.90	19	155393.40
8	140185.10	20	152686.70
9	145083.40	21	149338.40
10	149920.50	22	145906.60
11	154120.50	23	142526.50
12	158087.10	24	139272.60

ANALYSIS

(1) The heat gain through walls and roofs is negative from 1:00 am to 10:00 am (i.e., heat is transferred to the outside through the structure because of the lower temperature of outside surfaces of walls and roofs). Figure 12 shows the variations in rates of heat transfer through the structure.

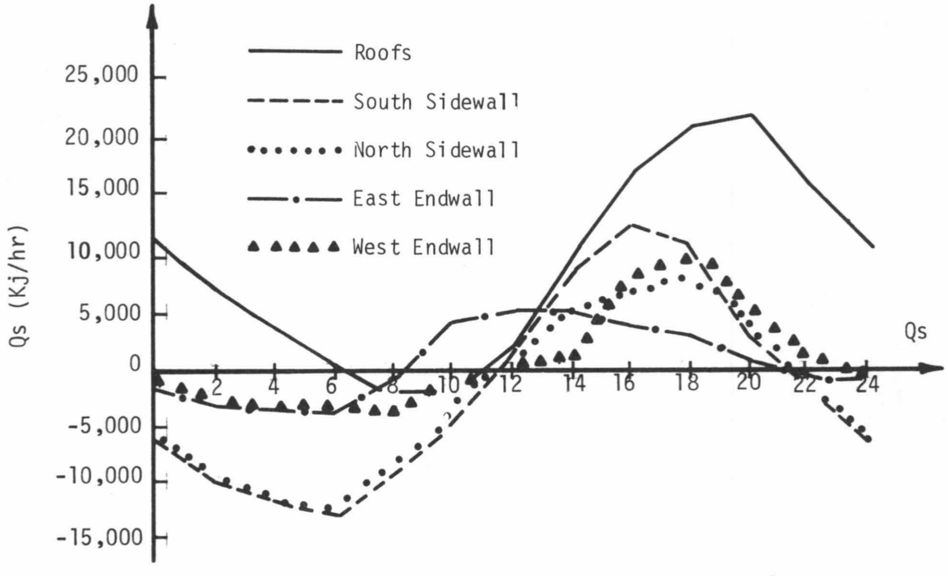


Figure 12: Heat gain through walls and roofs

(2) The solar radiation heat gain through openings can be quite large if there are no eaves on the building. In the example above, the maximum heat gain was 78692.2 Kj/hr at 7:00 and 17:00. With no eaves, the maximum increases to 164534.0 Kj/hr at 12:00. The other factor which affects solar radiation through openings is the width of openings. Some comparisons are shown in Table 13.

Table 13: Required ventilation rates at various times as a function of opening width

Width of opening(m)	Required ventilation(m^3)	Time
0.5	172513.0	17:00 *
1.0	179025.0	17:00
1.5	181479.0	17:00

* 5:00 p.m.

It can be seen that the width of the opening does not have a large effect on the required ventilation rate if the width is large enough and the layer house is oriented east-west. The required ventilation rate increases by 11.2 percent when the width of the opening changes from 1.0 M to 1.5 M under the condition of no eaves. If the house is naturally ventilated, the ventilation rate through the openings can be computed when the width of the ridge vent is known. Comparing two effects of openings on ventilation, the best width of opening for summer ventilation can be estimated. This procedure will be discussed in another article.

Another factor is the distance between the lower edge of an opening and the ground. The heat gain through the openings will be increased if this distance is decreased, given the same length of eaves. If the eaves are large enough, the effect is negligible. In this example, if we change the distance from 1.0 to 2.0 m, the heat gain through the openings will be changed only at 7:00 am and 5:00 pm from 78692.2 to 29179.4 Kj/hr. At other times, the heat gain through the openings is unchanged because the eaves shade the openings.

(3) The orientation of the layer house has a great effect on ventilation. The ventilation rates shown in Table 14 were calculated for houses located at different azimuths. It is apparent that the house facing south is in the best orientation for ventilation if the prevailing wind is not considered.

Table 14: Required ventilation rates as influenced by building orientation

r_1(deg)	Required ventilation rate	Time
0 (south)	179025.0 (m^3/hr)	17:00
-45 (south-west)	219868.0	16:00
45 (south-east)	228907.0	16:00
90 (east)	243697.0	16:00

(4) There is at least one significant source of building heat besides the sensible heat from the layers and solar radiation through openings. The heat gain through the roof is substantial. If the roof is uninsulated, consisting only of layers of asphalt felt roofing and lumber, the required ventilation rate will be 248107.3 m^3/hr at 14:00, an increase of 38.6 percent. It is advisable to insulate the roof to reduce the required ventilation rate.

(5) If the building location is moved from 30 deg. to 48 deg. north latitude (e.g, the the incidence of direct solar radiation on surfaces is changed) but the same outside and inside weather parameters are kept, the required ventilation rate will be 196188.3 m^3/hr at 13:00 compared to 179025.0 m^3/hr at 17:00. The primary reason for the increase in the required ventilation rate is the increase in the heat gain through the opening on the south sidewall.

SUMMARY

From the preceding discussion and calculations, it is obvious that the ventilation rate for a layer house which has openings on both sidewalls and does not have a ceiling can be calculated from a sensible heat balance equation even though the procedures are complicated. The main steps are as follows

(1) Calculate the heat gain from the layers.

(2) Estimate the direct solar radiation, sky-diffuse radiation, reflected radiation from the ground, shaded area of openings, and incidence of solar radiation through openings.

(3) Find the outside temperature from local weather information; calculate the sol-air temperature on the various surfaces of the building.

(4) Calculate the thermal resistance, density, and specific heat for the composite walls and roofs.

(5) Calculate the heat gain through walls and roofs at different solar times.

(6) Calculate the required ventilation rate at different solar times. Determine the time when the maximum ventilation requirement occurs.

It should be observed that some of the sources of heat gain, including heat gain through walls, are quite small. At night the building will lose heat through walls. The walls have little effect on the required ventilation rate. The roof structure, however, is very important in the estimation of summer ventilation. Adequate thermal resistance in the roof is neccessary to reduce the required ventilation rate in summer. The heat lag time is determined by the thermal properties of the materials of walls and roof.

SYMBOLS

A_{11},A_{12}	Dimensionless factors defined by equations (20) and (21), respectively.
b_1	The width of surrounding ground, m.
B	The width of the layer house, m.
C_p	Specific heat of dry air, Kj/Kg-°C.
C_w	Specific heat for whole wall or roof, Kj/Kg-°C. C_i--for inside layer of material. C_m--for internal layer. C_o--for outside layer.
d	The sun's declination, degrees.
D_1,D_2	The length defined by equations (27) and (28), respectively, m.
E	Equation of time, hour.
Egg	Egg production, dimensionless.
E_v	The width of eaves, m.
F_{dif}	Diffuse radiation factor, dimensionless.
F_{gi}	Ground-surface angle factor, dimensionless. F_{gr} = ground to roof. F_{gw} = ground to wall.
F_i	The area of building surfaces, m^2. i=1--6.
F_s	Sky-surface angle factor, dimensionless. F_{sr} = sky-roof, F_{sw} = sky-wall.
h	Hour angle, deg.
h_o,h_i	The combined convection and radiation heat transfer coefficient, Kj/hr-m^2-°C. h_o refers to outside surfaces, h_i refers to inside surfaces.
H	The height of layer house, m.
H_1	The height of sidewall, m.
I	Total incidence of solar radiation, Kj/hr-m^2. I_1 and I_2 refer to roof, I_3 and I_5 refer to sidewalls, I_4 and I_6 refer to endwalls.
I_d	The incidence of direct solar radiation, Kj/hr-m^2.
I_{dif}	The diffuse sky radiation, Kj/hr-m^2.
I_n	Incidence of direct solar radiation upon a surface normal to the sun's rays, Kj/hr-m^2.
I_{ref}	Solar radiation reflected from surrounding surfaces, Kj/hr-m^2.
K_w	Thermal conductivity of materials of walls and roof, Kj-m/hr-m^2-°C. K_o = outside layer, K_i = inside layer. K_{m1}, K_{m2},... refer to interior layers from outside to inside.
K_s	Sky clearness number, dimensionless.

L	The length of a layer house, m.
L_m	The thickness of interior layers of walls and roof, m.
L_i	The thickness of inside layer of wall or roof, m.
l_o	The latitude, degrees.
L_{loc}	Local longitude, degrees.
L_{st}	Standard meridian, degrees.
L_w	The thickness of wall or roof, m.
n	The day of year, dimensionless.
m	The number of layers in the house, dimensionless.
M	Air flow mass, Kg/hr.
M_n	Factor defined by equation (34), ^oC.
N_n	Factor defined by equation (35), ^oC.
O_{ph}	Distance from the lower edge of opening to ground,m.
P	Atmospheric pressure, KPa.
P_w	Water vapor pressure, KPa.
P_{ws}	Water vapor pressure at saturation, KPa.
Q	Required ventilation rate, m^3/hr.
Q_a	Sensible heat gain from layers, Kj/hr.
Q_e	Heat gain produced by equipment, Kj/hr.
Q_r	Solar radiation heat gain through openings, Kj/hr.
Q_s	Solar radiation heat gain through walls and roof, Kj/hr.
Q_{sup}	Supplemental heat supplied by heaters, Kj/hr.
Q_v	Sensible heat lost in ventilation air, Kj/hr.
r_1	The azimuth angle of a surface, degrees.
R_{hi}	Relative humidity of air inside a layer house, dimensionless.
s	The angle between a surface and the horizontal, degrees. s_r refers to roof.
t_e	Sol-air temperature, ^oC. t_{em} = 24-hour mean value. t_{e1} = the first harmonic, etc.
t_{dew}	Dew-point temperature of air inside the layer house.
T_i	Absolute temperature, k.
t_i	Air temperature inside a layer house,^oC.
t_o	Outside air temperature, ^oC.
t_{oa}	Monthly average daily temperature in July, ^oC.
t_{oamax}	The monthly average daily maximum temperature in July, ^oC.
t_w	The temperature at any point of wall or roof, ^oC.
U	Overall heat transfer coefficient, Kj/hr-m^2-^oC.
V_n	Factor given by equation (44), Kj/hr-m^2-^oC.
W_t	The mean weight of a layer, N.
W_1	The width of an opening, m.

W_1	The width of an opening, m.
W_2	The width of unshaded part of opening, m.
X_c	Feed consumption, N/day-bird.
Y_n	Factor defined by equation (47), dimensionless.
Y_s	Fraction of total heat dissipated as sensible heat, dimensionless.
Z_n	Factor given by equation (48), dimensionless.
α	Absorptivity of materials for solar radiation, dimensionless.
α_1	Factor defined by equation (5), dimensionless.
α_w	Thermal diffusivity, m^2/hr.
ε_g	Reflectance of ground surface, dimensionless.
ε_s	Absorptivity of the building when calculating the solar radiation heat through openings, dimensionless.
Θ	Incidence angle for a surface, degrees.
Θ_1	Local civil time.
Θ_s	Solar time, $_s=1,2,\ldots,24$.
λ_n	Factor given by equation (51), dimensionless.
ρ_a	Air density, Kg/m^3.
ρ_w	Wall equivalent density for a composite wall, Kg/m^3. r = roof, o = outside layer of structure, m = interior layer, i = inside air.
σ_n	Factor defined by equation (45), m^{-1}.
ϕ_a	The solar time when t_{oamax} occurs, hour.
ϕ_n	Lag angle defined by equation (49), radian.
Ψ_n	Lag angle given by equation (38), radian.
ω_n	Angular velocity of sinusoidal wave, radian.
β	Altitude angle of the sun, degrees.
δ	The sun's profile angle, degrees.

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Virginia's Agricultural Experiment Stations

1 —— Blacksburg
Virginia Tech
Main Station

2 —— Steeles Tavern
Shenandoah Valley Research Station
Beef, Sheep, Fruit, Forages, Insects

3 —— Orange
Piedmont Research Station
Small Grains, Corn, Alfalfa, Crops

4 —— Winchester
Winchester Fruit Research Laboratory
Fruit, Insect Control

5 —— Middleburg
Virginia Forage Research Station
Forages, Beef

6 —— Warsaw
Eastern Virginia Research Station
Field Crops

7 —— Suffolk
Tidewater Research and Continuing Education Center
Peanuts, Swine, Soybeans, Corn, Small Grains

8 —— Blackstone
Southern Piedmont Research and Continuing Education Center
Tobacco, Horticulture Crops, Turfgrass, Small Grains, Forages

9 —— Critz
Reynolds Homestead Research Center
Forestry, Wildlife

10 —— Glade Spring
Southwest Virginia Research Station
Burley Tobacco, Beef, Sheep

11 —— Hampton
Seafood Processing Research
and Extension Unit
Seafood