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/Metod teplotekhnicheskogo rascheta ventiliruemykh okon/

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by G L Cairns

METHOD FOR THE CALCULATION OF THE IMPROVEMENT IN THERMAL INSULATION PROVIDED BY VENTILATED AS COMPARED TO UNVENTILATED WINDOWS

(Metod teplotekhnicheskogo rascheta ventiliruemykh okon)

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By reducing the heat losses and heat inputs through transparent building enclosure structures, a considerable diminution is achieved in both the thermal capacity of heating systems and the refrigerating capacity of air-conditioning plants. One effective means of reducing the transmission flows through windows during the heating season is to use the air extracted from the room to ventilate the air-space between the glazings. The heat transmission coefficient of a ventilated window is between two-thirds and one-third of that of an unventilated window /1/. In addition, the temperature of the inner glazing is higher and the heat losses, occasioned by the heating of the external air which enters the room at the window due to lack of proper sealing, are less.

It is improper to apply to ventilated windows the laws governing heat transmission through opaque enclosing structures through which air can permeate /2,3/. With ventilated windows heat transfer is effected by combined convection and radiation at the surfaces of the glazings and in the air-space between them, whereas with porous, opaque enclosing structures it is determined principally by the thermal conductivity of the materials forming the cavity construction.

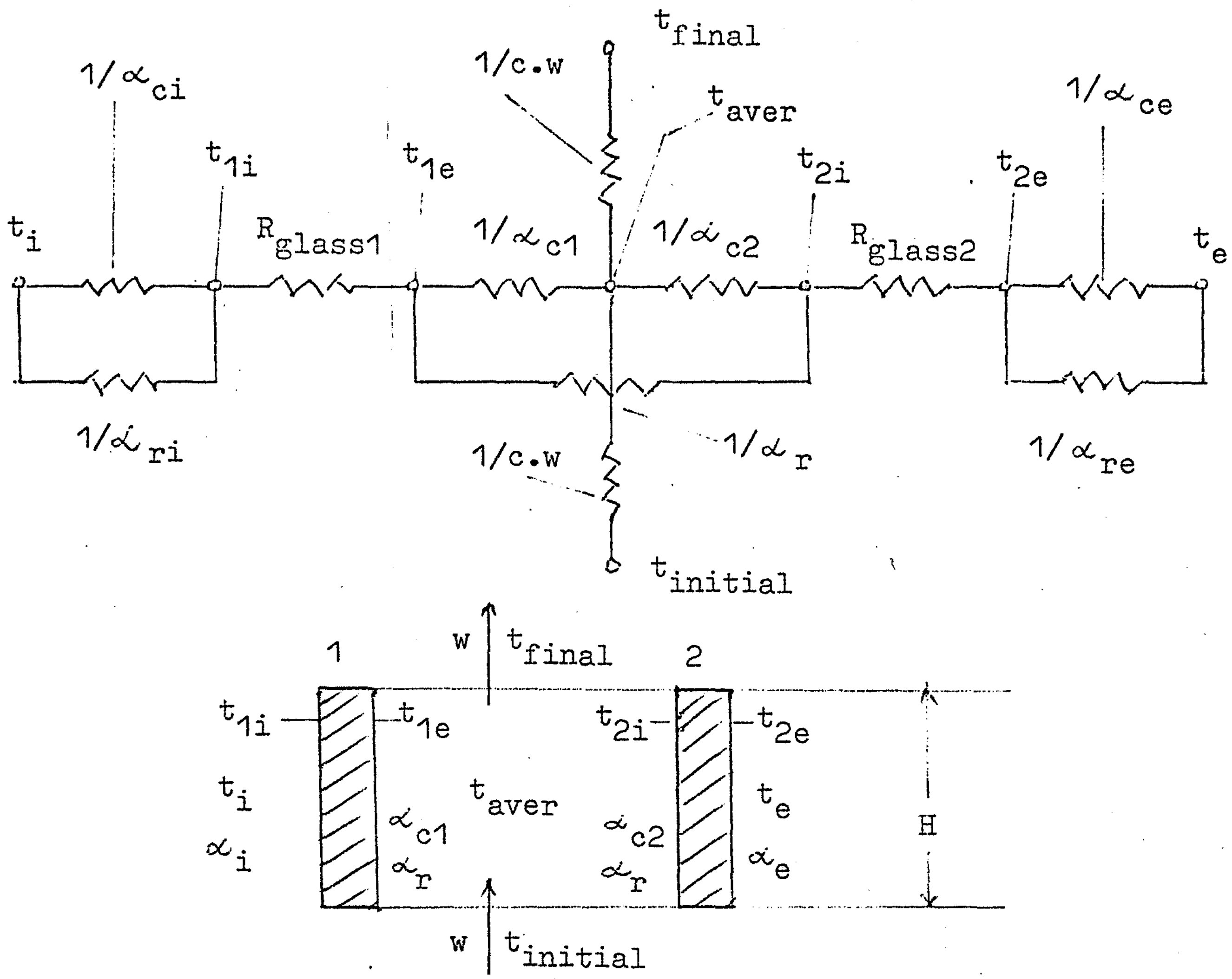
Fig.1 shows a sketch and heat diagram of a ventilated window of height H. The dimensions of the opening are assumed to be sufficiently great and the effect of any inclination out of the vertical on the heat transmission process to be negligible. Air infiltration due to imperfect sealing is ignored. The ventilation of the cavity between the glazings is effected by the mass flow (per 1 m window width) with an initial temperature, t_{init}, and a final temperature, t_{fin}. In the general case, the initial temperature may differ from the internal air temperature t_i and the external air temperature t_e. Appropriate indices are used to distinguish the heat-exchange coefficients in the sketch and the associated resistances in the diagram. The coefficient and resistance values are assumed not to vary with the window height for average glazing and cavity air temperatures. Fig.1 represents the case for a double window. With triple windows, by the quantity R_{glass2} is understood the sum of the thermal resistances of the glazings (taking into account the sashes) and the air-space enclosed between them.

Presented in this way, the problem resolves itself into a known uni-dimensional one, which is described by the differential equation

$$\left[k_e\ (t_x - t_e) - k_i\ (t_i - t_x)\right] dx = c\ W\ d\ t_x, \qquad (1)$$

where t_x = the ventilated cavity air temperature at a distance x from the air inlet,

k_i and k_e = the coefficients of thermal transmission from the indoor air to the cavity air and from the latter to the outdoor air respectively. Their values, having regard to the reduced radiation



N.B. i = internal
e = external
c = convection
r = radiation
1 = inner glazing
2 = outer glazing

Fig.1 Sketch and heat diagram of ventilated window coefficient of heat exchange in the cavity to the temperature of the air in it, are obtained from the expressions (Fig.1) :

$$k_i = \frac{1}{\dfrac{1}{\alpha_{ci} + \alpha_{ri}} + R_{glass1} + \dfrac{1}{\alpha_{c1} + \alpha_r \dfrac{t_{1e} - t_{2i}}{t_{1i} - t_{av}}}} ; \qquad (2)$$

$$k_e = \frac{1}{\dfrac{1}{\alpha_{c2} + \alpha_r \dfrac{t_{1e} - t_{2i}}{t_{av} - t_{2i}}} + R_{glass2} + \dfrac{1}{\alpha_{ce} + \alpha_{re}}} ; \qquad (3)$$

For local temperatures, t_x, the solution of Eqn (1) assumes the form

$$\frac{t_x - t_{cav}}{t_{init} - t_{cav}} = \exp\left(- \frac{k_i + k_e}{c\ w}\ x\right), \qquad (4)$$

and the mean cavity-air temperature is determined from the relationship

$$E = \frac{t_{av} - t_{cav}}{t_{init} - t_{cav}} = \frac{1 - \exp\left(- \dfrac{k_i + k_e}{cw / H}\right)}{\dfrac{k_i + k_e}{c\ w / H}} . \qquad (5)$$

The cavity temperature, t_{cav}, is the weighted mean temperature, at which the heat flows through the ventilated window inner and outer glazings are identical and equal to the heat flows in absence of ventilation, i.e.

$$k_i\ (t_i - t_{cav}) = k_e\ (t_{cav} - t_e) = k_i^o\ (t_i - t_{cav}^o) =$$

$$= k_e^o\ (t_{cav}^o - t_e) = k_o\ (t_i - t_e) , \qquad (6)$$

where the index o both here and below denotes the corresponding parameters in absence of ventilation.

From Eqn (2) it follows that

$$\frac{k_i\ k_e}{k_i + k_e} = \frac{k_i^o\ k_e^o}{k_i^o + k_e} = k_o \qquad (7)$$

and

$$\Delta R = \frac{t_{cav} - t^o{}_{cav}}{k_o\ (t_i - t_e)} , \qquad (8)$$

where k_o = the unventilated window heat transmission coefficient,

ΔR = the variation in the resistance to the heat transmission of the inner and outer glazings due to ventilation. When ventilation is provided by the internal air, $t_{cav} > t^o{}_{cav}$ and the resistance of the inner glazing falls, while that of the outer glazing rises by the amount ΔR.

Though it is ssible by using an iterative method to determine ΔR and consequently also the heat transmission coefficients k_i and k_e as a function of the air flow, the possibilities of using such a method are limited owing to the awkwardness of the computations and a degree of uncertainty of the key convection heat exchange equations under gravitational-viscosity air-flow conditions in the air-space between the glazings. It is better to express the desired quantities in terms of the known unventilated window parameters and the air change rate. The temperature difference ($t_{cav} - t^o{}_{cav}$) is due to the heat flow introduced by the ventilation air. This same heat flow causes a temperature deviation in the window cavity by the amount $(t_{av} - t_{cav})$ (see Eqn (5)), and so it is possible to write

$$(k_i + k_e)(t_{cav} - t^o_{cav}) = (k_e + k_i)(t_{av} - t_{cav}) =$$
$$= c\ w\ /\ H\ (t_{init} - t_{fin})\ , \qquad (9)$$

in which the right-hand part represents the heat flow introduced by the ventilation air and the left-hand part the difference in heat flows through the inner and outer glazings. The coefficients, k_i and k_e, as already remarked, are assumed constant over the height of the window at the mean cavity-air temperature.

Using Eqn (9) for the case of window ventilation by the indoor air $(t_{init} = t_i)$ and making some simple rearrangements, we obtain

$$k_i = k^o_i\ (1 + E) \qquad (10)$$

and

$$k_e = \frac{k_o}{1 - \dfrac{k_o}{k^o_i\ (1 + E)}} \qquad (11)$$

where E = the ventilation effectiveness index, computed according to Eqn (5);

k^o_i and k^o_e = the heat transmission coefficients of the unventilated window inner and outer glazings. Their magnitude is determined from the condition of equality of the air-cavity temperature, t^o_{cav}, to the arithmetic-mean temperature of the inner faces of the twin glazings according to the expressions :

$$k^o{}_i = \frac{2\ k_o}{1 + \beta} \qquad (12)$$

and

$$k^o{}_e = \frac{2\ k_o}{1 - \beta} \qquad (13)$$

where

$$\beta = \frac{(R^o{}_i + R_{glass1}) - (R^o{}_{glass2} + R^o{}_e)}{R_o} ; \qquad (14)$$

$R^o{}_i$, $R^o{}_e$, R_o = the resistances of the unventilated window to the absorption, giving up and transmission of heat respectively;

R_{glass1} and $R^o{}_{glass2}$ = the reduced thermal resistances of the glazings (taking into account the sashes). In triple windows, the quantity $R^o{}_{glass2}$ includes the resistance of two glazings and the air-space enclosed between them. For normal resistance values, β is equal to 0.2 for double and 0.25 for triple windows.

The sum of the coefficients k_i and k_e equals :

$$k_i + k_e = \frac{4\ k_o}{\left[2\ \dfrac{1 + \beta}{1 + E} - \left(\dfrac{1 + \beta}{1 + E}\right)^2\right]} = \varepsilon\ 4\ k_o\ , \qquad (15)$$

where ε = the correction for the quantity 4 k_o.

Substituting for k_i and k_e in Eqn (5), we obtain for the ventilation effectiveness index, E :

$$E = \varphi\ E^o = \varphi\ \frac{1 - \exp\left(- \dfrac{4\ k_o}{cw/H}\right)}{\dfrac{4\ k_o}{cw/H}}\ , \qquad (16)$$

where E^{o} = the basic ventilation effectiveness index, determined from the condition of equality of the sum of the coefficients k_i and k_e to the quadruple heat transmission coefficient of the unventilated window;

φ = a correction factor allowing for the deviation of the basic from the design effectiveness index. Its value depends on the ventilation air flow rate; for double windows it is practically equal to 1, but for triple windows it varies between 0.90 and 0.94 and may for practical purposes be assumed equal to 0.92.

The basic effectiveness index was used to calculate the correction ε when computing the factor φ, which is fully admissible as its value varies to only a minor extent for a wide range of variation of the effectiveness index.

The design ventilated-window heat transmission coefficient referred to the temperature difference $(t_i - t_e)$ and, in the final analysis, determining the room heat loss, is equal to

$$k = k_i \frac{t_i - t_{av}}{t_i - t_e} , \qquad (17)$$

and so for window ventilation by the indoor air $(t_{init} = t_i)$ after some rearrangement we finally obtain

$$\frac{k}{k_o} = 1 - E = 1 - \varphi \frac{1 - \exp\left(- \frac{4\ k_o}{cw/H}\right)}{\frac{4\ k_o}{cw/H}} . \qquad (18)$$

From Eqn (18) it follows that the ventilation effectiveness index, E, characterizes the relative reduction in the heat transmission coefficient, $\Delta k/k_o$, due to the ventilation. Eqn (18) is represented in Fig.2. The factor φ is assumed equal to 1 for double, and 0.92 for triple windows.

The ventilated window heat transmission coefficient, referred to the design temperature difference $(t_i - t_e)$ and determining the heat loss, k^e, through the outer glazing is calculated in similar fashion according to the expression

$$\frac{k^e}{k_o} = 1 + k_e / K_i\ E\ , \qquad (19)$$

in which the coefficient ratio k_e/k_i is equal to

$$\frac{k_e}{k_i} = \frac{1}{2\,\dfrac{1 + E}{1 + \beta} - 1} \qquad (20)$$

Where β is determined in accordance with Eqn (14).

The inner glazing temperature rise due to ventilation is

$$t_{1i} - t^o_{1i} = (R^o_i\ k_o - R_i\ k)\ (t_i - t_e)\ , \qquad (21)$$

where R^o_i and R_i = the resistances to heat absorption by the inner glazing of the unventilated and the ventilated window;

k_o and k = the design heat transmission coefficients of the unventilated and ventilated window.

Assuming $R_i/R^o_i = k^o_i/k_i$, we finally obtain

$$\theta_{1i} = \frac{t_{1i} - t^{o}_{1i}}{t_i - t_e} = R^{o}_{i}\, k_o \frac{2\,E}{1 + E}\,, \qquad (22)$$

where $R^{o}_{i}\, k_o = 0.33$ for double, and 0.22 for triple windows.

The temperature rise of the outer glazing subjected to the passage of the ventilating air flow is calculated according to the expression :

$$\theta_{2i} = \frac{t_{2i} - t^{o}_{2i}}{t_i - t_e} = \gamma \frac{E}{1 + E}\,, \qquad (23)$$

where $$\gamma = 2\,k_o\,(R_{glass2} + R^{o}_{e}) \frac{1 + \beta}{1 - \beta}\,, \qquad (24)$$

being equal to 0.45 for double, and 0.6 for triple windows.

Expressions (22) and (23) are represented in Fig.3.

To prevent the condensation of water vapour on the glazing surface, the temperature t_{2i} must be above the inflowing air dew point t_d. When the internal air used to provide ventilation has an initial temperature t_i of from 18 to 20°C and a relative humidity of from 20 to 35 per cent, the value of t_d is between 2 and 4.5°C.

Calculations show that for double windows water vapour condensation on the inner face of the outer glazing begins at an outdoor temperature $t_e = -3°C$.

For triple windows the minimum effectiveness index (E_{min}) design values and the air change rate w/H (per 1 m^2 of window), necessary to maintain a temperature $t_{2i} = 5°C$, are given in Table 1. Eqns (23) and (16) were used to make the calculation,

t_i having a value of $20^{o}C$ and $(t^{o}_{2i} - t_e)(t_i - t_e)$ a value of 0.5.

TABLE 1

t_e, ^{o}C	E, mm	w/H, $kg/m^2.h$
- 5	-	-
- 10	0.017	0.3
- 15	0.164	4.5
- 20	0.284	8.7
- 25	0.408	15.0
- 30	0.525	24.4
- 35	0.637	40.0
- 40	0.743	64.7
- 45	0.844	156.5

The results of the calculation with experimental data are expressed (18) as a function of the dimensionless coefficients. As a result we obtain

$$k = \frac{1}{S} - \Delta k = \frac{1}{s} - \varphi \frac{1 - \exp(-4/S)}{4} , \qquad (25)$$

where $k = \frac{k}{cw/H}$; $S = \frac{cw/H}{k_o}$; $k_i = \frac{k_i}{cw/H}$;

H = the window height,

w, c = the mass flow rate (per 1 m window width) and thermal capacity of the air,

k, k_o = the heat transmission coefficients of the ventilated and unventilated window,

Δk_i = the window heat transmission coefficient increment due to ventilation, in this case

$$k = k_o - \Delta k_i \; ; \quad k = \frac{1}{S} - \Delta k_i .$$

The calculation results obtained for k and Δk as a function of S according to Eqn (25) are given in Table 2.

TABLE 2

S	Double windows (φ = 1)		Triple windows (φ = 0.92)	
	Δk	k	Δk	k
0	0.25	-	0.23	-
0.5	0.25	1.75	0.23	1.77
1	0.24	0.76	0.22	0.78
2	0.22	0.28	0.20	0.30
4	0.16	0.10	0.15	0.11
6	0.12	0.05	0.11	0.06
8	0.10	0.03	0.092	0.04
12	0.07	0.013	0.064	0.019
16	0.055	0.007	0.051	0.012
20	0.045	0.005	0.041	0.009

On comparing the computed with the experimental results, they are found virtually to coincide /1,2/, thus testifying to the accuracy of the proposed method.

CONCLUSIONS

The summarizing graph in Fig.2 testifies to the effectiveness of the ventilation of windows in improving their thermal insulation performance, the inner and outer glazing temperature being then appreciably raised (Fig.3). To avoid condensation on the inner face of the outer glazing, the design air change rate must be not less than that indicated in Table 1.

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Captions to Figures 2 and 3 on page 15 of the original:

Fig.2 The ventilated/unventilated window heat transmission coefficient ratio, k/k_o, as a function of the quantity $\frac{cw/H}{k_o}$ for (1) double and (2) triple windows.

Fig.3 Relative rise in the temperature of the inner face of the glazings of ventilated windows

1 - inner glazing; 2 - outer glazing;

\- - - - double windows; ——— triple windows.

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