AIR CONDITIONS OF BUILDINGS AND ALLOWANCE FOR AIR PENETRATION IN CALCULATION OF THE HEATING DUTY

by
V.N.Bogoslovskii and V.P.Titov

Kuibyshev Institute of Building Moscow.
Dept. of Heating and Ventilating
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The heating duty for modern multi-storey buildings depends on their air conditions. The air flow through the walls and between rooms affects the temperature in the rooms, alters their heat losses and the design heating capacity of the heating systems.

The air exchange in the rooms takes place due to external wind, gravity, and operation of the fans. Air enters the building through imperfectly fitting windows, through butt joints, through pores and capillaries in external walls, and is heated to the temperature of the inside air. Through the doors opening to the staircases or corridors and through leaky internal walls, air moves throughout a building and gets out through extracting ventilating systems and leakages in the walls of the upper storeys on the leeward side.

Air penetration reduces the heat storage in the walls(by infiltration of cold air through the walls, by condensation of humid internal air on the inside surface of walls), and increases fuel consumption for heating the rooms.

The intensity of air penetration depends on the height of a building and its orientation. The location and the dimensions of the infiltration zone vary over a heating season, which complicates the selection of the capacity and the control of the heating systems for individual rooms.

AIR CONDITIONS OF A BUILDING

In most cases complete imperviousness of the walls is not technically possible. In designing and constructing of buildings we aim at minimum permissible, or, as is commonly known, at the required resistances to air penetration of the walls.

The air conditions of a building are determined by the air penetration resistance of the external and internal walls. Low (not restricted by the building standards) resistances of internal structures to air penetration lead to increased air infiltration into the buildings, leakage of air from room to room, and to a decrease in the natural ventilation of rooms on the upper storeys, particularly in tall buildings.

In technical calculations associated with air conditions of a building use is made of different air penetration characteristics of the structures and materials, such as: air penetration resistance R_i, air penetration coefficient, "resistance characteristic" of a wall S, coefficient of local resistance, and coefficient of flowrate. S and R_i are used most often.

The intensity of air penetration depends on the differences between air pressure on the internal and external sides of the wall.

To determine the pressure distribution inside and outside, and the air flowrates through the building it is necessary to calculate the air conditions of the building as a whole. The following data must be known: the shape, planning and dimensions of the building, air penetration characteristics of all the elements of the building, aerodynamic coefficients, wind velocity, and external and internal air temperatures.

The problem amounts to solving a system of equations of air balances of the rooms, complicated by the non-linear relation between air flowrate and differential pressures for windows, doors, and ventilating ducts.

The air conditions are calculated by the hydro- and electro-analogy method, also on linear lattices*, on a digital computer, or by N.N.Razumov's semigraphical method.

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*See M.A.Latyshenko's article in this issue.

To estimate the effect of the air conditions in buildings on the heating duty one can use simplified calculation methods.

Let us consider three different instances:

a) a multi-storey building with mechanical air supply and extraction for all rooms (administrative public, and residential buildings with air heating systems and mechanical air extraction from flats, or buildings without mechanical ventilation systems);

b) a multi-storey building with only extract ventilation and natural infiltration;

c) a multi-storey building in which, in addition to extract ventilation with natural infiltration, provision is made for preheated external air supply to the staircase.

Instance a. Fig.1 shows the layout of a building with pressure distributions plotted relative to the conventional zero which is assumed to be the pressure on the external surface at the highest point on the leeward side.

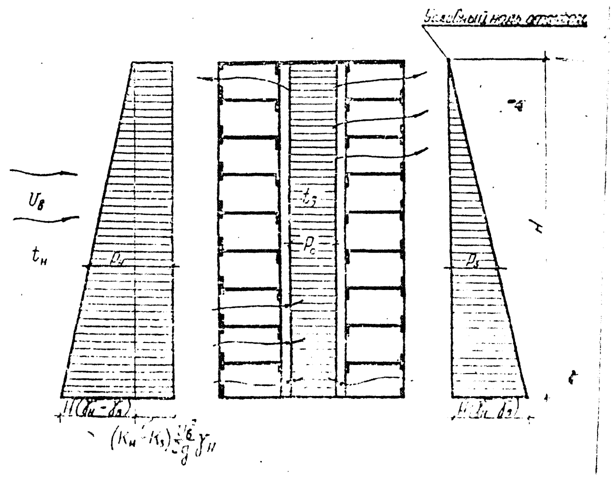


Fig.1. Layout of a building and distributions of pressures causing air flow through the building structures (coventional zero datum (q).

In Fig.1 K_{ww} and K_{lw} = aerodynamic coefficients on the windward and leeward sides of the building;

v_w = wind velocity, m/s;

γ_{ex}, γ_{in} = volumetric weight of the external and internal air, kg/m^3;

H = height of the building, m;

g = acceleration due to gravity, m/s^2;

p_{ww}, p_{lw} = pressure on the windward and leeward sides of the building at arbitrary levels, kg/m^2;

p_o = pressure constant over the height of the staircase, kg/m^2.

If external air passes in turn through windows and doors, the problem concerning the air conditions of the building can be reduced to calculation of the air conditions of the stairwell with uniform penetrability of the walls over the height.

A solution of the problem for the case when the penetrability of the building walls is identical for different storeys both on the windward and leeward sides shows that the difference between pressure outside the building and the pressure inside the staircase for any storey n is

$$\Delta p_{n,\text{л.к}} = p_{n.\text{н(з)}} - p_0 = h_{\text{эт}}\left[\frac{N}{2}-(n-1)\right](\gamma_{\text{н}}-\gamma_{\text{в}}) \pm \frac{K_{\text{н}}-K_{\text{з}}}{2}\,\frac{v_{\text{в}}^2}{2g}\,\gamma_{\text{н}}. \quad (1)$$

Here h_{st} = height of a storey, m;

N = the number of storeys in the building;

n = number of a storey considered

(Plus corresponds to windward side, and minus corresponds to leeward side of the building).

For the ground floor on the windward side $\Delta p_{1,stc}$ is highest and equals

$$\Delta p_{1,\text{л.к}} \approx \frac{h_{\text{эт}}N}{2}(\gamma_{\text{н}}-\gamma_{\text{в}}) + \frac{K_{\text{н}}-K_{\text{з}}}{2}\,\frac{v_{\text{в}}^2}{2g}\,\gamma_{\text{н}}. \quad (2)$$

To calculate the intensity of air infiltration through the external walls of individual rooms it is necessary to know the differential pressures on two sides of the wall (on the outside $p_{n,ww(lw)}$ and in the room $p_{n,x}$ $\Delta p_{n,room}$ $p_{n,ww(lw)}$ $p_{n,x}$. $\Delta p_{n,room}$ can be found by the graphical method, and also from the condition

$$\frac{\Delta p_{n,\,\text{пом}}}{\Delta p_{n,\,\text{л.к}}} = \frac{S_{\text{ок}} G^2}{(S_{\text{ок}} + S_{\text{дв}}) G^2} = \frac{S_{\text{ок}}}{S_{\text{ок}} + S_{\text{дв}}},$$

i.e.

$$\Delta p_{n,\,\text{пом}} = \Delta p_{n,\,\text{л.к}} \frac{S_{\text{ок}}}{S_{\text{ок}} + S_{\text{дв}}}. \qquad (3)$$

Here S_{wn}, S_{dr} = resistance characteristics of the windows of a room (or a flat) and of a door opening to the staircase. S_{wn} is a conventional characteristic calculated for the average range of the differential pressures from the Equation:

$$S_{\text{ок}} G^2_{\text{ок.ср}} = s_{\text{л}} \frac{G_{\text{ок.ср}}}{F_{\text{ок}}} + s_{\text{т}} \left(\frac{G_{\text{ок.ср}}}{F_{\text{ок}}}\right)^2;$$

$$S_{\text{ок}} = \frac{s_{\text{т}}}{F^2_{\text{ок}}} + \frac{s_{\text{л}}}{F_{\text{ок}} G_{\text{ок.ср}}},$$

where S_L and S_T = coefficients determining the nature of air penetration through the window;

$G_{wn.av}$ = flowrate determined for average pressure difference, kg/h;

F_{wn} = area of the windows in a room (or a flat), m^2.

Instance b. The layout of the building is similar to the one shown in Fig.1. Extraction ventilation is installed in the rooms on all floors. The extract ducts ensure the air exchange in the rooms G_{ex} kg/h required by the natural ventilation standards ($t_{ex} = +5^{\circ}C$). Consequently, the extract duct resistance characteristic of the n-th storey is determined by the formula

$$S_{\text{в},\,n} = \frac{h_{\text{эт}} (N - n + 1)(\gamma_{+5} - \gamma_{\text{в}})}{G^2_{\text{н}}}. \qquad (4)$$

Here $\gamma + 5$ and γ_{in} = volumetric weight of the external air at $t_{ex} = +5^{\circ}C$ and of the internal air, respectively.

When every storey is provided with individual extract ducts, the magnitude of the resistance characteristic remains constant at different pressure drops over a winter. In the case of a combined system of extract ducts calculations show the $S_{ex.d,n}$ varies little for the lower storeys, and for the upper storeys it sharply increases with the decrease in external air temperature. This makes it necessary to install individual extract ducts in rooms in the upper third of the building.

Let us discuss a building with individual ducts ($S_{ex.d,n}$ = const). Pressure distribution on the external side of the building (see Fig.1) and the magnitudes of the resistance characteristics $S_{ex.d,n}$, S_{wn}, and S_{dr} are known. We have to determine the air pressure in the staircase p_o and in the rooms of all the storeys $p_{n,x}$.

The problem is solved according to the following procedure:

1) An approximate value of pressure in the staircase is assigned (in the conventional scale) which can be determined from the expression:

$$p_0 \approx \frac{p'_{1,x} + p'_{N,x}}{2}, \qquad (5)$$

where $p'_{1.x}$ and $p'_{N,x}$ = pressures in the rooms on the ground floor and on the upper storey, found on the windward and on the leeward sides, respectively, on condition that the doors opening to the staircase are hermetically sealed.

$$p'_{1,x} = p_{1,\text{н}} \frac{S_{\text{в},1}}{S_{\text{ок}} + S_{\text{в},1}}; \quad p'_{N,x} = p_{N,\text{з}} \frac{S_{\text{в},N}}{S_{\text{ок}} + S_{\text{в},N}}. \qquad (6)$$

2) Pressure $p_{n,x}$ in the rooms opening to the staircase is determined graphically.

The approximate value of p_o adopted earlier is refined by the formula:

$$p_0 = \frac{\sum_m p_{i,x}}{m}, \qquad (7)$$

where m = total number of rooms or flats opening to the staircase.

4) When necessary the values of $p_{n,x}$ are found again by using the improved value of p_0.

For determining the intensity of air infiltration a calculated pressure difference on a storey n will be $\Delta p_{n,room} = p_{n,ww(lw)} - p_{n,x}$.

This calculation procedure is applicable when the plan of the building is the same for all floors, and when air infiltration through the external door is slight compared with the air total infiltration for the building.

Instance c. The formulation of the problem is different from the version b only by the fact that we need to calculate the air conditions of the rooms under conditions when the pressure in the staircase is given. This pressure is ensured by the operation of the air supply system, or by air entering the staircase through the rooms on the ground floor (non-typical storey). The condition of the air in the staircase can differ from that in rooms on other floors.

Quantity of air in kg/h passing through the walls in the cases a, b, and c can be found by the formulae:

for walls

$$G_0 = \frac{\Delta p_{\text{пом}}}{R_{\text{о, н}}} F_0; \qquad (8)$$

for butt joints

$$G_c = \frac{\Delta p_{\text{пом}}}{R_{\text{с, н}}} \Sigma l_c; \qquad (9)$$

for windows

$$G_{\text{ок}} = \frac{-s_{\text{л}} + \sqrt{s_{\text{л}}^2 + 4 s_{\text{т}} \Delta p_{\text{пом}}}}{2 s_{\text{т}}} F_{\text{ок}}; \qquad (10)$$

for external doors (when closed)

$$G_{дв} = (p_{1,н(з)} - p_0)^{0,5} S_{дв}^{-0,5}. \qquad (11)$$

Here $R_{o.i}$, $R_{lj,i}$ = resistances to air penetration of the walls and of the butt joints; F_o, Σl_{lj} = wall area and the length of butt joints in the room under discussion.

ALLOWANCE FOR THE AIR CONDITIONS WHEN CALCULATING HEAT EXCHANGE OF A BUILDING

For the heat loss calculation of the walls, and in determining the minimum temperature on the inside surface the intensity of infiltration is usually adopted for ground floor conditions. The procedure for this calculation has been published earlier.

Additional heat losses (kcal/h) for air infiltration in the heat balance of a room must be taken into account for each storey individually by the formula

$$\Delta Q_{инф} = AGc_{в}(t_{в} - t_{н}), \qquad (12)$$

where A = coefficient, taking into account some heating of air during infiltration through the structure. (For windows the average value of the coefficient A is 0.8; for the wall, 0.6; for the butt joints, 0.7);

Gc_a = thermal capacity of the infiltrating air flow,kcal/h.degC;

c_a = specific heat of air, equal to 0.24kcal/kg.degC.

In calculation of additional heat losses for air infiltration in modern buildings it is sufficient to take into account the air infiltration through the windows only. The intensity of air infiltration in each room depends on the external conditions which vary over the heating period. The calculation of additional heat losses should amount to determining the maximum heat losses for each room.

In analysing the nature of variation in additional heat losses for infiltration over winter it is convenient to make use of comparative units of heat losses. A comparative unit of heat losses for air infiltration of n-th storey at any external air temperature t is determined by the formula:

$$j_{n.t} = \frac{\Delta Q_{\text{инф}.\,n.\,t}}{\Delta Q_{\text{инф}.\,1.\,t_{\text{н}}}}. \qquad (13)$$

Here $\Delta Q_{inf,n,t}$ = additional heat losses for infiltration of the n-th storey at external air temperature t with allowance for wind velocity depending on it;

$\Delta Q_{inf,1,t_{ex}}$ = the same, as above, for the ground floor on the windward side for the rated winter conditions.

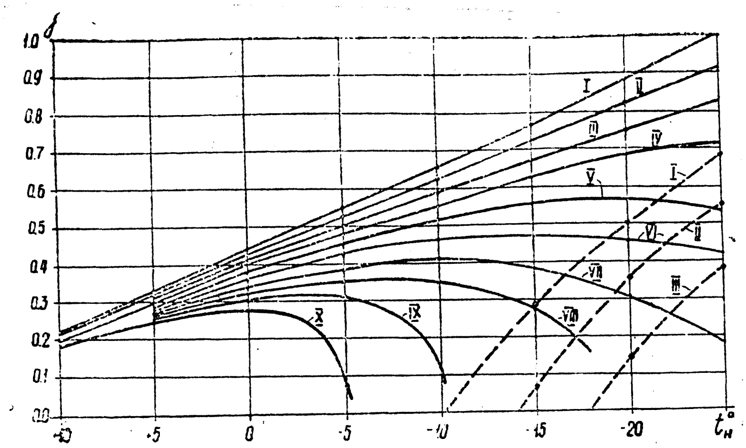
Comparative heat losses for infiltration for a ten-storey building at different external air temperatures are given in Fig.2 (solid lines for the leeward side).

With increase in temperature the values of $j_{m.t}$ in(a)decrease proportionately for the lower half of the building; and in the upper half increase to a certain maximum,afterwards decreasing. In(b)they decrease proportionally for all storeys, the maximum values of $j_{n,t}$ corresponding to rated winter conditions.

Maximum values of comparative heat losses for infiltration for different storeys in(a)and(b)at N = 10 (see the Table) were calculated for buildings with symmetrical floor plans, relative to the staircase.

The values of $j_{n.max}$ for the discussed versions (see Table) make it possible to determine a maximum value of heat losses for infiltration into any storey. For this purpose it is necessary to caleulate, according to the given recommendations, the additional heat losses for the ground floor under the rated winter conditions. We find this by multiplying the value obtained by $j_{n.max}$.

Instance (a)



Instance (b)

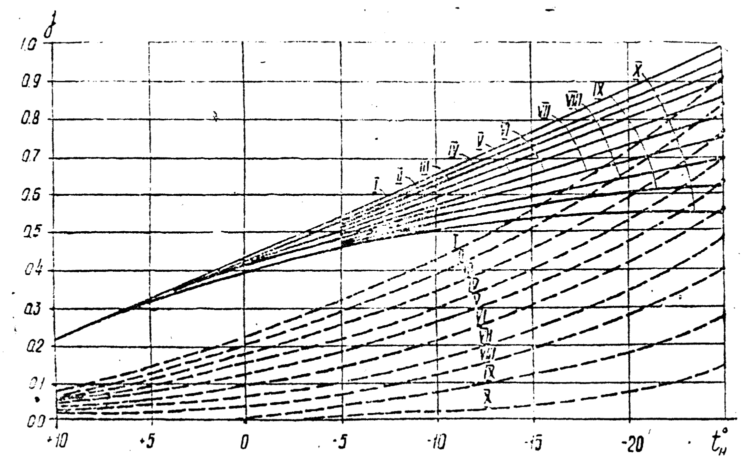


Fig.2. Values of comparative heat losses for infiltration for different storeys in a 10-storey building.

Table 1. Values of $j_{n,max}$ for different storeys of buildings with a different number of storeys.

The number of storeys	Storey																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
XX	1	0,95	0,90	0,85	0,8	0,75	0,7	0,65	0,5	0,45	0,4	0,3	0,3	0,3	0,25	0,2	0,2	0,2	0,15	0,1
XIV	1	0,95	0,90	0,8	0,7	0,65	0,55	0,45	0,4	0,35	0,3	0,25	0,25	0,2						
X	1/1	0,9/0,95	0,8/0,95	0,7/0,90	0,55/0,85	0,45/0,8	0,4/0,75	0,35/0,7	0,3/0,6	0,3/0,55										
VIII	1	0,9	0,8	0,7	0,5	0,45	0,4	0,35												
IV	1	0,8	0,6	0,5																

Note. The numerator indicates for case a, and the denominator indicates for case b.

In rooms for which $j_{n,max}$ is observed higher than the rated temperature, some overheating will occur over the period of low external air temperatures. If j_n reaches maximum values under rated conditions, overheating is found at higher temperatures.

EXAMPLES OF CALCULATION

Example 1. Calculate the additional heat losses for infiltration for a 10-storey administrative building equipped with intake and extract ventilation. The building is in Moscow. The height of a storey h_{st} = 3m. Windows on the windward and leeward sides are identical in area- $10m^2$ for one room. $R_{wn.i} = 0.133 \frac{m^2.h.mm\ W.G.}{kg}$ The resistance to air penetration of the internal doors opening to the corridors and the staircase $R_{door.i} \approx 0$ (the doors are not hermetic. The aerodynamic coefficients $k_{ww} = 0.8$; $K_{lw} = -0.4$.

Solution 1. Differential pressure $\Delta p_{1,stc}$ for the staircase space at the level of the ground floor on the windward side is caculated by the formula (2):

$$\Delta p_{1,\text{л.к}} = \frac{3 \cdot 10}{2} (1{,}43 - 1{,}21) + \frac{0{,}8 + 0{,}4}{2} \cdot \frac{4{,}73^2}{2 \cdot 9{,}8} \cdot 1{,}43 = 4{,}3 \ \text{кг/м}^2.$$

Here wind velocity for the rated winter conditions of Moscow is determined as the average wind velocity over the building height by the formula:

$$v_{\text{в}} = 8 + 0{,}143 t_{\text{н}} + 0{,}03 \cdot \frac{1}{2} h_{\text{эт}} N = 8 + 0{,}143(-26) + 0{,}03 \cdot \frac{1}{2} \cdot 3 \cdot 10 = 4{,}73 \ \text{м/сек}.$$

2. The rated differential pressure $\Delta p_{1,room}$ is found by formula (3) and is $\Delta p_{1,room} \approx \Delta p_{1,stc} = 4.3 \text{kg/m}^2$ since $R_{door.i} \approx 0$.

3. From the value of the coefficient of air penetration of a window

$$I_{window} = \frac{1}{R_{wn.i}} = \frac{1}{0.133} = 7.5 \ \frac{\text{kg}}{\text{m}^2\text{.h.mm W.G.}}$$

we find the values of S_L and S_T (using data given by E.I.Semenova):

$$S_L = 0.06; \quad S_T = 0.008,$$

and by formula (10) we find the amount of air admitted through the windows into a room on the ground floor:

$$G_{\text{ок}} = \frac{-0{,}06 + \sqrt{0{,}036 + 4 \cdot 0{,}008 \cdot 4{,}3}}{2 \cdot 0{,}008} \cdot 10 = 196 \ \text{кг/ч}.$$

4. Additional heat losses for infiltration for the ground floor rooms on the windward side per m^2 of a window are determined by formula (12):

5. Using the Table we adopt the values of $j_{n,max}$ which govern the heat losses for infiltration of rooms of the remaining storeys.

Example 2. Calculate additional heat losses under Moscow conditions for infiltration for a 10-storey residential building equipped with natural ventilation. The air penetration characteristic of the door opening to the staircase $S_{dr} = 92 \times 10^{-6}$. The air exchange required by standards for a two room flat G_{ex} = 200kg/h. The height of one storey h_{st} = 3m. Window area of a flat is 10m² ($S_{wn} = 130 \times 10^{-6}$).

Solution 2. The values of the resistance characteristics of the extract grilles are determined at $t_{ex} = + 5^{o}C$ (for the case of individual extract ducts) by the formula (4).

The values of $S_{ex.d}$ for different storyes:

Storey	$S_{ex.d}$	Storey	$S_{ex.d}$
1	$49 \cdot 10^{-6}$	6	$24 \cdot 10^{-6}$
2	$44 \cdot 10^{-6}$	7	$19,5 \cdot 10^{-6}$
3	$39 \cdot 10^{-6}$	8	$14,5 \cdot 10^{-6}$
4	$34 \cdot 10^{-6}$	9	$9,8 \cdot 10^{-6}$
5	$29 \cdot 10^{-6}$	10	$4,9 \cdot 10^{-6}$

The values of pressures acting on the building from the outside (see Fig.1)

Storey	$p_{n,ww}$	$p_{n,lw}$	kg/m²	storey	$p_{n,ww}$	p_{lw}	kg/m²
1	8,3	6,2	"	6	5,1	3,0	"
2	7,7	5,6	"	7	4,4	2,3	"
3	7,0	4,9	"	8	3,7	1,6	"
4	6,4	4,25	"	9	3,1	1,0	"
5	5,7	3,6	"	10	2,4	0,3	"

2. The values of p'_x for a lower room on the windward side and for an upper room on the leeward side of the building are calculated by the formula (6):

$$p'_{1,x,н} = 8,3 \frac{49 \cdot 10^{-6}}{130 \cdot 10^{-6} + 49 \cdot 10^{-6}} = 2,3 \; кг/м^2;$$

$$p'_{N,x,з} = 0,33 \frac{4,9 \cdot 10^{-6}}{130 \cdot 10^{-6} + 4,9 \cdot 10^{-6}} = 0,09 \; кг/м^2.$$

Approximate value of pressure in the staircase is

$$p_0 = \frac{2,3 + 0,09}{2} \approx 1,2 \; кг/м^2.$$

3. Pressures p_x on the windward side and on the leeward side are determined by the graphical method

Storey	$p_{x,ww}$	$p_{x,lw}$	kg/m^2	Storey	$p_{x.ww}$	$p_{x.lw}$	kg/m^2
1	1,5	1,2	"	6	0,9	0,5	"
2	1,4	1,1	"	7	0,7	0,4	"
3	1,2	1,0	"	8	0,5	0,3	"
4	1,1	0,8	"	9	0,2	0,2	"
5	1,0	0,6	"	10	0,1	0,1	"

The final pressure value in the staircase is found by formula (7):

$$p_0 = \frac{15}{20} = 0,75 \; кг/м^2.$$

The improved value of pressure in a room on the ground floor on the windward side at $p_o = 0.75 kg/m^2$ is

$$p_{1,x,ww} = 1.3 kg/m^2.$$

4. Quantity of air passing through the windows on the ground floor is calculated by the formula (10):

$$G_{ок} = \sqrt{\frac{8,3 - 1,3}{130 \cdot 10^{-6}}} = 240 \; кг/ч;$$

for $1m^2$ of a window it is $24 kg/m^2.h$.

5. Additional losses for infiltration on the ground floor per m^2 of a window are calculated by the formula (12):

$$\frac{\Delta Q_{\text{инф}, 1.\ t_н}}{F_{ок}} = 0,8 \cdot 25 \cdot 0,24\,(18+26) = 210\ \textit{ккал/м}^2 \cdot \textit{ч}.$$

Additional heat losses for infiltration of rooms on the remaining storeys are found in a similar way or from the tabulated values of $j_{n,max}$.

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SUBSCRIPTS

V_w = wind velocity

γ_H; $\gamma_B = \gamma_{ex}$, γ_{in}

H = ww = windward

(З) = lw = leeward

ЭТ = st = storey

ЛК = stc = staircase

ЖВ = Dr = door

ОК = Wh = window

ПОМ = room

СР = av = average

$G_H = G_{ex}$ = external

$S_{BN} = S_{ex.d.n}$ = extracting duct

$S_B = S_{ex.d}$ = extracting duct

$R_{ОИ} = R_{oi}$ = air penetration

$R_{СИ} = R_{lj,i}$ = butt joint

$G_C = G_{lj}$ = butt joint

$S_{Л} = S_L =$)
) air penetration coefficients
$S_T = S_T =$)

$C_B = C_a$ = air

$\Delta Q_{ИНР} = \Delta Q_{inf}$

$t_H = t_{ex}$ = external

$\Sigma lc = \Sigma l_{lh}$