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# Calculation of the velocity of air in the air gap facade systems, where natural ventilation

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**Abstract**
The formation of air and thermal conditions in the natural ventilation of the air gap in the facade system are discussed. Differential equation that describes the distribution of the temperature adjustment layer is obtained. Approximate equation to determine the velocity of air in the gap is obtained. The estimation of the maximum attainable velocity of air in the layer is obtained. The results obtained may be using in evaluating emissions of fibers from mineral wool insulation of facade system.

**Keywords:** facade system, air space, air velocity, natural ventilation layer, the intensity of solar radiation.

## Introduction

Facade systems with ventilating air gap have an architectural attractiveness and high thermal performance [1, 2]. The existence of a ventilation of an air gap provides correct moisture condition of inclosing structures, what helps to attain its durability. The ventilation of an air gap is provided by existence of air holes in the bottom part of a gap. External air getting into the lower air hole of a gap becomes warm with the help of heat transfer with the walls of the gap, wallows up inside the gap and goes out from the tope air hole. While moving inside the air hole, air moistures because of the moisture exchange with the thermal insulating material layer. Also while moving the air becomes saturated with water vapor. The faster air moves – the faster it becomes saturated. If the air which goes out from the air gap remains unsaturated, then there is no condensate formation in the gap and moisture condition of the facade is correct. If the partial pressure of water vapor in the exit from the air gap is equal to the pressure of the water vapor with the temperature, that the air has, then there is condensate formation in the gap. In order to calculate the moisture conditions of a facade system it is necessary to do a calculation of the velocity of air moving inside the air gap, moreover in a most unprofitable case: without wind and with closed splits between the tiles of the surfacing screen [3].

Another utilization of knowledge of the air velocity in the air gap is the valuation of fiber emission from the mineral wool that is thermal-insulating material, while operating of the facade system [4]. In this article method of a calculation that can be easy used for the calculating of moisture conditions, fiber emission, thermal insulating characteristics while projecting of ventilated facades is presented. Mathematical model for the detailed calculation in winter conditions is presented in [5]. It is improved and used for summer conditions in this article.

## Equation of distribution of air temperatures for the height of air gap of ventilated facade.

Calculating of the air temperature is done in case, that the velocity of air in the gap is known. Air temperature in the air gap , $t_{gap}$, °C, depends on geometric characteristic of a gap and on thermotechnical characteristics of the wall and screen of the facade. Also it depends on outdoor and inside air temperature. Direction and velocity of the wind also influence on the air velocity in the gap, but it can be neglected in case of random character. Sun radiation has a big influence on air velocity, it covered by conventional temperature of outdoor air that can be determinated by formula:

$$t_{ext}^{con} = t_{ext} + \frac{I \cdot \rho}{\alpha_{ext}} \qquad (1)$$

Air temperature value in the gap, $t_{gap}$, depends on the height and changes because of $t_{ext}$ at the entrance in the gap up to limit value of the temperature in the gap, which is equal to temperature in still air in the gap, in other words, the higher (further from entrance to the gap) the part of the facade is situated – the more $t_{gap}$ value is.

Let the air velocity in the gap be known and equals $v$ m/s. Thermal balance equation for the elementary layer of air in the gap that has a thickness $\Delta x$:

$$-t_i \cdot c_{air} \cdot v \cdot d \cdot \gamma_{air} + t_{i-1} \cdot c_{air} \cdot v \cdot d \cdot \gamma_{air} + \frac{t_{in} - t_{gap}}{R_{constr}} \cdot \Delta x - \frac{t_{gap} - t_{ext}^{con}}{R_{screen}} \cdot \Delta x = 0 \quad (2)$$

The first term in this equation expresses the amount of heat that is taken up by the flow of air from the elementary layer of the gap; the second term shows the amount of heat that gets into the elementary layer from below, the third summand shows the amount of heat that gets into the elementary layer from wall with the thermal insulation, the fourth shows the amount of heat that goes out from elementary layer through the covering element of the facade.

Transformation of (2) leads to differential equation:

$$\frac{dt_{gap}}{dx} \cdot \frac{c_{air} \cdot v \cdot d \cdot \gamma_{air}}{\frac{1}{R_{constr}} + \frac{1}{R_{screen}}} + t_{gap} = \frac{\frac{t_{in}}{R_{constr}} + \frac{t_{ext}^{con}}{R_{screen}}}{\frac{1}{R_{constr}} + \frac{1}{R_{screen}}} \quad (3)$$

Formula in the right part of equation presents air temperature in the gap without changes of the air temperature in the height and is called $t_0$. Such a temperature can be if there is not any air movement. Coefficient of derivate is called $x_0$. Its physical meaning will be explained further.

$$t_0 = \frac{\frac{t_{in}}{R_{constr}} + \frac{t_{ext}^{con}}{R_{screen}}}{\frac{1}{R_{constr}} + \frac{1}{R_{screen}}} = \frac{t_{in} K_{constr} + t_{ext}^{con} K_{screen}}{K_{constr} + K_{screen}} \quad (4)$$

$$x_0 = \frac{c_{air} \cdot v \cdot d \cdot \gamma_{air}}{\frac{1}{R_{constr}} + \frac{1}{R_{screen}}} = k \cdot v \quad (5)$$

Symbols, accepted in equations (1) – (5) are following:

$t_{in}$, $t_{ext}$ – inside and external air temperatures, $^oC$;

$t_{ext}^{con}$ - conventional external air temperature with account for sun radiation, getting on the wall, $^oC$;

$\rho$ – solar absorption coefficient, unit;

$\alpha_{ext}$ – heat transfer coefficient of the outer surface, $W/(m^2 \, ^oC)$;

$I$ – intensity of solar radiation (direct and diffuse) on a vertical surface, $W/m^2$;

$R_{constr}$, $R_{screen}$ – resistance to heat transfer from the room air to air gap of the structure and from the air gap to the outer air, respectively, $m^2 \, ^oC/W$;

$K_{constr}$, $K_{screen}$ – heat transfer coefficient of construction parts from inside air to air gap and from air gap to external air, $W/m^2 \, ^oC$;

$x$ –distance from the entrance in the air gap to the point considered, $m$;

$v$ - air velocity in the gap, $m/s$;

$c_{air}=1005 \ J/(kg^oC)$ – air specific heat;

$\gamma_{air} = 353/(273+t_{ext})$– air density at a temperature $t_{ext}$, , $kg/m^3$;

$d$ – air gap width, $m$.

With allowance for these designations equation (2) takes up a simple view:

$$x_0 \frac{dt_{gap}}{dx} + t_{gap} = t_0 \quad (6)$$

The obvious initial condition for this equation is $t_{gap} = t_{ext}$ with $x = 0$. Thus the solution of the equation (6) is:

$$t_{gap} = t_0 - (t_0 - t_{ext}) \cdot e^{-\frac{x}{x_0}} \quad (7)$$

This equation describes the temperature distribution for the height of a facade air gap. If $t_{ext}$ – initial air temperature at the entrance to the gap, then $(t_0 - t_{ext})$ value is a maximum deviation of an air temperature in the ventilated gap from its initial value. It can be seen from the equation (7) that with increase of $x$, value $t_{gap}$ tends to $t_0$ value. As it follows from formula (7), the $x_0$ value is the height, on which temperature excess $(t_0 - t_{gap})$ becomes less, than its limit value $(t_{ext} - t_0)$ in $e$ times.

The obtained Equation (7) allows to calculate the temperature distribution over the height of the air gap at a known air velocity.

**Average air temperature in the air gap of a facade system. The approximate formula for the calculation of the air velocity in the air gap. The evaluation of the maximum air velocity in the air gap.**

Equation (7) lets us achieve an equation for average air temperature in the air gap. With the height of a facade L average temperature is determined by integration of the obtained dependence (7) and by division of the obtained integral to the height of the facade:

$$t_{middl} = \frac{1}{L}\int_0^L t_{gap} dx = \frac{1}{L}\int_0^L \left( t_0 - (t_0 - t_н) \cdot e^{-\frac{x}{x_0}} \right) dx = \frac{1}{L}\left( t_0 \cdot L - x_0 \cdot (t_0 - t_н)\left[1 - e^{-\frac{L}{x_0}}\right]\right) = t_0 - (t_0 - t_н) \cdot \frac{x_0}{L} \cdot \left[1 - e^{-\frac{L}{x_0}}\right] \quad (8)$$

This formula can get practical use while evaluating air velocity in the air gap. According to [5] air velocity in the air gap under zero wind condition is expressed by the formula:

$$v = \sqrt{\frac{0{,}08 \cdot L \cdot (t_{middl} - t_{ext})}{\sum_i \xi_i}} \quad (9)$$

Where $L$ – height difference from the entrance of the air in the gap to the exit from it (the height of the facade ), $m$;

$\sum_i \xi_i$ – sum of the local resistance coefficients.

The method, which is presented in [5], supposes simultaneous solution of (8) and (9) by iterations. However formulae (8) and (9) let us obtain an approximate formula for the calculation of the air velocity in the air gap. For that the value of $t_{middl}$ is substituted from (8) in (9). The obtained equation is solved regarding air velocity. In addition, value $e^{-L/x_0}$ is neglected in (8). In practical problems this value is small (less than 0,1), that's why it doesn't have significant impact on the end result (picture 1). The approximate formula looks like:

$$v \approx \sqrt{\frac{0{,}0016\cdot(t_0-t_{ext})^2\cdot k^2}{\left(\sum_i \xi_i\right)^2}+\frac{0{,}08\cdot L\cdot(t_0-t_{ext})}{\sum_i \xi_i}-\frac{0{,}04\cdot(t_0-t_{ext})\cdot k}{\sum_i \xi_i}} \quad (10)$$

Where $k$ – coefficient, which according to (5) is:

$$k=\frac{c_{air}\cdot d\cdot\gamma_{air}}{\frac{1}{R_{constr}}+\frac{1}{R_{screen}}}$$

Due to the calculation of the air velocity in the air gap by formula (10) one can calculate vertical temperature distribution of air by formula (7), and then use the obtained results for the calculation of fiber emission from the mineral wool.

Formulae (8) and (9) also let get evaluation of the maximum air velocity in the air gap determined by convection transfer. One can use this value while evaluating fiber emission and the durability of the mineral wool [4]. As follows from (10) – air velocity is proportional to $\sqrt{(t_{middl}-t_{ext})}$, therefore it increases monotonically with the rise of (tср – tн). Other properties remain intact during use of the facade. It follows from

$$t_{cp}-t_н=t_0-(t_0-t_н)\cdot\frac{x_0}{L}\cdot\left[1-e^{-\frac{L}{x_0}}\right]-t_н \quad (11)$$

The transformation of (11) leads to (12):

$$t_{middl}-t_{ext}=t_0\left(1-\frac{x_0}{L}\cdot\left[1-e^{-\frac{L}{x_0}}\right]\right)+t_н\left(\frac{x_0}{L}\cdot\left[1-e^{-\frac{L}{x_0}}\right]-1\right)=\left(1-\frac{x_0}{L}\cdot\left[1-e^{-\frac{L}{x_0}}\right]\right)\cdot(t_0-t_н) \quad (12)$$

Maximum of $(t_{middl}-t_{ext})\big|_{max}$ is possible, when $\frac{x_0}{L}\to 0$. This follows from the fact that function $f(\frac{x_0}{L})=\left(1-\frac{x_0}{L}\cdot\left[1-e^{-\frac{L}{x_0}}\right]\right)$ has a maximum, when $\frac{x_0}{L}\to 0$, which in its turn is evident from the monotonically decreasing character of the function, as its derivative $\frac{df}{d(\frac{x_0}{L})}$ is negative on the half-interval of values of argument $\frac{x_0}{L}\in(0;1]$

Therefore, maximum $(t_{middl}-t_{ext})$ is possible when $\frac{x_0}{L}=0$ and it is:

$$(t_{middl}-t_{ext})\big|_{max}=\lim_{\frac{x_0}{L}\to 0}\left(1-\frac{x_0}{L}\cdot\left[1-e^{-\frac{L}{x_0}}\right]\right)\cdot(t_0-t_{ext})=(t_0-t_{ext}) \quad (13)$$

The substitution of (13) in (9) leads to:

$$v_{max}=\sqrt{\frac{0{,}08\cdot L\cdot(t_0-t_{ext})}{\sum_i \xi_i}} \quad (14)$$

The substitution of formula of $t_0$ from (4) in (14) leads to:

$$v_{max}=\sqrt{\frac{0{,}08\cdot L}{\sum_i \xi_i}\cdot\left(\frac{t_{in}K_{constr}+t_{ext}^{con}K_{screen}}{K_{constr}+K_{screen}}-t_{ext}\right)}=\sqrt{\frac{0{,}08\cdot L}{\sum_i \xi_i}}\sqrt{\frac{(t_{in}-t_{ext})K_{constr}+(t_{ext}^{con}-t_{ext})K_{screen}}{K_{constr}+K_{screen}}} \quad (15)$$

Taking into account that the coefficient of heat transmission of screen of facade $K_{screen}$ is much more than the coefficient of heat transmission of construction $K_{constr}$, it follows from (15):

$$v_{max}\approx\sqrt{\frac{0{,}08\cdot L}{\sum_i \xi_i}}\sqrt{(t_{in}-t_{ext})\frac{K_{constr}}{K_{screen}}+(t_{ext}^{con}-t_{ext})}=\sqrt{\frac{0{,}08\cdot L}{\sum_i \xi_i}}\sqrt{(t_{in}-t_{ext})\frac{K_{constr}}{K_{screen}}+\frac{\rho I}{\alpha_{ext}}} \quad (16)$$

Formulae (15) and (16) let us easily evaluate maximum air velocity in the air gap. If there is no solar radiation, air velocity is mainly defined by the inside-outside temperature difference. In summer season this temperature difference is very small, that's why air velocity is defined by solar radiation intensity. Maximum air velocity will be observed under simultaneous maximum of $(t_{in}-t_{ext})$ and $I$. This value will express the evaluation of the maximum air velocity in the air gap facade system on the chosen set of climatic data.

**Examples of the calculation of air velocity in the air gap.**

Calculations of the air velocity in the air gap facade system let to illustrate procured formulae. The calculations were performed for the brick wall of a building with the facade system in Moscow. The facade system height was 10 m, the mineral wool layer thickness was 120 *mm*, the resistance to heat transfer of screen of facade was 0,06 $m^2\ {}^oC/W$, the resistance to heat transfer of wall with thermal insulation was 3,3 $m^2\ {}^oC/W$. Climatic characteristic were set for Moscow. Calculations were performed with monthly average air temperature values and solar radiation intensity (solar radiation was set for the south facade of a building).

Air velocities in the air gap facade system are given in different months of a year in the picture 1. They are calculated by iterative method [5] and on approximate formula (10) without including solar radiation. Close values of quantities were procured.

Air velocities in the air gap facade system are given by the monthly average climatic characteristics values in the picture 2, which are calculated by formula (10) with and without taking into consideration solar radiation intensity, and also estimate of maximum value of this velocity by formula (16) with maximum difference $(t_{in}-t_{ext})$ during the year and with maximum value of I during the year. It can be seen from the picture, taking account of solar radiation has increased the rated air velocity in the gap. It is forbidden to neglect the influence of solar radiation at the calculations of air velocity in the gap.

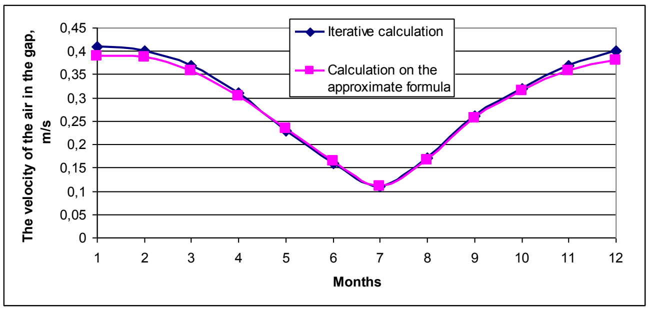


**Fig.1. Air velocities in the air gap facade system which are calculated by the monthly average climatic characteristics values by iterative method [5] and approximate formula (10).**

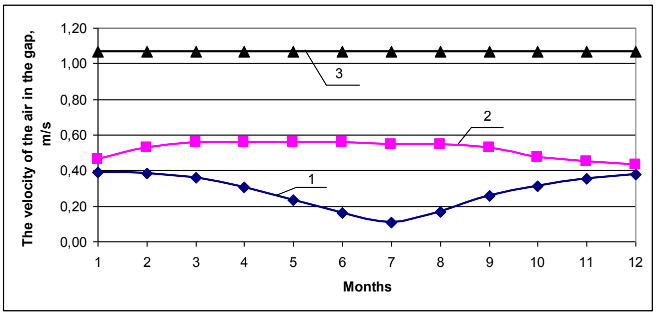


**Fig. 2. Air velocities in the air gap facade system which are calculated with and without taking into consideration the influence of solar radiation. 1- without taking into consideration solar radiation; 2 – taking into consideration solar radiation; 3 – maximum possible monthly average velocity of the air movement in the air gap facade system.**

## Conclusion

This accomplished dynamic thermal modelling in the air gap of a facade system allows realize calculations with the help of relatively simple, engineering formulae. This makes possible to implant the calculations into engineering practice [6] and to increase the accuracy of calculations of thermophysical properties of inclosing structures, what in its turn can reflect on the economic basis when enclosing structures are chosen [7-12].

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