Simulation of conjugate heat and moisture transfer in multilayer porous materials with ventilated channels

V Yu Borodulin* and M I Nizovtsev
Kutateladze Institute of Thermophysics, 1 Ac. Lavrentyev Ave., Novosibirsk, Russia

*E-mail: borodulin@itp.nsc.ru

Abstract. A physical and mathematical model for calculating the thermal and moisture state of the facade of a building with ventilated channels has been developed. The model is based on the joint solution of a system of non-stationary differential equations of heat and moisture transfer in multilayer porous materials. In addition, equations describing heat and mass transfer in ventilated air channels are included in the model. The calculations of the thermal and moisture state of the brick wall of the building, insulated from the outside with heat-insulating panels with ventilated channels, have shown that the selected geometry of the ventilated channels provides a low level of moisture content in the facade materials.

1. Introduction
During the reconstruction and new construction of buildings, two main facade insulation systems were most widely used. These are systems with a stucco facade (External Thermal Insulation Composite Systems – ETICS) and with a ventilated facade (Ventilated Cladding Systems) [1]. Intense rains and condensation processes on the external surface may involve biological growth or mechanical damage in the ETICS [2]. Ventilated facade systems, as a rule, are devoid of these lacks [1]. The development of ventilated facade systems has led to enhancement of systems based on panels [3]. The use of such panels gives numerous advantages such as standardization, industrializing manufacturing process, improving quality of the insulation, and reducing prices [3]. A new facade system for building thermal insulation based on panels with longitudinal ventilated channels is proposed in [4]. Laboratory and full-scale experimental studies of panels with ventilated channels show their high performance and low moisture content in the thermal insulation [5]. For further development of facade systems based on panels with ventilated channels, it is necessary to develop methods of physical and mathematical modeling and calculation of thermal and moisture processes with phase transitions. This article is devoted to questions of the development and testing of these methods.

2. Physical and mathematical model for simulating processes in the ventilated facade system
To calculate the thermal and moisture state of the facade with ventilated channels, a new physical and mathematical model is developed. It is based on the approach proposed in [6].
The approach is based on the joint solution of a system of non-stationary differential equations of heat and moisture transfer in multilayer porous materials. In addition, equations which describe the processes of heat and mass transfer in ventilated air channels are included in the model. The model considers a two-dimensional statement of the problem (Figure 1). Therefore the ventilated panel and the wall of the building are a system of plane layers. The air channels in the panel are replaced by a continuous slit with passage area equal to the total area of the all channels. The figure 1 shows the basic geometric and physical parameters of the model. The thickness of the insulating layer of the panel is $L_{x1}$, the wall thickness of the building is $L_{x2}$, and the air channel is $L_x$. The height of the panel and the ventilated duct is $L_y$, the temperature and relative humidity of the outdoor air are $t_a$ and $\varphi_a$, and the temperature and relative humidity of the indoor air are $t_r$ and $\varphi_r$, respectively. The flow of external air enters the ventilated channel from the bottom of the channel and moves along it with a speed $u$.

The heat and mass transfer on the inner surface of the wall and on the surface between the air flow and the thermal insulation in the panel is described by the Newton relationship. The heat flux at the boundary is determined by the difference in air and surface temperature, and the mass flow of water vapor is determined by the difference in the corresponding concentrations.

The system of equations describing the distribution of temperature and relative humidity inside the layered system and in the air flow has the following form:

$$
\frac{\partial t}{\partial \tau} = \frac{\partial}{\partial x} \left( \lambda \frac{\partial t}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial t}{\partial y} \right) + h_v \frac{\partial}{\partial x} \left( \delta \frac{\partial \varphi}{\partial x} \right)[P_s] + h_v \frac{\partial}{\partial y} \left( \delta \frac{\partial \varphi}{\partial y} \right)[P_s],
$$  \(1\)

$$
\frac{\partial \varphi}{\partial \tau} = \frac{\partial}{\partial x} \left( D \frac{\partial \varphi}{\partial x} \right) + \frac{\partial}{\partial y} \left( D \frac{\partial \varphi}{\partial y} \right) + \frac{\partial}{\partial x} \left( \delta \frac{\partial \varphi}{\partial x} \right)[P_s] + \frac{\partial}{\partial y} \left( \delta \frac{\partial \varphi}{\partial y} \right)[P_s],
$$  \(2\)

$$
\frac{\partial \varphi_c}{\partial \tau} + u \frac{\partial \varphi_c}{\partial y} = \frac{\alpha \varphi(T_c)}{\rho c_{pm} L_x} \left( t_u + t_u - 2t_u \right).
$$  \(3\)

Here $t$ is the temperature, $\tau$ is the time, $\varphi$ is the relative air humidity, $c$ is the volumetric heat capacity of the material, $\lambda$ is the thermal conductivity coefficient, $\delta$ is the vapor permeability coefficient of the material, $h_v$ is the latent heat of phase transitions, $P_s$ is the pressure of saturated
water vapor, $W_{f}$ is the moisture capacity of the material, $D$ is the moisture conductivity coefficient of the material, $\rho_{s}$ is the density of saturated vapors, $u$ is the air flow rate in the channel, $\rho_{a}$ is the density of dry air, $c_{pa}$ is the specific heat of dry air, $c_{V}$ is the specific heat of water vapor, $l_{x}$ is the width of the air channel, and $R_{v}$ is the gas constant of the vapor. Besides, index “a” refers to outside air, index “w” refers to the wall of the channel, which borders on the insulating material, and index “c”, refers to air moving through the channel. The temperature function is a complex:

$$\gamma(t) = \frac{\partial \psi}{\partial t} - G(t).$$

The pressure of saturated water vapor in the model is expressed in exponential form:

$$P_{s} = \exp(\psi(t)),$$

where $\psi(t) = \frac{1500.3 + 23.5 \cdot t}{234 + t}$, and $G(t) = \frac{1}{273.15 + t}$.

In the model the following dependence was used to describe sorption [6]:

$$W = W_{f} \left( \frac{b - 1}{b - \psi} \right),$$

here $b$ is the coefficient that corresponds to the choice of material.

Discretization of equations (1) and (2) was carried out by the finite volumes method. An implicit scheme was used. The approximation in spatial variables $x$ and $y$ provided the second order of the convergence, and in time $\tau$ it provided the first one. To discretize the transport equations (3) and (4), the finite-difference approximation was used by an implicit scheme with the first order of convergence in the spatial variable $y$ and time $\tau$. The convergence of solutions was assessed using Runge's rule. The computations were performed on a regular grid. As a result, the following step values were chosen: $dx = 0.02$, $dy = 0.02$, and $dt = 0.01$.

The system of algebraic equations obtained as a result of discretization was solved by the Seidel iterative method.

To validate the model and check the operability of the selected algorithm, the problems of establishing stationary heat and moisture transfer in layered systems were solved with Dirichlet, Neumann and Robin boundary conditions. The solutions of these problems are known and can be obtained by analytical methods.

3. Boundary and initial conditions

On the surface that separates the air flow in the channel and the thermal insulation in the panel, the conditions of equal heat and mass flows are set:

$$\alpha_{c} \cdot \left( t_{c} - t_{w} \right)_{x = x_{0}} = -\lambda_{0} \frac{\partial t}{\partial x}_{x = x_{0}},$$

$$\beta_{c} \cdot \left( \rho_{c} - \rho_{w} \right)_{x = x_{0}} = -\delta_{0} \frac{\partial P}{\partial x}_{x = x_{0}},$$

where $P$ is the partial pressure of water vapor at the border of the panel. The index “c” indicates the air flow in the channels.

On the inner surface boundary, conditions are as follows:

$$\alpha_{c} \cdot \left( t_{c} - t_{w} \right)_{x = x_{2}} = -\lambda_{1} \frac{\partial t}{\partial x}_{x = x_{2}},$$

$$\beta_{c} \cdot \left( \rho_{c} - \rho_{w} \right)_{x = x_{2}} = -\delta_{1} \frac{\partial P}{\partial x}_{x = x_{2}}.$$
Here, the heat and mass transfer coefficients related to the inner surface of the wall are indicated by the index “r”. Index “1” refers to the material of the wall on which the panel is mounted. At the border between brickwork and mineral wool insulation the boundary conditions that ensured continuity of the solution in the different layers were implemented.

For \( y = y_0 \) and \( y = y_1 \), the conditions for nonpenetration of heat and moisture flows are set:

\[
\frac{\partial \tau}{\partial y} \bigg|_{y=y_0} = 0, \quad \frac{\partial \tau}{\partial y} \bigg|_{y=y_1} = 0
\]

\[
\frac{\partial \varphi}{\partial y} \bigg|_{y=y_0} = 0, \quad \frac{\partial \varphi}{\partial y} \bigg|_{y=y_1} = 0.
\]

For the equations (3) and (4) at the channel entrance, at \( y = 0 \), variable values of temperature and relative humidity corresponding to variable environmental conditions were set:

\[
t_e \bigg|_{y=0} = t_e(\tau),
\]

\[
\varphi_e \bigg|_{y=0} = \varphi_e(\tau).
\]

A non-uniform distribution of temperature and relative humidity of the material which corresponds to the steady-state regime for the climatic conditions in August were taken as the initial conditions in the inner layers of the wall structure.

The relative humidity and air temperature in the channel at the initial moment of time were taken equal to the initial values \( t_e(0) \) and \( \varphi_e(0) \).

4. Results of computations

The moisture state of a 250 mm thick brick wall of a building, insulated from the outside by 160 mm thick thermal insulation panels with longitudinal ventilated channels were calculated. Cross-sectional area of each channel was \( 40 \times 20 \) mm\(^2\) and a distance between them was 130 mm. Mineral wool (density of 105 kg / m\(^3\)) was used as insulation in the panels. The calculation was carried out at an indoor temperature of +21 °C and its relative humidity of 55%. The outdoor temperature and relative humidity were set by the monthly average values of a typical year according to the results of observations for the climatic conditions of Novosibirsk [7].

The calculations were carried out for a 3 year cycle, starting from August of the first year. The distribution of initial temperature and moisture in masonry and mineral wool was assumed to be equilibrium for August.

![Figure 2. Average moisture content of mineral wool.](image-url)
Figure 2 shows changes in the average relative moisture content of the entire mineral wool panel. According to the calculation results there were two periods of increase in moisture of mineral wool each year. The first maximum corresponded to the end of summer. This time of a year is characterized by high outdoor temperature and rather high relative humidity. In consequence of which moisture is sorbed in the wall materials. The second peak corresponds to winter - early spring (with a maximum in January-February). During this period the low outdoor temperatures at high relative humidity contribute to the movement of vapor moisture from the room through the building envelope and its sorption in the building materials. The average moisture content of mineral wool did not exceed 3.7%. Such increase is not significant and practically does not effect on the heat-shielding properties of the thermal insulation.

The calculation results show that the insulation in the thermal insulation panel is in a relatively dry state during the year and there is no danger of fungus growth in it. This is evidenced by the data in Figure 3, where dots show hydrothermal conditions in which the thermal insulation is at different points in time. Isopleths (Lim1, Lim2) are also shown here.

![Figure 3. The air relative humidity in mineral wool.](image)

As a result of the calculations, the moisture flux density and the direction of the flow at the boundary of the layers of masonry – insulation of the panel were determined (Figure 4a).

![Figure 4. Density of the moisture diffusion flow a) at the boundary between masonry and thermal insulation; b) at the boundary between thermal insulation and air channel.](image)
From the analysis of the results presented in the figure, it follows that in the cold period in autumn, winter and spring, the moisture flux was directed from the brickwork to the thermal insulation (positive value of the moisture flux). In summer, on the contrary, the flow was directed from the insulation to the brickwork (negative value of the moisture flux). The average moisture flux density into the thermal insulation during the cold period was \( j_{av} = 0.078 \text{ mg/(m}^2\text{s)} \).

An analysis of the diffuse moisture flux at the boundary between thermal insulation and ventilated channel was performed (Figure 4b). As a result, a decrease in the moisture flux over three months with the lowest outdoor temperature (December, January and February) was revealed. To clarify the reason dependences in air relative humidity along the height of the ventilated channel were constructed (Figure 5a). It turned out that the relative humidity of the air increased along the height of the channel and reached 100% in its upper part. This was the reason for the decrease in moisture flux into the ventilated channel in December-February (Figure 4b). Relative humidity of 100% in the upper part of the ventilated channel can lead to its narrowing due to the formation of an ice layer. For comparison, similar calculations were performed (Figure 5b) for the panels with a distance between the ventilation channels of 62 mm. In this case relative humidity in the upper part of the channel from December to February did not reach 100% and there was no danger of ice formation.

![Figure 5. The air relative humidity along the height of the channel vs the distance between the channels: a) 130 mm, b) 62 mm (1-December, 2-January, 3-February).](image)

In full-scale experiments it was noted [5] that the air temperature in the channels during the sunny day can significantly (by 10°C or more) exceed the outdoor temperature due to solar insolation.

![Figure 6. The air relative humidity vs height of the ventilated channel at a distance between the channels of 130 mm in January with an increase in its temperature due to solar radiation by: 1 – 0°C, 2 – 1°C, 3 – 2°C.](image)
Figure 6 shows the results of calculating the distribution of relative humidity along the height of the ventilated channel (the distance between the channels is 130 mm) for the month of January with an additional increase in air temperature due to solar insolation. The calculation results show that with an increase in air temperature of 1 °C, the relative humidity at the channel outlet did not exceed 95%, and there was no danger of ice formation.

**Conclusions**

A physical and mathematical model has been developed for calculating the thermal and moisture state of the building’s facade, insulated with panels with ventilated channels in a multi-year operation mode. The calculations of the moisture conditions of the brick wall of the building have shown that the selected geometry of the ventilated channels provides a low level of the moisture content of the facade materials.

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