Nonstationary heat and mass transfer in the multilayer building construction with ventilation channels

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Abstract. Results of numerical modeling of the coupled nonstationary heat and mass transfer problem under conditions of a convective flow in facade system of a three-layer concrete panel for two different constructions (with ventilation channels and without) are presented. The positive effect of ventilation channels on the energy and humidity regime over a period of 12 months is shown. Used new method of replacement a solid zone (requiring specification of porosity and material structure, what complicates process of convergence of the solution) on quasi-solid in form of a multicomponent mixture (with restrictions on convection and mass fractions).

1. Introduction
Ventilated facade systems are widespread used in civil engineering in various climatic zones (increase in energy efficiency, increase in service performance of materials of walls).

A large number of articles (analytical, experimental, numerical modeling), including the solution of a problem with use of Lie groups have been devoted to the calculation of flows in ventilation channels. Fundamental work on free-convective flows in vertical channels or mass transfer through the wall construction (considering various materials, designs, regulating mechanisms, etc.). Practically there are no works where the coupled nonstationary problem of mass transfer through the wall construction and air flow (in the ventilation facade and along the wall surface) is investigated.

Assessment of the impact of air flow on the remove moisture from the structure of the facade is made in [17], but the solution to the problem of mass transfer and hydrodynamics of the flow are made separately.

In this article performed numerical modeling of the coupled nonstationary heat and mass transfer task in conditions of convection for facade system with and without ventilation channels in heat-insulating panel (figure 1). Modeling was made using a new method, consisting in the replacement of solid region for a multicomponent mixture.

Standard factory-produced panel has overall dimensions (mm): height – 2800, width – 4500, thickness – 300. Assumed the possibility of using symmetry conditions, it’s used a three-dimensional section of the panel (figure 2).
2. General problem definition

2.1. Initial and boundary conditions

Figure 3 shows the scheme of the computational domain with the added air zones providing influence of external conditions.

Figure 3. Scheme of the computational domain with calculated conditions
1 – velocity, temperature and relative humidity; 2 – atmospheric pressure; 3 – symmetry conditions.
Upper and bottom end surfaces of the panel – wall.
All lateral surfaces – symmetry conditions
In zone Air(in) – constant value of temperature and relative humidity
In zones Concrete and Insulation – initial values of relative humidity

2.2. Thermophysical properties of materials and environmental conditions

Data are taken from [18] – [22].

| Material        | Density (for panel materials - volume weight), kg / m³ | Coefficient of heat conduction, W / m C °C | Specific heat capacity, J / kg C °C |
|-----------------|-------------------------------------------------------|------------------------------------------|-----------------------------------|
| Steel concrete  | 2400                                                  | 2.04                                     | 840                               |
| Insulation      | 100                                                   | 0.05                                     | 840                               |
| Air             | 1.225                                                 | 0.0242                                   | 1006.43                           |
| Water vapor     | 0.5542                                                | 0.0261                                   | 4.61                              |
Table 2. Environmental conditions

| Month       | I  | II | III | IV  | V  | VI | VII | VIII | IX  | X  | XI | XII |
|-------------|----|----|-----|-----|----|----|-----|------|-----|----|----|-----|
| Average monthly air temperature, C | -6.6 | -6.3 | -1.5 | 4.5 | 10.9 | 15.7 | 18.3 | 16.7 | 11.4 | 5.7 | 0.2 | -3.9 |
| Average monthly relative air humidity, % | 89 | 85 | 72 | 68 | 62 | 67 | 70 | 76 | 82 | 80 | 90 | 93 |

Value of molecular diffusion factor is set to constants for each field of calculation (m²/s):
- Reinforced concrete: \( D_{\text{con}} = 1.97 \cdot 10^{-7} \)
- Heat-Insulation: \( D_{\text{ins}} = 1.55 \cdot 10^{-5} \)
- Air: \( D_{\text{air}} = 2.17 \cdot 10^{-5} \)

3. Model description

3.1. Method of replacement a solid zone on a multicomponent mixture

Modeling of heat and mass transfer in a solid requires defining the characteristics of porosity and structure of the material. The solution of such problem, coupled with the influence of the air flow, is connected with the difficulties of the process of convergence of the solution.

The material structure parameters determine the values of the various transfer potentials, which can be reduced to a diffusion coefficient or vapor conductivity.

The method consists in replacing a solid body with a multicomponent mixture, the components of which allow us to set the thermophysical properties of a body. The mass diffusion coefficients in the mixture is set programmatically.

Mixture composition:
1. air (carrier medium)
2. water vapor
3. "reinforced concrete"
4. "thermal insulation"

In zones occupied by the air flow the mixture consists only of air and water vapor. In these zones set boundary conditions of the first kind (values of temperature, velocity and relative humidity).

In the zones occupied by the elements of the panel construction the mixture consists of air, water vapor and one of the quasi-solid components.

The correspondence mixture properties to solid bodies is provided as follows:
1. Density (kg/m³)
   Density for "solid" region cannot be specified through the densities of the components of mixture (mixture law). Therefore, the density is specified with UDF (User Defined Function), which allows to set constant density values for each computational domain.
2. Thermal conductivity (W/m K) and heat capacity (J/kg K)
   \[ k = \sum_i Y_i k_i \]
   \[ Cp = \sum_i Y_i Cp_i \]
   where \( Y_i \) – mass fraction of \( i \) component.
   \( k_i \) and \( Cp_i \) – thermal conductivity and heat capacity of \( i \) component respectively.
   The necessary values in the region are set through the values of quasi-solid components (mixture law).
3. Relative air humidity
\[
\varphi = \frac{P_{H_2O}}{P_{sat}}
\]

Partial pressure of water vapor (Pa):

\[
P_{H_2O} = Y_{H_2O} \frac{\mu_{air} - P_0}{\mu_{H_2O}} \frac{1}{1 + Y_{H_2O} \frac{\mu_{air}}{\mu_{H_2O}}}
\]

\(\mu_{air}, \mu_{H_2O}\) – molar masses of dry air and water vapor (kg/kmol)

\(Y_{H_2O}\) – mass fraction of water vapor

\(P_0\) – atmosphere pressure (Pa)

In the case of mixture, instead of \(\mu_{air}\) there should be a value of \(\mu_{mix}\) (molar masses of mixture), but in order to specify adequate moisture content in quasi-solid regions, the molar masses of the components of "concrete" and "insulation" are set equal to the molar mass of dry air (28.966 kg/kmol).

Saturation pressure (Pa):

\[
P_{sat} = P_0 \exp \left\{ \frac{T}{T} - 1 \right\} \sum_{i=1}^{\infty} F_i \left[ a \left( T - T_p \right)^{i-1} \right]
\]

\(T\) – current temperature (K)

The values of the constants \(P, T, T_p, a, F\) are taken from [23].

4. The mass transfer intensity was set by the diffusion coefficient for each calculated domain with UDF (User Defined Function).

Taking into account that the calculation is carried out mainly in conditions of sorption humidification, the processes of phase transformation of water vapor and the accumulation of moisture in the material are not considered.

In the conditions of sorption humidification, the influence of these processes is taken into account by setting the increased values of the thermal conductivity coefficients of the materials.

3.2. System of basic equations for the liquid zones

Conservation equation:

\[
\nabla \left( \rho \vec{v} \right) = 0
\]

\(\nabla = \left\{ \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right\}\) – operator nabla

\(\rho\) – density (kg/m³)

\(\vec{v}\) – velocity vector (m/s)

Momentum conservation equation:

\[
\frac{\partial}{\partial t} \left( \rho \vec{v} \right) + \nabla \left( \rho \vec{v} \vec{v} \right) = -\nabla p + \nabla \left[ \rho \vec{v} \right]
\]

\(t\) – time (s)

\(p\) – static pressure (Pa)

\(\tau = \mu \left[ \nabla \vec{v} + \nabla \vec{v}^T - \frac{2}{3} \nabla \cdot \vec{v} I \right]\) – stress tensor (Pa)

\(\mu\) – molecular viscosity (kg/m s)

\(I\) – unit tensor
Energy equation:
\[
\frac{\partial}{\partial t} (\rho \bar{E}) + \nabla \left( \bar{\nu} (\rho \bar{E} + \bar{p}) \right) = \nabla \left( k_{\text{eff}} \nabla T - \sum_i h_i \bar{J}_i + \left( \tau_i \right) \right)
\]  
(3)

\( k_{\text{eff}} \) – effective conductivity (\( k + k_t \), where \( k_t \) is the turbulent thermal conductivity)

\( \bar{J}_i \) – diffusion flux species \( i \) (kg/m² s)

\( E = h - \frac{p}{\rho} + \frac{\nu^2}{2} \)

\( h = \sum_i Y_i h_i \) – enthalpy (J/kg)

\( h_i = \int_{T_{\text{ref}}}^{T} C_p dT \) – enthalpy of species \( i \)

\( T_{\text{ref}} = 298.15 \) K

Species transport equation:
\[
\frac{\partial}{\partial t} (\rho Y_i) + \nabla (\rho \bar{\nu} Y_i) = -\nabla \bar{J}_i
\]  
(4)

\( \bar{J}_i = -\left( \rho D_i + \frac{\mu_i}{Sc_i} \right) \nabla Y_i \)

\( D_i \) – mass diffusion coefficient (m²/s)

\( \mu_i \) – turbulent viscosity (kg/m s)

\( Sc_i = 0.7 \) – turbulent Schmidt number

3.3. System of basic equations for the quasi-solid zones
In these zones, the following parameters are established: \( \bar{v} = 0 \); the constant value of the mass fraction of one of the components "concrete" or "insulation" (the mass fraction of the second component is equated to zero).

Energy equation:
\[
\frac{\partial}{\partial t} (\rho h) = \nabla \left( k \nabla T - \sum_i h_i \bar{J}_i \right)
\]  
(5)

Species transport equation:
\[
\frac{\partial}{\partial t} (\rho Y_i) = \nabla (\rho D_i \nabla Y_i)
\]  
(6)

4. Numerical modeling
Numerical modeling was executed in the program ANSYS FLUENT 17.0. Discretization of the system of integro-differential equations is carried out by the finite volume method [24], [25]. The resulting system of linear algebraic equations was solved by the iterative PISO method. The algorithm of PISO is effective in case of the solution of the equations of Navier-Stokes for nonstationary tasks [25].

As the interpolation scheme of equation for the correction pressure used scheme PRESTO! recommended for the decision in nonstationary tasks and in cases with the big-time step [26].

Mesh consists from the hexahedral elements (figure 4), quantity – 287280.
Figure 4. Mesh

Since the time scale of mass transfer and hydrodynamics are of a different order, as a first stage of the simulation, a stationary isothermal hydrodynamic calculation was carried out.

Results of the first stage are used as starting conditions of the second stage (that improves process of convergence). At the second stage solved non-isothermal unsteady problem of coupled heat and mass transfer in conditions of convection. Temperature and relative humidity are changed every month during the year.

The beginning of calculation – November. Internal air conditions are constant: temperature is 17 °C, relative air humidity of 40%.

5. Results
Figures 5 and 7 show the distribution of relative humidity in the central cross-section of the calculated area (including air zones).

Figures 7 and 8 show the relative humidity and temperature graphs in the panel body (in the center of the panel between the ventilation channels).

The average value of the flow velocity in ventilating channels – 0.017-0.02 m/s.

Figure 5. Field of relative humidity distribution (ventilation channels)
1 – November; 2 – February; 3 – May; 4 – August; 5 – October
Figure 6. Relative humidity distribution (ventilation channels)

Figure 7. Temperature distribution (ventilation channels)

Figure 8. Field of relative humidity distribution (without ventilation channels)

1 – November; 2 – February; 3 – May; 4 – August; 5 – October
Figure 9. Relative humidity distribution (without ventilation channels)

Figure 10. Temperature distribution (without ventilation channels)

6. Conclusions
1. The airflow velocity in the ventilation channels does not significantly affect the heat transfer.
2. The air grid (in the form of ventilation channels) has a positive effect on the heat loss of the panel – 10-15% lower than in construction without ventilation channels.
3. In panel with ventilation channels the relative humidity does not exceed the value of 100%, which positively affects its functional properties.

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