HEAT TRANSFER IN EXTERNAL WALLS MADE FROM AUTOCLAVED AERATED CONCRETE

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Abstract

The paper is devoted to the analysis of heat and moisture transfer processes in walls made from autoclaved aerated concrete blocks. The paper gives theoretical calculation of heat and moisture transfer processes in autoclaved aerated concrete walls as well as is based on practical measurements. Analyzing experimental data, the model for heat and moisture transfer processes in walls made from autoclaved aerated concrete blocks was created and tested. The influence of drying process in autoclaved aerated concrete wall on the heat transfer process of the wall was also studied in this paper. The offered model of calculations takes into account the property of autoclaved aerated concrete as a porous material to enable the most accurate description of heat and moisture transfer processes in the external walls of enclosures in various exploitation conditions. In contrast to already known calculation models of the heat engineering properties of external walls, this model takes into account material internal structural changes, which consider the irregular structure of autoclaved aerated concrete, allowing for each separate diffusion process in layers.

Key words: material and construction.

Introduction

This paper presents theoretical research of modeling of the heat and moisture transfer processes in autoclaved aerated concrete walls. In the European Union, former USSR republics and the Baltic States there are held various researches, technological and practical activities dedicated onto the decision of the heat engineering problem of walling and materials. Although there are made many different experiments that give grounds for theoretical and practical basis of various heat engineering issues, the investigation of the heat and moisture transfer processes and the possibility to model them is still essential. It is important to evaluate not only a construction material, but also its production, construction and building prospects and creation of an effective modeling method. Thus, it is necessary to analyze the properties of autoclaved aerated concrete external walls using modern thermo-physical methods. When analyzing the processes in autoclaved aerated concrete, it is necessary to simulate them. It is especially urgent to investigate heat and moisture transfer processes in external walls made from autoclaved aerated concrete of new generation, both external and internal climatic factors, and the finishing material impact on them. The term autoclaved aerated concrete of new generation, in our publication, is understood as autoclaved aerated concrete blocks with bulk density 350 - 450 kg/m³, a dimensional accuracy of +/- 1 mm and forming joints in wall with glue mortar.

Structure of model and algorithm

Using the theoretical model and experimental data, a simulation of moisture migration and heat transfer processes for an exterior wall of aerated concrete of new generation as well as an analysis of the results of the calculations were made (Vilnītis M., Noviks J., Gaujēna B., Paplavskis J., 2010). During the period from March 2009 till May 2011, moisture of the block wall of aerated concrete of new generation, in terms of weight, decreased from 24% to 6.2%; experimental (Тамм Ю., Йыгиоя Э., 2006) data are shown in Table 1.

Data, given in Table 1, on the aerated concrete walls' drying can be described by the following equations:

$$Y(t) = 22.57\exp(-0.0017t) \tag{1}$$

$$Y(t) = 24.02 - 0.0456t + 3\times10^{-5}t^2 \tag{2}$$

where

$Y(t)$ – weight of moisture, shown in %,
t – time, shown in days

Experimental results and approximation curves are given in Figure 1.

Equation (1) describes the aerated concrete drying process as a relaxation in a constant time period, which is equal to approximately 590 days. Taking into account that by increasing the time of drying, the main target for humidity is to be balanced, we are recommending the equation (1) to be replaced with following equation (3):

$$Y(t) = 5.0 + 20.13\exp(-0.0033t) \tag{3}$$

Figure 2 shows that equation (1.3) can be used both in the start of the drying process of block and for the longer time intervals.

Table 1

		Moisture in terms of weight, %		
Date	Amount of days	South side	North side	Average
17.03.2009	0	25.5	22.2	23.9
19.05.2009	63	21.6	21.4	21.5
05.09.2009	172	17.4	15.4	16.4
31.10.2009	228	17.2	14.6	15.9
17.03.2010	365	12.1	13.3	12.7
18.05.2010	427	8.4	8.5	8.5
28.08.2010	529	9.2	7.1	8.2
12.03.2011	725	8.8	6.3	7.6
08.05.2011	782	6.4	6.1	6.2

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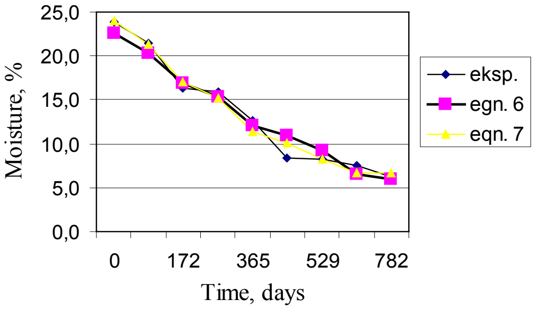

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Figure 1. **Daily moisture changes in the exterior wall of aerated concrete of new generation**

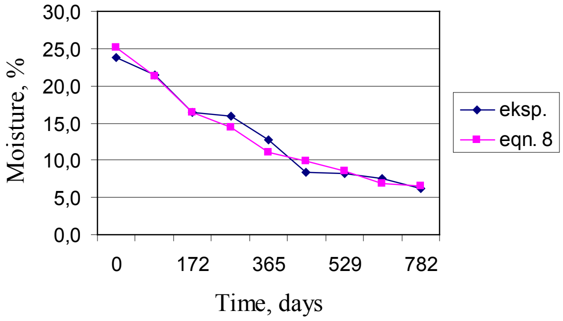

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Figure 2. **Daily moisture changes in the exterior wall of aerated concrete of new generation**

But approximation (2) corresponds to the relaxation process with constant time $\tau_{saus.}$ which is approximately 300 days or 7200 hours. Balancing between a constant time period and steam permeability coefficient 0.23 (MHG / (m • h • Pa), a square meter of 375 mm thick walls of aerated concrete of new generation with a specific weight of 400 kg/m3 weighs ~ 150 kg. So, 20% of weight of moisture is that part which evaporates during the drying process. This water mass is about 30 kg. So, in 7200 hours the humidity in the form of vapor with a 30 kg mass will pass through the half of wall thickness (375/2 mm) with the vapor pressure which is equal to 3.4 Pa (0.026 mm Hg). At a room temperature of 20°C where water vapor pressure is up to 20 mm Hg (Кошкин Н. И., Ширкевич М. Г., 1960), unbalanced relative humidity with a size of only 0.1% relative humidity would make a sufficiently significant pressure drop, which approximately in 7200 hours would dry an aerated concrete block.

It is clear that the high aerated concrete material vapor permeability is essential for an outer wall in its drying process, where the plaster noticeably does not hold moisture of the material on the top, and between the inner and outer walls of the plane there is a slight drop in pressure. For example, in a building with a height of 4 m (up to the roof eaves), the inner room and outdoor temperature difference is 20°C, air pressure in the room (floor level) will differ from the outside pressure by 3.5 Pa (Фокин К.Ф., Табунщиков Ю.А. & Гагарин В.Г., 2006), which is virtually equal to the above estimate of the pressure. This means that the internal space and outdoor air temperature difference may cause a pressure drop that is sufficient to aerated concrete moisture vapor transmission to ensure clearance from the wall in about a 300-day period.

As a further factor, the pressure drop of the wind will be evaluated, which allows to «ventilate» connected pores in aerated concrete. In the case of wind speed of 5 m/s, wind pressure, which is calculated using the Bernoulli formula (Перехоженцев А., Григоров А., 2006), will be about 16 Pa, but if speed is 2 m/s - 2.6 Pa. This means that even a slight breeze to the building walls pressure (proportional to the square of wind speed), which is sufficient ventilation of aerated concrete pores, affects the drying process.

As a last factor, we will examine aerated concrete block drying time if air flow is not vented in the pores and drying occurs only by moisture diffusion. At a temperature of 0°C and pressure 760 mm Hg, the water vapor diffusion coefficient in air is equal to 0.21×10^{-4} (m^2/s]) (Кошкин Н. И., Ширкевич М. Г., 1960). Diffusion process can be described by equation (1.4):

$$M = D\frac{\Delta C}{\Delta l}St \qquad (4)$$

where

M - the mass, which is transmitted through the layer with the thickness Δl and area S of concentration difference ΔC at the amount of time t,

D - the diffusion coefficient.

So, at a humidity of 100% and a temperature of 17°C, the water vapor concentration in the air will be 16 g/m3 in the inside part of block walls of aerated concrete of new generation. Assuming S = 1 m², Δl = 0.375/2 m or 0.19 m, one can obtain that in 1 second the diffusion process can move 1.77×10^{-6} kg in 1 day - 0.15 kg, and in 300 days, respectively, - 46 kg of water. The assessment carried out shows that the moisture transfer by diffusion is comparable to the moisture transfer with pore vapor permeability of the new generation aerated concrete. Thus, the model process and the computer program must take into account these two components for walls of the new generation aerated concrete during the drying process.

A program block scheme is shown in Figure 3. The program is designed for heat transfer and moisture migration modeling for autoclaved aerated concrete with the specific weight between 350 to 450 kg m³, using combined analytical simulation method. For this purpose, autoclaved aerated concrete exterior walls can be conventionally divided into, small areas, each

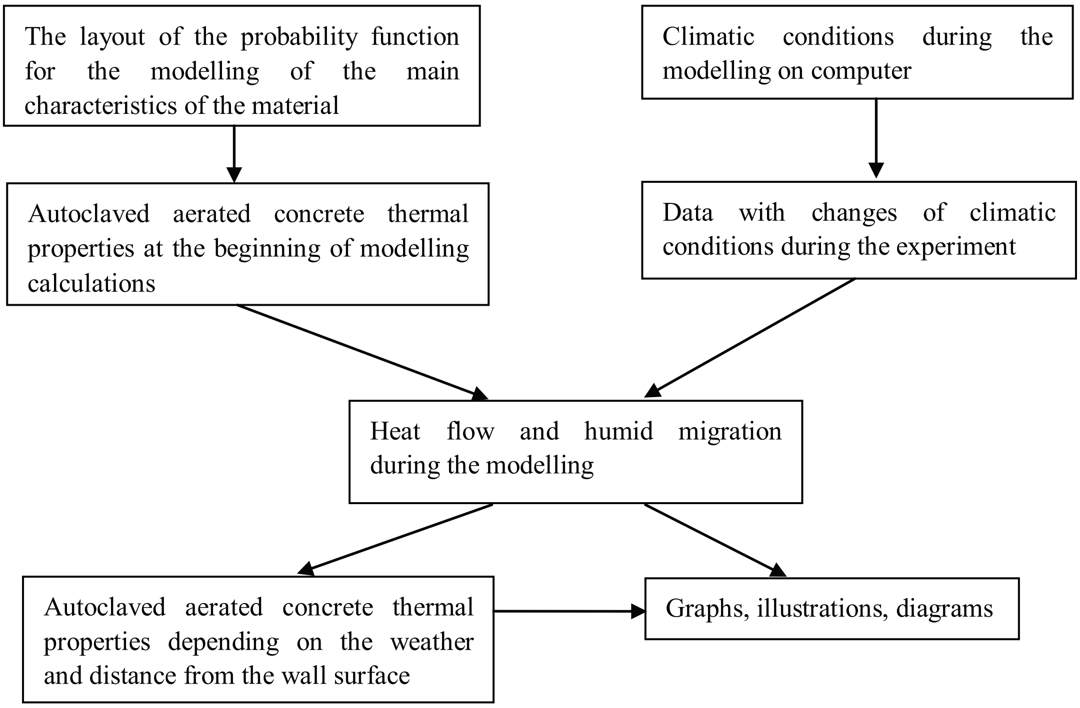

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Figure 3. **Program block scheme**

of which provides an analytical relationship. In their turn, these, parameters for each of the areas are selected randomly, but according to the layout in the autoclaved aerated concrete material.6

Climatic conditions during the modeling on a computer, in the simplest case, can in one or several data file preparations, where indoor and outdoor air temperature, solar radiation, air humidity inside and outside is shown.

As a layout of the probability function for the modeling of the main characteristics of the material, a smooth layout, the layout of a normal, Poisson layout, or any other specific layouts may use in cases where it is necessary to accurately reflect the specific material. Properties (University of Latvia. Environmental and Technological Processes Laboratory for Mathematical Modeling, 2011.10.11.).

The calculations of modeling of autoclaved aerated concrete thermal properties, at the moment of the beginning of experiment, were performed with the statistical test method (the Monte Carlo method). Moreover, the size of the basic area in the modeling course should be corrected for cell sizes of material (40-80 cells per square centimeter).

The calculations of heat transfer and moisture migration in the course of modeling should select an appropriate pace so that the processes that are affected by daily fluctuations are estimated without significant errors (University of Latvia. Environmental and Technological Processes Laboratory for Mathematical Modeling, 2011.10.11.).

The data of thermal properties of autoclaved aerated concrete, depending on weather and distance from the wall surface, graphs, charts and illustrations are created, taking into account the possibility for comparison with the previously obtained experimental results.

Moisture migration and heat transfer process modeling

Analytical equations of elementary material parts with coordinates expressed with the vector x, includes the following variables:

$$\mu_3(\vec{x}),\ p_3(\vec{x}) \tag{5}$$

$$\mu_2(\vec{x}),\ p_2(\vec{x}) \tag{6}$$

$$\nu_1(\vec{x}),\ p_1(\vec{x}) \tag{7}$$

$$T(\vec{x}) \tag{8}$$

where $\mu_3(x)$ – humidity specific weight %; $p_3(x)$ – saturated water vapor pressure attributable to closed pores; $\mu_2(x)$ – humidity specific weight %; $p_2(x)$ – water vapor pressure attributable to open non-aerated pores; $v_1(x)$ – relative air humidity %, $p_1(x)$ – water vapor pressure attributable to open connected (aerated) pores; T(x) – temperature.

Taking into account the above-introduced markings, a moisture migration equation system for autoclaved aerated concrete material elemental parts can be written as follows:

$$\frac{\partial}{\partial t}\mu_3 = -D_{32}(\mu_{20}-\mu_2)\text{, if } \mu_3 > 0\text{, } \frac{\partial}{\partial t}\mu_3 = 0\text{, if } \mu_3 = 0 \tag{9}$$

$$\frac{\partial}{\partial t}\mu_2 = -\frac{\partial}{\partial t}\mu_3 - P_{10}{}^{-1}D_{21}(p_{20}-p_1) \tag{10}$$

$$\frac{\partial}{\partial t}p_1 = -D_{11}\frac{\partial^2}{\partial x^2}p_1 + V_x\frac{\partial}{\partial x}p_1 - D_{21}(p_1-p_{20}) \tag{11}$$

where t – time; $D_{32}(T)$ – the ratio that shows the diffusion of moisture between the autoclaved aerated concrete 2nd and 3rd ‘layers’; $\mu_{20}(T)$ – layer final moisture saturation (about 10%); $p_{20}(\mu_2, T)$ – saturated water vapour pressure attributable to non-aerated open pores; $D_{21}(T)$ – the ratio of moisture diffusion in the second layer of pores; $D_{11}(T)$ - the ratio of moisture diffusion of air from open interconnected pores; V_x – the rate of the air flow in the direction of the connected pores wall surface; P_{10} – the ratio which depends on the number of open interconnected pores in autoclaved aerated concrete material elemental parts.

Without taking into account the complex and distinctive pore structure of autoclaved aerated concrete, size $P_{10}(X, T)$ can be expressed as follows:

$$P_{10}(\vec{x},T) = \left(\frac{RT}{\mu_B}\right)\rho_B K_1{}^{-1} = \frac{\mu_{\text{в}}\rho_B}{\mu_B\rho_{\text{в}}K_1}P_0 \approx 6000P_0 \text{ if } K_1 \approx 0.2 \tag{12}$$

where R - universal gas constant; $\mu_A = 18$ – water molecules in the molar mass; p_A – water density in liquid state; $\mu_a = 29$ – air molar weight, p_a - air density; P_0 - atmospheric pressure.

Some material layers can be described with the following parameters:

$$D_{11}(\vec{x},T)\,,\ D_{21}(\vec{x},T)\,,\ D_{32}(\vec{x},T)\,,\ V_x(\vec{x},t) \tag{13}$$

$$\mu_3(\vec{x},t)_{t=0}\,,\ \mu_2(\vec{x},t)_{t=0}\,,\ \mu_{20}(\vec{x},T)\,,\ P_{10}(\vec{x},T) \tag{14}$$

where D_{11}(x, T) depends on the coordinates, taking into account the uneven pore structure (i.e. slightly less than the diffusion ratio of the atmosphere); D_{21}(x, T) depends on the coordinates, taking into account the average pore surface area of the material layer; D_{32}(x, T), P_{10}(x, T) and V_x(x, T) depends on the coordinates, taking into account different material properties, for which an air flow rate of material pores V_x (x, T) is proportional to the pressure difference between the outer walls surfaces.

In equations 9 and 10, values can be modeled using different distribution functions, for example, the simplest case D_0[1 - d_0ε(x)],)] where D_0 is determined, but d_0 size constant is not determined, while ε(x) is a randomly chosen value in the range [-1, +1] .]1) Moreover, in the first approximation this value depending on the temperature can be ignored, so that temperature effect is estimated with p_{20} (μ_2, T) and (albeit to a lesser extent) with μ_{20} (T).)

Taking into account special properties of a single layer of the material, humidity migration takes place not only in the perpendicular direction to external wall (relatively denoted as x direction), but also in the parallel direction (y and z). Therefore, equation 12 would be better written down in the following way:

$$\frac{\partial}{\partial t}p_1 = -D_{11}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}\right)p_1 + +\left(V_x\frac{\partial}{\partial x}+V_y\frac{\partial}{\partial y}+V_z\frac{\partial}{\partial z}\right)p_1 - D_{21}(p_1 - p_{20}) \tag{15}$$

where the average speed of air flow in material V_y and V_z are equivalent to zero, they may differ from zero only in the light of the uneven structure of the small pores in the material layer. Moreover, there is executed the condition div (V) = 0, which means that the source of the air flow inside the material and the source of leakage (loss) are not decided.

Humidity transfer equations 9 – 11 and 15 should be supplemented with starting and boundary conditions and heat transfer equations. Drawing up heat transfer equations, the heat that arises from moister evaporation is not taken into account. It is possible, considering the fact that the autoclaved aerated concrete wall drying process takes place over several years while the temperature variation of wall thickness is diminishing in a few. However, drawing up the equations, the heat which arises from frozen water should be taken into account because the speed in which the water turns into ice (moves into another state) is not limited to humidity migration velocity in autoclaved aerated concrete block pores. It takes into account only the beginning of autoclaved aerated concrete exterior wall drying, stage, as the humidity level of autoclaved aerated concrete blocks after production is relatively high. While on the stage of construction, autoclaved aerated concrete is sufficiently dried, humidity distribution in the wall thickness is homogeneous and the outer surface of the bordering structure cannot freeze in winter period. In a simple case, it may be estimated with the value D_{32}(T), which depends on the temperature – if it is above 0°C, then the value is constant, if the temperature is below 0°C, then the value is zero (diffusion does not happen as the water is frozen).

The results of simulation

It can be concluded that a small time step allowable value of the direct calculation scheme is characterized by a large diffusion coefficient value. In real life, the diffusion coefficient, taking into account the liquid into the pores of the damp, is much lower. The diffusion equation solution "stabilized", taking into account some material "layers" the presence of distributed sources, and the allowable step at a time can be considerably higher. The direct scheme resulting solution stability will be further tested in experimental trials in the calculation. The above parabolic equation direct solution scheme can be improved with a stable, implicit scheme in use.

Figure 4 reported aerated concrete block layers with 1 mm distance, the temperature changes have been made during the calculation. Outer air temperature is modeled with a stepwise function - a step change in 1 hour step in solving the heat conduction equation has been chosen equal to 1 second. The figure shows the transition process, which takes about 3 hours, heat waves are also visible, the phase of the outside air temperature is lagging behind and the increase of the distance increases from the outer surface. Block thickness is 375 mm, the transition process will last longer than 3752 = 14 times and generally account for about 40 hours. This figure shows also the effective depth of the "high frequency" components of temperature fluctuation. 20 mm depth of the model stepwise temperature change seems already almost completely smoothed.

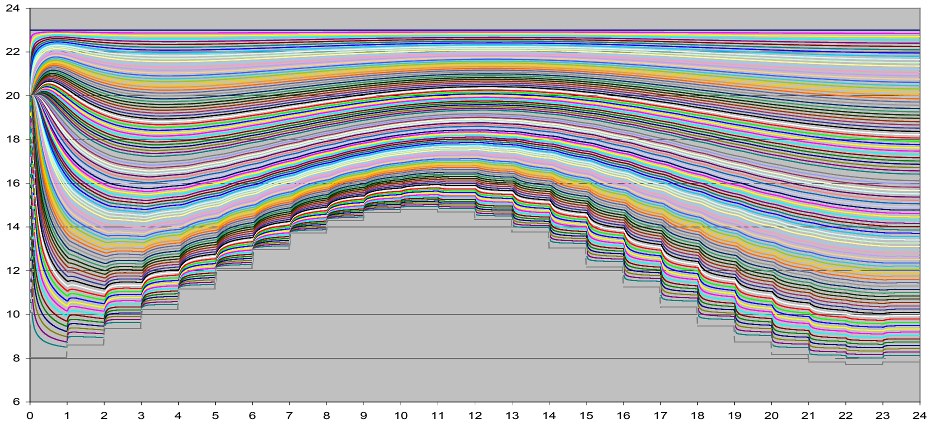

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Figure 4. **Calculation of a temperature in 1 day after installation of the block wall. The initial temperature of blocks is 20°C, room temperature 23 ° C, block thickness is chosen equal to 100 mm. This was calculated using the direct scheme with a time step of 1 second. On the x axis, clock time is marked, on the y axis - temperature in Celsius.**

Conclusions

A study shows that the moisture diffusion transfer in the form of magnitude is comparable to the moisture transfer of pore vapor permeability for aerated concrete of new generation, so when modeling these two components of outer wall of aerated concrete of new generation in the drying process must be taken into account.

Unlike the pre-positioning of exterior wall thermal properties of model-based calculations, in this case it is used in the structural material (internal) variable that is evaluated by the above material mixed layer interactions, taking into account different moisture migration processes in each of the layers.

Equations 5 – 10 and the relationship $D_{11}(T)$, $D_{21}(T)$, $D_{32}(T)$, $\omega_{20}(T)$, $p_{10}(\omega_2,T)$, $L(T,\omega)$, $c(T,\omega)$ represent a complex nonlinear system of equations that can be successfully used in the prediction of thermal process for aerated concrete of new generation in both time and space and in different functions for buildings, using a variety of finishing materials and modeling of climatic conditions.

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