EFFECT OF THERMAL RADIATION ON THE SURFACE DEGRADATION OF MATERIALS OF BUILDING CLADDINGS

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Abstract:

The improvement of thermal technical properties of insulation layers is a crucial point of reconstruction of all building objects, in the first place of the large block of flats from the socialistic period in Czechoslovakia, with the aim to extend their lifetime. However, a typical phenomenon of such reconstruction is the occurrence of algae on the outer surface of the new insulation system and consequently their surface degradation. This phenomenon can be explained by the night condensation of vapour from porous material structures, driven by the heat radiation, in Central European climatic conditions active namely in two “windows“ in the infra-red wavelength range. The mathematical model of evolution of temperature and moisture fields is based on the physical laws of conservation of mass and energy. The numerical simulation of this process, coming from the method of discretization in time and from the finite difference method, makes use of the original software, written in the Pascal code. The comparison of result from numerical simulation and laboratory experiments leads to some recommendations, how to avoid the algae coatings.

Keywords:

heat and moisture transfer in porous media, thermal radiation, building insulations, numerical simulation

INTRODUCTION

The complex reconstruction of old buildings, especially of the large block of flats, based on the panel technology, occurring especially in all Central European countries from the former Soviet Block, including the Czech and Slovak Republics, cannot avoid the improvement of their insulation system to reduce their energy consumption. The most frequent method is to supply (at least one) additional insulation layer with propitious thermal insulation and accumulation characteristics, as indicated at Fig. 1. Nevertheless, the practical experience with this type of reconstruction shows that the bio-corrosion, consisting in the progressive damage of claddings, starting from their outer surfaces, by the population of algae, is active even in such locations where it was not known before the reconstruction at all; Fig. 2 shows four examples of the status of reconstructed outer walls after several months. Algae occur also at various unexpected and unwanted places of the city, even on seemingly flat surfaces, as documented at Fig. 3.

This phenomenon has been discussed especially in the German literature (for more details see [1] and [10]) as a part of a general problem with economical, political, ecological, etc. aspects: what to do with the heritage of the “DDR” panel architecture; however, the world-wide character of the problem is evident e.g. from several chapters of [3]. The comparative heuristic analysis, based on both practical observation and laboratory experiments, results in the hypothesis that the main reason for the appearance of algae is the (quasi)periodic night condensation of vapour from porous building materials that cannot evaporate or dissipate in the construction; other sources of liquid water, needed for algae, are rain, snow, etc. However, most simple mathematical models of heat transfer in buildings are not able to predict such phenomena, whereas other models require expensive measurements of non-standard physical characteristics in form of (semi)empiric functions of several variables, whose validity is doubtable. This contribution tries to explain the presence of humidity, crucial for the population of algae, using rather simple mathematical formulae, coming from the conservation laws of classical physics, and standard macroscopic material characteristics, whose values can be found in the literature or (for experimental materials, e. g. for the insulation layers based on the wood waste) measured in common laboratories of building physics.

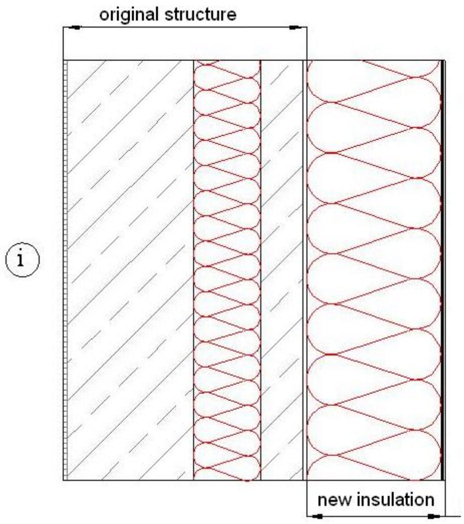

Figure 1: Typical project of reconstruction of buildings – adding a new insulation layer

Figure 2: Algae on humid claddings of reconstructed buildings

Figure 3: Attack of algae observed on various structures and equipments in the city

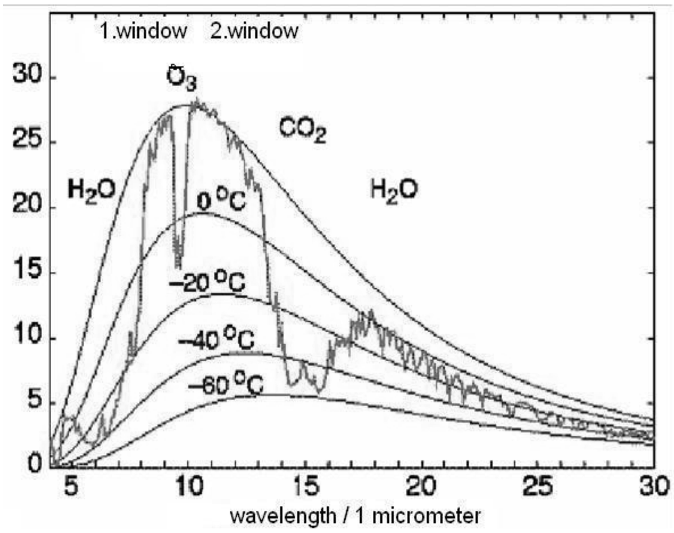

Figure 4: Emission spectrum from the summer humid atmosphere (in W.m^2), related to the wave-length (in µm)

THERMAL RADIATION AND CONDENSATION OF VAPOUR – OBSERVATIONS AND MEASUREMENTS

The condensation of vapour from air to liquid water is typically driven by the radiation of the Earth to the universe, as discussed in [11]. The emission from the Earth surface, compared with the smooth spectra of radiation of the ideal black body at the temperature at most 20°C, is realized namely in two remarkable domains of wavelengths, so-called “wavelength windows”, as evident from Fig. 4. The effect of such radiation needs the humid atmosphere and attains its maximum during summer nights. Fig. 5 documents how the complete exchange of window in a block of flats in Brno-Bystrc (the new thermal resistance is 1.1 W/(mK)) supports the water condensation.

Figure 5: Glass of a new window, non-transparent thanks to the condensation of water

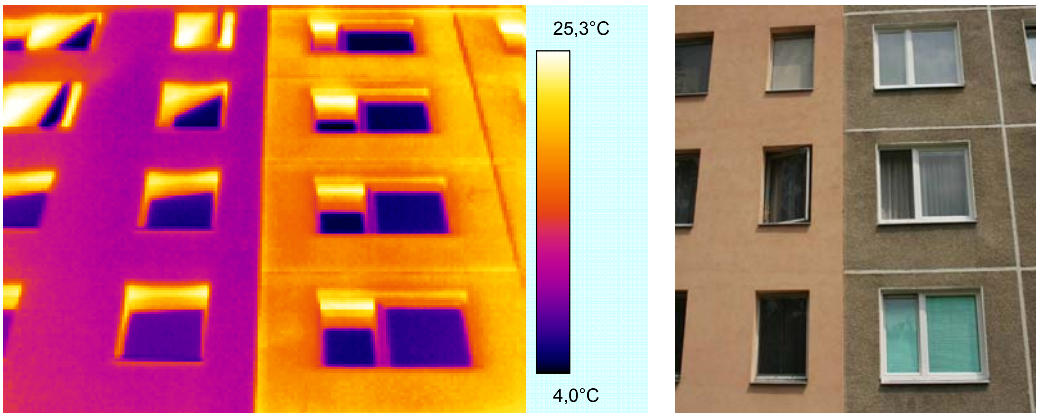

Figure 6: Thermo-visual measurement of a partially reconstructed building

Let us notice one convincing example: the thermo-visual snapshot of a partially reconstructed building in the same locality (with the classical snapshot for comparison) at Fig. 6 has been done accidentally in the cloudless summer night. The surface of the facade part with no additional insulation layer has the average temperature 18.8 °C, whereas the air temperature is 14.4 °C; the surface of its remaining part, improved by the scheme from Fig. 1, has the average temperature 12.2 °C. Since the relative humidity is 85 %, the conditions for condensation of water are satisfied even on the surface with an additional insulation layer.

Fig. 6 was the motivation for the arrangement of the following experiment: nine material samples with various values of surface emissivity, prepared in the laboratory, were tested under similar conditions as the panels observed above. The thermo-visual camera FLIR was installed on the roof of the Planetarium of M. Kopernik in Brno to receive a sequence of snapshots in a sufficiently long time interval with equidistant time steps. Fig. 7 shows two examples of such snapshots for various temperatures of external environment. Fig. 8 documents the significant temperature decrease during 90 minutes, depending on the choice of coating; the dashed curve shows the development of the temperature of external environment. The results of this type can be helpful for the decision, which surface coating could offer a chance to prevent or reduce the occurrence of liquid water with its unpleasant consequences.

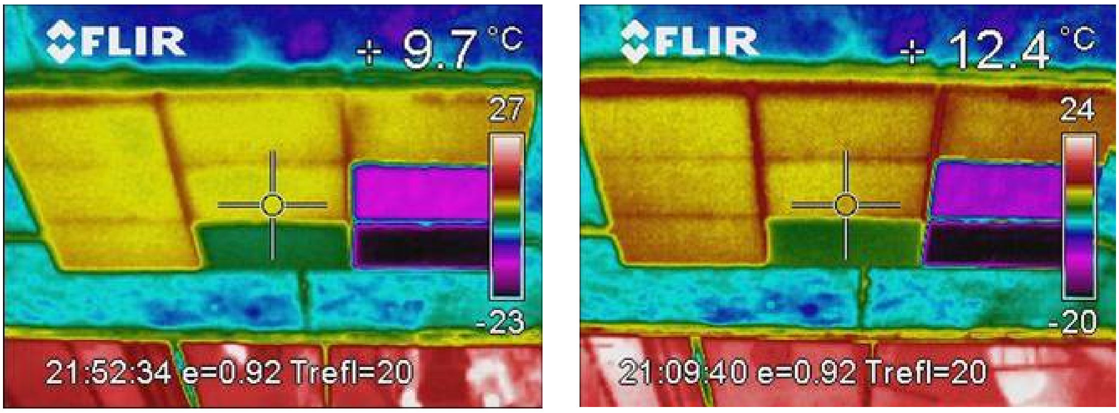

Figure 7: Examples of snapshots obtained by the thermo-visual kamera FLIR

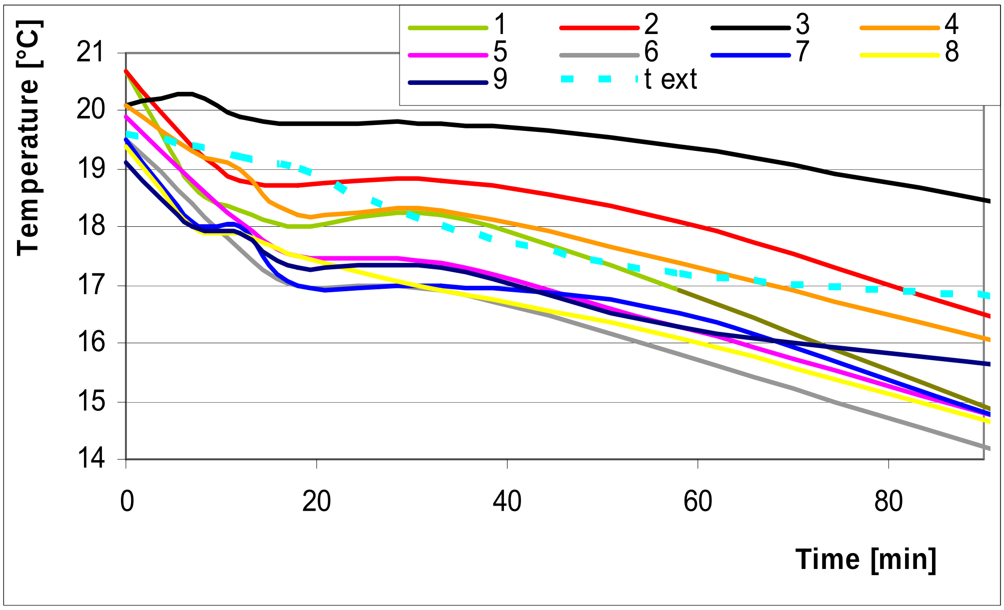

Figure 8: Temperature measured for 9 samples with various surface coatings

The observations of building objects, namely those with some visible damage, the relevant measurements on real structures and the experiments prepared in laboratories give very similar results. The dominant physical mechanism for the analysed phenomena seems to be the condensation of liquid water from the atmosphere, as explained above. However, since all experiments under realistic conditions are rather long and expensive (or their validity is not sufficient), namely for the purpose of the development of new insulation layer we are in need of some reliable mathematical simulation of such process of heat and moisture transfer.

PHYSICAL BACKGROUND AND MATHEMATICAL MODELLING

Some version of the analysis of simultaneous heat and moisture transfer in a porous medium (which is an admissible idealisation for most materials used in civil engineering) belongs to rather frequent problems not only in the literature and corresponding research software codes, but in last decades also in some commercial software packages – an extensive overview of numerical models and software means with numerous references can be found in [13]. Nevertheless, most such solvers are not suitable for our simulations – either they involve non-realistic simplifications (as constant "effective" material characteristics as e. g. the heat conduction factor, whose values in real situation can be changed 10-times due to the presence of humidity) or they suggest semi-empirical relations with complicated material characteristics, whose general calibration could be even more expensive than the experiments for a selected class of building materials.

The classical approach to the analysis of heat and moisture transfer, based on the original Luikov theory, has been explained in [8], p. 210: using some simple physical assumptions, making a balance of thermal and diffusive fluxes, we can derive a system of two partial differential equations of evolution with some reasonable initial and boundary conditions where two fields of unknown quantities occur – of the temperature and of the moisture potential; in some applications such system can be extended by the third field of the potential of pressure filtration. The Luikov model is relatively simple and its mathematical verification including the existence and uniqiuness results and the convergence of numerical approximations (using the theory of Sobolev spaces and the Rothe sequences for the discretization in time) is accessible even for the engineers without special knowledge of new results from the measure theory, function spaces, etc.; its main drawback is the assumption that all material coefficients degenerate to constants, well-known as Luikov, Posnov and Kossovich numbers. Unfortunately, all attempts to extend the result to variable material coefficients bring substantial mathematical and numerical complications – cf. [12]. Similar arguments limit the usage of both RC electrical analogues for simulation of the coupled process of heat and mass transfer, described in [8], p. 209, and of numerical techniques based on standard integral transforms, sketched in [8], p. 211.

More advanced models (by Glasser, Kiessl, etc.) are based in the extensive experimental work and suggest a lot of new physical characteristics – for their overview see [12] again; some complex HAM models cover the heat, air and moisture transfer both in the building constructions (walls, roofs, windows, etc.) and in the rooms (where the buoyancy driven air flow, described by the Navier-Stokes equations, often dominates). Their physically correct formulation should come out from the conservation laws of scalar quantities, formulated in [5], pp. 9 and 371, namely for mass, inertia and energy. Such general formulation, applicable to a rather wide class of problems of heat and moisture transfer in porous media (without air flow) has been presented in [7]; however, the setting of all suggested variable material coefficients generates a lot of problems of their identification, including both the arrangement of laboratory experiments and the numerical approaches and some stochastic analysis of the uncertainty of obtained values.

In our considerations let us assume that all material characteristics can be described at their macroscopic level by some "effective" values, in general dependent on some unknowns, but this dependence can be expressed by certain deterministic functions. Moreover, let us suppose that the macroscopic isotropy is valid. Let t be the positive time, starting from zero ($t = 0$), and let $x = (x_1,x_2,x_3)$ denote the Cartesian coordinate in some domain Ω or in its arbitrary subdomain ω belonging to the 3-dimensional Euclidean space (in practice, in one insulation layer – this can be often reduced to the 1-dimensional problem). We shall use the standard notation $\nabla = (\partial/\partial x_1,\partial/\partial x_2,\partial/\partial x_3)^T$ for gradients of functions. Let $\lambda(u)$ be the heat conduction factor, $c(u)$ the heat capacity and $\rho(u)$ the material density; formally we can introduce $\zeta(u) = c(u)\rho(u)$; u here is the dimensionless moisture content, related to the unite material volume. The redistribution of two unknown fields, prescribed for $t = 0$, will be studied in time – of the temperature $T(x,t)$ and of the above introduced moisture content $u(x,t)$. Moreover, in some considerations we shall use the decomposition $u = u_v + u_l$ where u_v will refer to vapour and u_l to liquid water. The balance of heat fluxes on ω can be expressed as

$$\int_\omega [\zeta(u)\, \partial T/\partial t - \partial L(u,u_l)/\partial t]\, \mathrm{d}x + \int_{\partial\omega} q\cdot\nu\, \mathrm{d}s(x) = 0 \tag{1}$$

where $\partial\omega$ refers to the boundary of a subdomain ω, supplied by the surface measure s and by an outward unit normal ν (almost) everywhere, and the classical Fourier law (see [8], p. 191) evaluates the heat flux q as

$$q = -\lambda(u)\nabla T\,. \tag{2}$$

The only non-standard term in (1), not included in most basic courses on heat propagation, is the second additive one on the left-hand side; $L(u,u_l)$ here characterizes the amount of heat energy lost by the phase change, taking into account the latent heat by [3], p. 419 (no presence of ice is allowed). An arbitrary choice of ω is allowed; thus, inserting (2) into (1) and applying the Green-Ostrogradski theorem, we receive

$$\zeta(u)\, \partial T/\partial t + \nabla\cdot[\, \lambda(u)\nabla T\,] = \partial L(u,u_l)/\partial t \tag{3}$$

which is the differential form of our governing equation for heat conduction; this equation must be evidently completed by the set of boundary equations. For the heat transfer between particular layers (made from different materials), following [8], p. 203, we have

$$q = -\alpha\,(T - T^*) \tag{4}$$

where T^* refers to the temperature from the adjacent layer and α is the heat convection factor. The same can be done even in case that T^* refers to the external environment. However, the thermal radiation, characterized by [3], p. 117, by the emitted energy flux

$$q = -S\varepsilon\,(T^4 - T^{*4})\,, \tag{5}$$

can be dominating on the interface between the structure and the free atmosphere; here S is the Stefan constant (whose value is $5{,}6697.10^{-8}$ W/(m^{2}K^4) – cf. [3], p. 116, and [9], p. 442) and ε is the surface emissivity (a number between 0 and 1).

The equation (3), supplied by some combination of boundary conditions of types (4) and (5), is a partial differential equation for the evolution of the temperature field T. Unfortunately, it cannot be solved directly because it is not realistic to believe to know the development of the moisture content u in advance. In some studies (like [9], referring to the software WUFI), the next step is to derive some equation for the diffusion transfer, similar to (3), to analyse the coupled problem of the heat and moisture propagation. The main complication is connected with the practical setting of corresponding material characteristics – it is even difficult to receive any reasonable value of a characteristic corresponding to $\zeta(u)$ by simple laboratory measurements. We shall use an alternative approach, based on the moisture balancing. Let u^* be the maximal admissible moisture content for the material, whose porosity is P. Let p be the partial pressure of vapour and p^* the partial pressure of saturated vapour, depending on the temperature T (for all details see [6], p. 410). Evidently

$$0 \le u \le u^* \le P\,, \quad p \le p^*(T)\,. \tag{6}$$

Then the diffusive flux can be evaluated for the vapour from the formula

$$q_v = (\delta/\mu)\nabla p \tag{7}$$

and for the liquid water from the similar one

$$q_l = \kappa(u_l)\nabla u_l\,; \tag{8}$$

in (7) δ denotes the diffusive transfer coefficient for air, μ the diffusive resistance of the material and κ (a prescribed function of u_l) the factor of capillary diffusion. The conservation of mass implies

$$\int_{\omega} (\partial u/\partial t)\, dx + \int_{\partial\omega} (q_u + q_v)\cdot\nu\, ds(x) = 0\,. \tag{9}$$

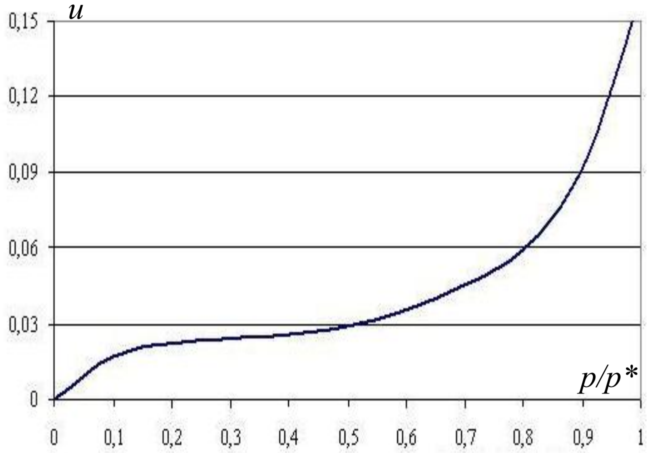

Figure 9: Typical sorption curve for an insulation material, based on the wood waste

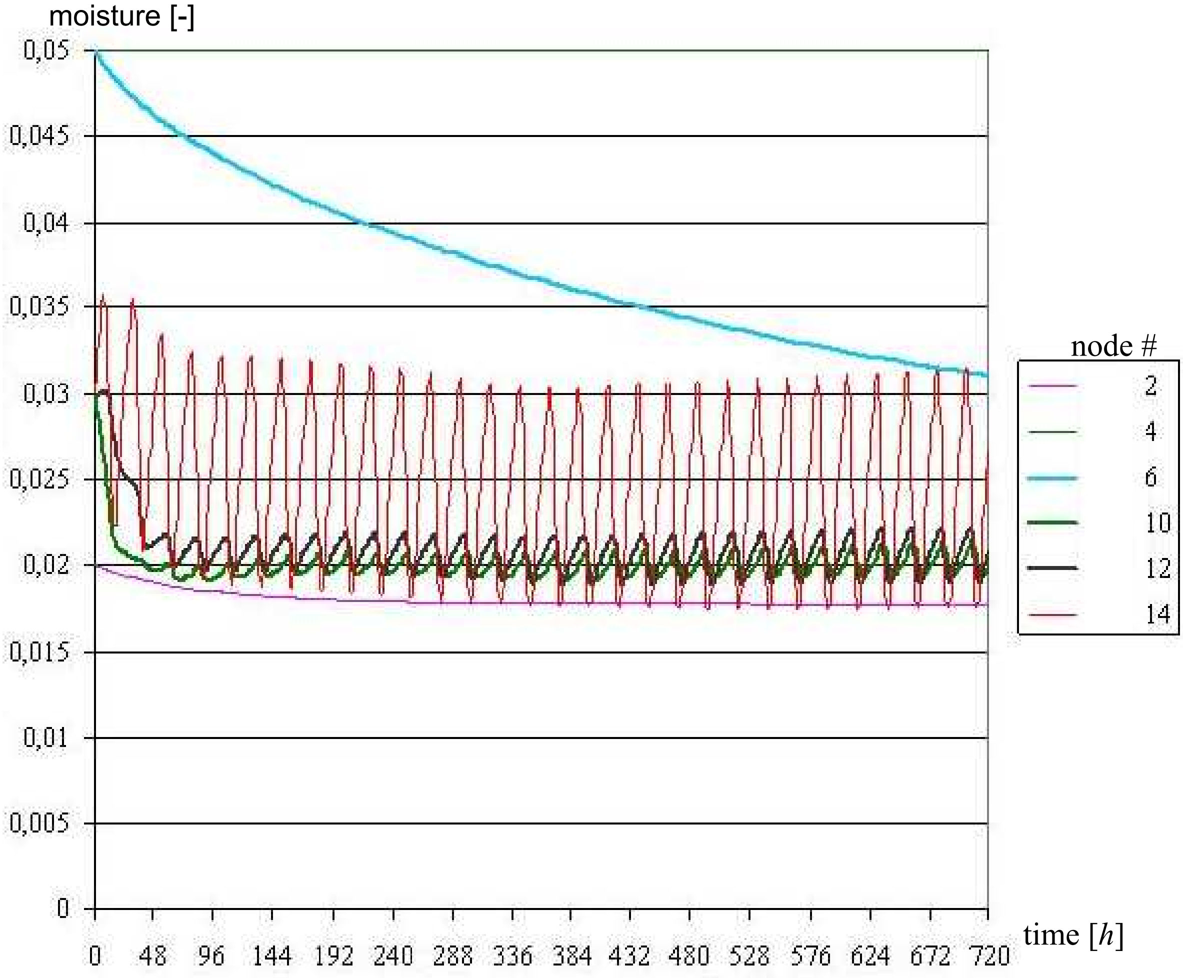

Figure 10: Results of one-dimensional numerical modelling of moisture redistribution in time

For fixed vectors q_v and q_l from (7) and (8), respecting the algebraic inequalities (6), we would be able to calculate u; this forms a good basis for the construction of an iterative numerical procedure. Although some micromechanical studies show that the process of occupying the pore space and its removing by the humidity in various phases in not fully reversible, we shall believe (following [3], p. 185) that there exist some monotone dependence between u and p/p^*, nearly independent of T, called sorption curve; its example is depicted at Fig. 9. By [2], p. 19, the universal gas equation can be adopted to determine u_v from p; this is the last missing information, needed for the evaluation of $u = u_v + u_l$. Applying the method in discretization in time and working (for simplicity) with equidistant time steps h, we are able in any discrete time $t = jh$ with an integer j to evaluate T, taking all values of u and u_l from the preceding time step $(j–1)h$, in practice from the numerical analysis of the equation (3) with corresponding boundary conditions, making use of the finite difference technique. Consequently we can evaluate $u = u_v + u_l$, using the above sketched internal iteration loop. If the redistribution of u or u_l is rather significant, we are able to repeat the calculation of T in the same time step with corrected values of u and u_l , etc. Let us notice that for the evaluation of u from the integral equation (9) the discrete mesh from the finite difference analysis of (3) is always prepared.

Clearly the process of moisture propagation is much slower than that of heat conduction, convection and radiation. Fig. 10 shows some selected results of one-dimensional numerical simulation with the insulation system from Fig. 1. Only the heat and moisture propagation in the direction perpendicular to insulation layers was considered, thus the whole mesh degenerates to the ordered finite set of collinear points. The nodes with higher numbers are closer to the exterior surface of the wall. The quasi-periodic changes of moisture correspond to the day cycles in one summer month (30 days).

CONCLUSIONS

We have demonstrated that the biological damage, characterized by the population of algae, is typical for buildings and structures with the proper exterior insulation. The growing of algae on the coldest places of the facade depends on the presence of liquid water, thus it is conditioned by the process of moisture saturation in insulation layers close to the exterior surface. This process can be (especially in summer) driven by the thermal radiation to the clear night sky.

Only the experimental work, accompanied by the numerical simulation, can result in an advice how to remove or restrict the moisture accumulation in the facade, to avoid such phenomena as those documented at Fig. 2. From the practical point of view there are two approaches: i) adding some pesticides or other special chemicals to the facade coatings, ii) testing the emissivity of coatings and optimizing their choice. Since i) is not very ecological and morover does not remove the moisture at all, ii) should be preferred in incoming projects of reconstructions of building claddings.

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