# MOISTURE TRANSPORT SURV EY

**O. Lebedev[2,3], D. Kirzhanov[2,3], V. Avramenko[2,3] and O. Budadin[1]**

[1]Technological institute of energetic surveys, diagnostic and nondestructive testing "WEMO", Russia, Moscow, 113162, Lusinovskaya street, 62, phone: +7(095) 237-72-88, fax:+7(095) 237-64-57
[2]Mechanical Engineering Institute of the Russian Academy of Sciences, M. Kharitonjevskij st. 4, 101990, Moscow, Russia
[3]Department of Physics, Moscow State University, Leninskye gory, Moscow, 119992, Russia Phone: +7 095 9393669, fax: +7 095 9391104, e-mail: olegleb@gmail.com

## ABSTRACT

Stephan's problem of a freezing front propagation inside a multilayer objects is discussed. For to solve this problem in practice numerical methods are used to integrate moisture and heat transfer equations while calculation of the current frost pane's coordinate inside external multilayer building envelopes whose surfaces' temperatures are measured over a while. When the Stephan's equation integration takes place, the phase transformation is taken into account by means of a sharp jump of the material's specific heat capacity at the point of the phase transformation. Examples of such calculation of the frost pane coordinate dependency of time inside multilayer constructions are presented. An algorithm of the current dew point coordinate determination inside multilayer objects is suggested.

**Keywords:** Thermal nondestructive testing, infrared, building, moisture, dew point, freezing

## INTRODUCTION

The task of the exploration of the liquid-solid phase transformation moisture dynamics conditions for the frost pane creation and movement (or it's defrosting) has a huge practical application area and significance cause it directly refers heat preservation problems, temperature and humidity control, longevity and durability of the considerable constructions. Moreover, the energy, accumulated during the melting, can be extracted at the time of the freezing, leading to a wide specter of heat engineering tasks. Probable application embraces numerous technologies, for example, steeling, soil freezing, thermal control systems for spacecrafts, surface industrial and residential constructions. This solution can be widely adopted in the building industry, where the problem of the current freezing pane location definition plays a significant role. Freezing edge location directly references longevity of the building envelopes. In fact, at the zone of freezing edge propagation extremely unfavorable exploitation conditions for building envelopes materials take place. This can lead to gradual durability reduction of the materials and finally can result in building destruction.

For non-doped materials phase transformation occurs at a fixed temperature causing a string edge between liquid and solid phases, for example when water freezes or a metal solidifies. Contrary to that inside a multicomponent media the phase transformation takes place at a range of the temperatures. In this case solid and liquid phases are separated one from another by means of a transient zone which is characterized by solid substances' specks inside the liquid. Such processes are typical for wax and polymer hardening, food defrosting and so on.

The theoretical analysis of a processes that takes place at the phase transformations means joint solution of the heat conductivity equation for the solid phase and equations for the mass, moment coefficient and energy preservation laws expression for the liquid phase, altogether linked by means of the boundary conditions for the liquid-solid edge. Even the natural convection is not taken into account and one-dimensional approximation is applied liquid-solid phase edge moves continuously and its current location is unknown a priori. One-dimensional approximation does not always adequately describe the process of moisture and heat transition. Solving this task in two- of three-dimensional case leads to bulky calculation complication. Cause to problems enumerated above there is only a limited number of analytical solutions for partially simplified cases and hence numerical methods are often used in practice.

Mathematical model of the liquid freezing processes in porous materials was first presented 1950's by Luikov who considered moisture and heat transition jointly [i].

## THEORETICAL BASICS

Let's formulate the problem of phase division edge propagation as a Stephan's problem within which an aggregative state change occurs at a defined temperature $T_k$ . In other words, there is a strict isothermal bound, devising solid and liquid phase regions. Further let's mark the solidified region's parameters with index '1' and the non-solidified region's parameters with index '2'.

The Stephan's problem for the liquid phase nearly the point of the phase transformation within one-dimensional approximation at the interval $x \in [0,1]$ is formulated this way:

$$\begin{cases} \dfrac{\partial^2 T(x,t)}{\partial x^2} + x x_\kappa(t)\dfrac{dx_\kappa(t)}{dt}\dfrac{\partial T(x,t)}{\partial x} = \\ \quad = x_\kappa^2(t)\dfrac{\partial T(x,t)}{\partial t}, \quad x \in [0,1] \\ x_\kappa(t)\dfrac{dx_\kappa(t)}{dt} = -Ste\dfrac{\partial T(x,t)}{\partial x}, \quad (x = x_k) \end{cases}.$$

Here $T(x,t)$ is the temperature distribution and $x_\kappa$ is the phase transformation edge coordinate. $Ste$ is the Stephan's number $Ste = \dfrac{C_2 \cdot \Delta T_{ref}}{L_y}$ where $C_2$ is the liquid phase heat capacity, $L_y$ – the hidden phase transformation heat and $\Delta T_{ref}$ – the 'reference' temperature [ii].

Object's aggregate state change in general case has two consequences, both influencing the heat mode inside the object: firstly, when the hardening edge moves, the hidden phase transformation heat extracts, secondly, heat engineering characteristics of the material are changed. Both equations for solid and non-solidified regions need to be solved in this case. Besides boundary conditions definition for the surface of the object:

$$\begin{cases} x_k = 0, \quad t \le 0 \\ T = f(t), \quad x = 0, t > 0 \\ T = 0, \quad x = 1, t > 0 \end{cases}.$$

The two conditions have to be defined at the hardening bound: heat balance equation and the temperature equality conditions .

$$\lambda_1 \left.\frac{\partial T}{\partial x}\right|_{x = x_\kappa - 0} - \lambda_2 \left.\frac{\partial T}{\partial x}\right|_{x = x_\kappa + 0} = L_v \frac{dx_\kappa}{dt};$$

$$T_1 \Big|_{x = x_k - 0} = T_2 \Big|_{x = x_k + 0} = T_k .$$

The first term expresses heat flow density $S_1$ which is taken away from the phase transformation edge through the solidified region; and the second term $S_2$ – heat flow density input non-solidified region.

The first part presents heat flow density cause by hidden phase transformation heat extraction. The phase transformation heat density during solidification is expressed by formulae .

$$L_v = wr\rho$$

Here $w$ is the moisture mass portion inside the material, $r$ – phase transformation heat of a unitary moisture mass in the material, $\rho$ – humid material density.

Exact analytical solution of the Stephan's problem is possible only for a limited set of the bodies' shapes and the boundary conditions. Cause to necessity of consideration of complex object with layers heterogeneous by heat engineering parameters and object's temperature and heat emission factor change with time, this problem unlikely has an analytical solution.

For to simplify this problem without significant reliability reduction of the results let's bring in an assumption of a quasi-stationary mode inside the solidified region. Really, the solidification process progresses rather slowly and so through the object's temperature changes, its distribution for every time moment can be considered as steady. The task about phase transformations can be significantly simplified if one admits temperature distribution in the solidified and non-solidified object regions. Because of this problem solution is reduced to the determination of the phase transformation edge coordinate using heat balance equation. At the same time special temperature distribution should be chosen as close to the real multilayer object's distribution as possible.

Because the considerable object's temperature does not equal to 0, as the solidification edge moves, object's enthalpy must change too. Heat flow caused by enthalpy change of the solidified body can be taken into account if one use effective value of phase transformation heat density is substituted into formulae instead it's real value. The effective value is expressed by following:

$$L_v^{eff} = L_v + \frac{C_1 \rho_1 \left( T_k - T_s \right)}{2} .$$

where $T_s$ is the temperature at the external body's surface.

Exact analytical solutions of the Stephan's problem presented at [iii] shows that approximate solutions based on non-steady mode of the solidified region replacement by quasi-steady mode with the  tare correspond to the first, most significant series terms of the temperature distribution at the object, found by means of the analytical solution. For the numerical integration of the Stephan's problem a finite-difference approximation of the heat conductivity equation and Stephan's conditions - have to be used. According to [iv,v] works' authors implicit integration scheme can be used without loss of solution stability. Besides essential calculation simplification such scheme lets raise calculation precision up to $\Delta t^2 + h^4$ by means of appropriate time step $\Delta t$ and coordinate step $h$ selection. As it is shown at the [vi], equality $\frac{a\Delta t}{h^2} = \frac{1}{6}$ (here $a$ is the temperature conduction factor of the object's material) fulfillment is enough to reach this condition.

Let's consider a multilayer wall as the discussed object. The space node $i$ of the wall's layer can be defined at the moment $j+1$ via the temperatures of the nodes with numbers $i-1$, $i$ and $i+1$ at the time moment $j$ as following:

$$T_{i,j+1} = \frac{T_{i-1,j} + 4T_{i,j} + T_{i+1,j}}{6} .$$

Freezing edge propagation can be calculated by a proportion being a finite-difference approximation of the (3) and (4) conditions:

$$\Delta x_{\kappa} = - \frac{\lambda \Delta t}{hw\rho\, r} \left( T_{i-1,j} - 2T_{i,j} + T_{i+1,j} \right) .$$

The (8) formulae analysis showed[iv] that analyzed scheme of the finite-difference approximation of conditions (3) and (4) is not sufficiently effective for to solve nonstationary Stephan's problem in the case of the significant material's heat engineering parameters dependency on temperature.

It is likely to refuse the (3) and (4) conditions and to take into account phase transformation process by means of a sharp jump of the material's heat capacity given by conditions:

$$c(T) = c_0(T) + wr\frac{d\chi}{dT} ,$$

where $\chi$ is the inclusion volume fraction of the humidity inside the media given by the following table values for water-ice phase transformation:

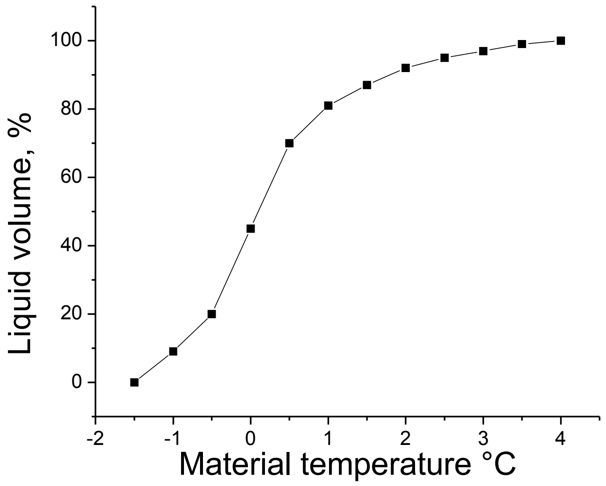

**Fig. 1. Liquid volume fraction dependency on material temperature.**

So, media cooling and freezing process inside a n-layer object is described by a system of one-dimensional equations of nonstationary heat conduction:

$$\rho_m c_m(t)\frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[r\lambda_m(T)\frac{\partial T}{\partial r}\right]$$

$$R_0 < r < R_n,\ t > 0,\ m = 1,..,n$$

This equation set is given in bubble coordinate frame for greater simplicity. When giving the curvature radius significantly greater than the material thickness, the task is reduced to a flat case. The (10) equation set is nonlinear because heat capacity density and heat conductivity factor for each layer can depend on temperature.

At the external (with index ‘ex’) and the internal (with index ‘in’) surfaces of the material a total set of boundary conditions can be given:

1) $\alpha_{in,ex}\left(T_{in,ex} - T\big|_{r=R_{0,n}}\right)$, the Newton’s law of the heat exchange;

2) $q_{in,ex}$, the heat exchange with the given heat flow value;

3) $A^{eff}_{in,ex}\sigma\left(T^4_{in,ex} - T^4\big|_{r=R_{0,n}}\right)$, the Stephan-Bolzman’s heat emission law;

4) $\varepsilon_{in,ex}\sigma T^4_{in,ex}$, the wall surfaces’ proper emission into the outer space.

So the boundary conditions at the external and internal surfaces of the wall are given as following:

$$-\lambda_1\frac{\partial T}{\partial r}\bigg|_{r=R_0} = \alpha_{in}\left(T_{in} - T\big|_{r=R_0}\right) +$$

$$+ A^{eff}_{in}\sigma\left(T^4_{in} - T^4\big|_{r=R_0}\right) + q_{in} - \sigma\varepsilon_{in}T^4\big|_{r=R_0}$$

…

$$\lambda_n\frac{\partial T}{\partial r}\bigg|_{r=R_n} = \alpha_{ex}\left(T_{ex} - T\big|_{r=R_n}\right) +$$

$$+ A^{eff}_{ex}\sigma\left(T^4_{ex} - T^4\big|_{r=R_n}\right) + q_{ex} - \sigma\varepsilon_{ex}T^4\big|_{r=R_n}.$$

At the and boundary conditions convective the heat emission factors $\alpha_{in,ex}$, the media temperatures near the inner and the outer material surfaces $T_{in,ex}$, the heat flow densities $q_{in,ex}$ and the effective radiation parameters' functions (reduces blackness degree of the surfaces and emitting media) $A_{in,ex}^{eff}$ are functions of time.

The contact between layer bounds, whose media has different heat engineering characteristics, considered as an ideal one and this way the following heat junction conditions take place:

$$\lambda_m \left.\frac{\partial T}{\partial r}\right|_{r=R_m-0} = \lambda_{m+1} \left.\frac{\partial T}{\partial r}\right|_{r=R_m+0},$$

$$T\big|_{r=R_m-0} = T\big|_{r=R_m+0}, \quad R_m = \sum_{m=1}^{m} h_m .$$

The conditions and are accompanied with the initial condition

$$T\big|_{t=0} = T_0(r) .$$

At the $t = 0$ moment the space temperature distribution inside the material is given by an unknown function $T(r, t = 0) = f(r)$ which can be constant and equal to some temperature $T_{beg}$.

## DISCUSSION

Let's consider an example of a numerical solution for a problem of a freezing plane placement calculation inside a 4-layer wall with the following parameters:

1. The external layer: brick (120 mm width);
2. The 2nd layer: reinforced concrete (100 mm width);
3. The 3rd layer: expanded polystyrene (200 mm width);
4. The internal layer: reinforced concrete (100 mm width).

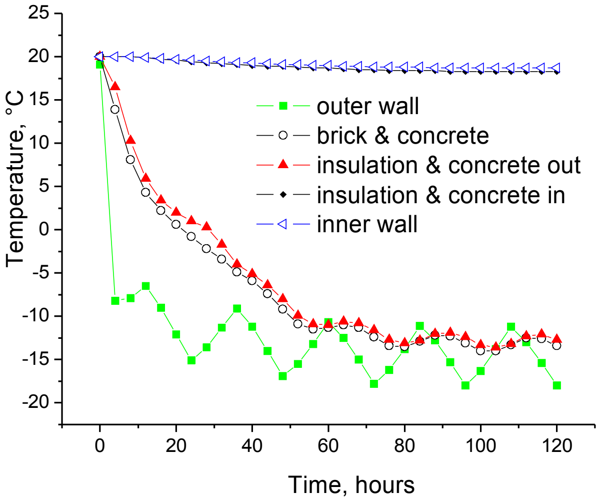

**Fig. 2. The temperature dynamics at the layer bounds for a 4-layer wall.**

The cool environment temperature oscillates with the linear law from -20 °C up to -10 °C during a 24 hour period. The heat emission factor at the external surface equals 23 W/sq. m °K. The warm environment temperature is constant and equals +20 °C. The heat emission factor at the warm surface is 6 W/sq. m °K.

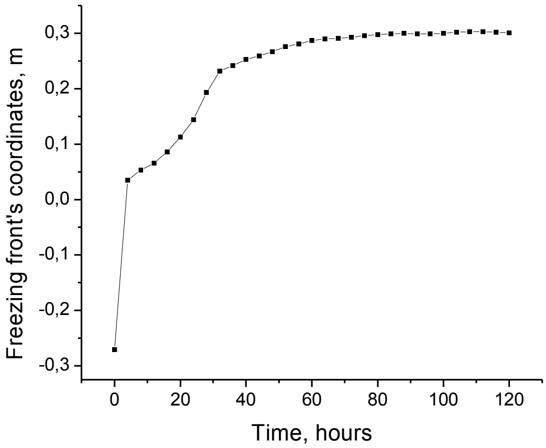

**Fig. 3. The freezing front location dynamics inside a 4-layer wall.**

The initial wall temperature is +20 °C. Calculation results of the wall surfaces' temperatures and the layers' bounds' temperatures dependencies on time are presented at the fig. 2. The freezing edge coordinate dependency on time is presented at the fig. 3.

Solving the problem of the determination of the freezing edge location inside multilayer constructions directly references the problem of dew point coordinate determination.

The dew point is the temperature at which the referential air humidity becomes equal 100 %. If the temperature at the heat insulator' surface (or the temperature of the inner surface of the wall) of a multilayer construction is higher than the dew point, the condensate formation would not occur.

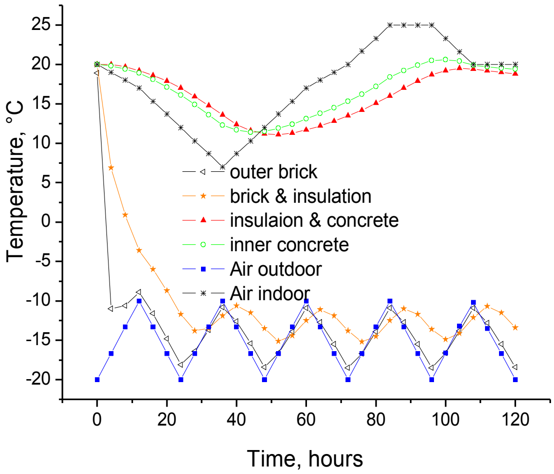

**Fig. 4 The temperature dependency on time at the layer bounds of a 3-layer wall.**

The monitoring of the current dew point coordinate movement and the timely analysis of the received data can prevent the condensate formation and thus helps to avoid the wall destruction and prevents fungus growth. The last factor is mostly significant in residential structures because of negative influence on people health of fungus colonies.

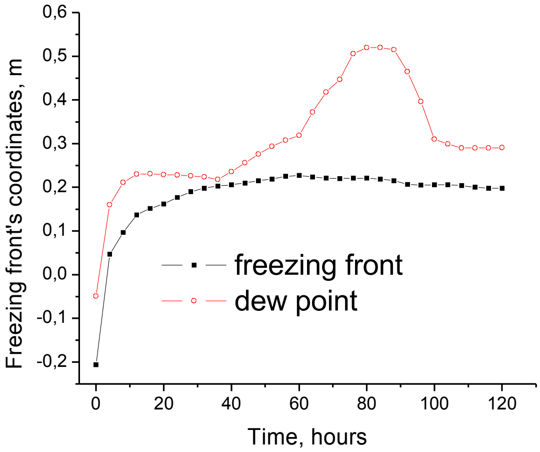

**Fig. 5. The dew point and the freezing position time dynamics inside a 3-layer wall.**

For the determination of the current dew point location inside the building envelopes it is necessary to set the referential humidity of the air indoors.

The calculation algorithm is built the following way:

The saturated vapor pressure is calculated using the corresponding temperature value.

The non-saturated vapor pressure is calculated using the saturated vapor pressure and the referential humidity value.

Taking into account non-saturated vapor pressure value inside the wall the dew point temperature is calculated for each point inside the wall.

The current dew point coordination is determined as the point for which the corresponding temperature value is lower than the dew point.

Let's consider a 3-layer wall with the following structure:

1. The external layer consists of brick (120 mm width).
2. The heat insulation (200 mm width).
3. The internal layer consists of the reinforced concrete (200 mm width).

The outdoors temperature is changed cyclically over a 24 hour period from -20 ºC up to -10 ºC. The inner (warm) temperature changes arbitrarily at the range +8 ºC…+25 ºC. The total process is considered during 5 days.

The calculation results are presented at fig. 4 and fig. 5.

## ALGORITHM AND TECHNOLOGY OF PRACTICE CONTROL

The summary thermal nondestructive testing and diagnostics of a building scheme is represented on fig. 6. The system is based on the complex analysis of the input data of different parameters of environment conditions and the investigated object and the calculation of this data using special model of heat and mass transfer.

The algorithm of the dew point and freeze pane movement analysis inside the buildings' walls is summarized on fig. 7.

The methodic of the diagnostics and the definition of the current position of the dew point and the freezing front of the buildings in practice by thermal nondestructive testing defines the technology and the parameters of the control. The calculation position of the dew point and the freezing front and the report issue with this data are the results of the survey.

The methodic gives the possibility:

to carry out distant temperature and moisture surveys of the buildings real time;

to carry out contact temperature, heat flux, air and material moisture surveys of the local zones of the buildings real time;

to identify the latent defects of the construction and calculate the position of dew point and freezing front of buildings.

using the results of the testing to define the accordance of the building quality to the project documentation and give the recommendations for improvement the building technology.

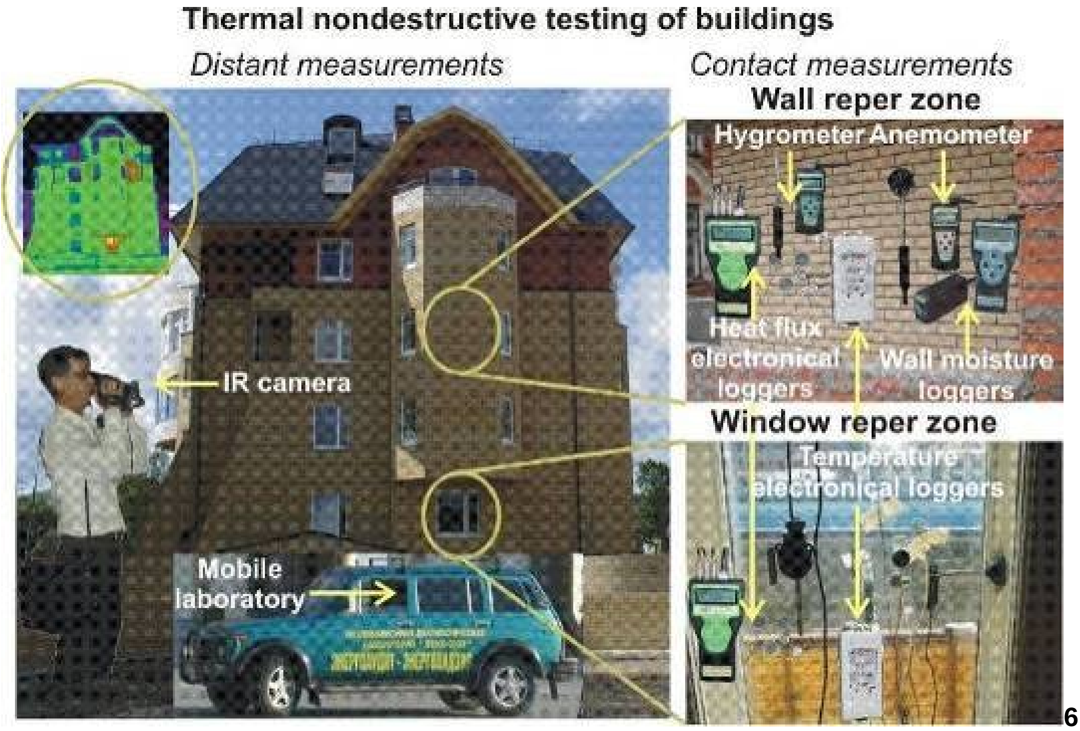

**Fig. 6. Scheme of thermal nondestructive testing and diagnostics of buildings.**

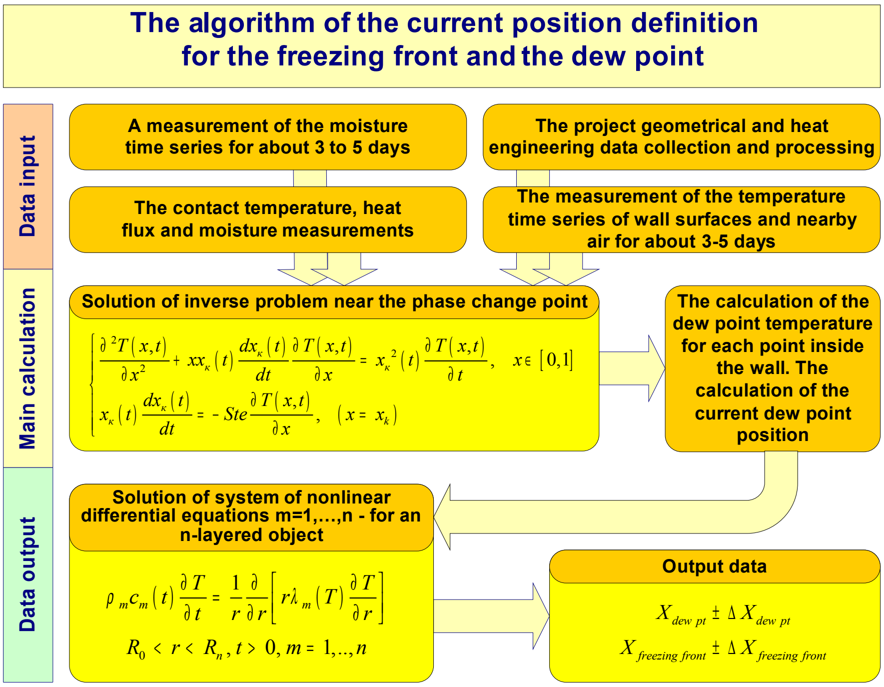

**Fig. 7. Algorithm of thermal nondestructive testing and diagnostics of buildings.**

The survey consists of two parts: an experimental one at which measurements take place and a data processing one. This part includes an IR camera survey and practice measurements of temperature, heat flux, wind velocity and air humidity at the reference zones of the building. In addition the liquid volume fraction in the building wall materials is measured. It the same time the electronical loggers of temperature and air humidity are mounted at the surface of the wall. The obtained experimental data is the input data for further processing by means of physical model. The data processing is based on the qualitative and quantitative analysis of the temperature fields spatial distribution at the buildings' surfaces and other additional parameters of the environment and features of testing processing. Qualitative analysis is used to express visual definition of the temperature anomalies and their analysis. Quantitative analysis is used for estimation of the current position of the freezing front and the dew point of buildings' walls.

## RESULTS OF PRACTICE CONTROL

The aim of this chapter is experimental verification of the adequacy of created method of definition of the current position of dew point and freezing front of the buildings in practice. The verification of the adequacy has been realized using, first, correlation of direct measurements and calculated based on the independent experimental results. And second it is tested using on the correlation between visual observations and calculated results of the current position of dew point.

The object under investigation is the 8th floor residential construction. The wall is the brick with the thickness 900 mm. The projected thermal resistance is 1.3 sq. m °C/W. The average temperature difference between indoor and outdoor air is 20 °C. In the reference zone the temperature of outdoor air is 0.2 °C, the temperature of indoor air is 18.0 °C.

The qualitative analysis of the of the building's IR images (fig. 8) shows that the temperature field distribution is uniform except the butt wall, especially at its last floor. According to this conclusion the reference zone been chosen on the last floor of the butt wall.

**Fig. 8. Outdoor IR images of building.**

Visual examination of the corresponding apartment's walls reveals some defects, e.g. spots of local moisture accumulation near the ceiling (fig. 9, left panel), wet walls, wet wallpaper and plaster detachment (fig. 9, right panel).

**Fig. 9. Indoor IR images of the reference zone of building.**

The variable series of the indoor and outdoor air temperature, temperature and heat flux at the inner and outer wall surfaces, air moisture and moisture load of the walls inside the room have been measured in the reference zone.

The measured temperature series are presented at fig. 10. The measured heat flux time series are shown at fig. 11. The data have been collected for about 4 days.

The calculated dew point and freezing front coordinate time dynamics are presented on fig. 12. It can be concluded that during a long period the freezing front was inside the wall and the dew point was sometimes indoors. Such dew point position facilitate to moisture condensation on indoors wall surface. This agrees with the visual and IR observations in the reference zone. So this fact confirms the reliability of the results using created method.

For the additional model verification of the method in the practice it has been created comparison by the direct experimental measurements and by numerical simulations based on independent experimental input data. Experimentally measured and calculated (using heat flux time series) temperature time series are represented in fig. 13. These temperature time series are close to each other with the correlation coefficient 0.94.

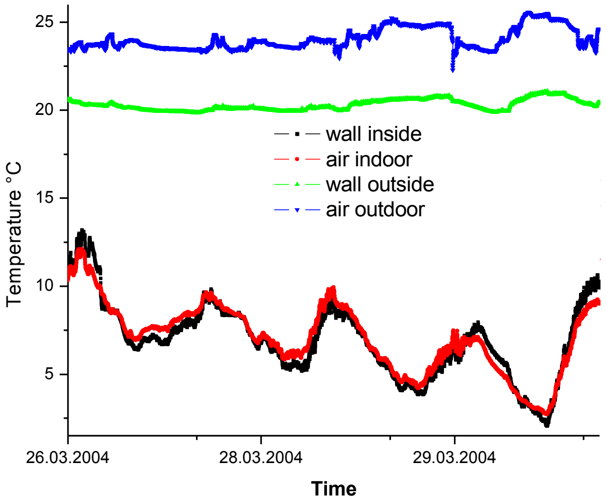

**Fig. 10. Temperature time series.**

The survey does not only state the construction is a damaged one. A defect elimination method the can be proposed for the displacement of the dew point outdoors. The transfer processes inside the wall can be changed locally by means of an installation of a heat-shielding material with calculated geometrical and thermal characteristics. Such installation can correct the heat & moisture balance and solve the problem.

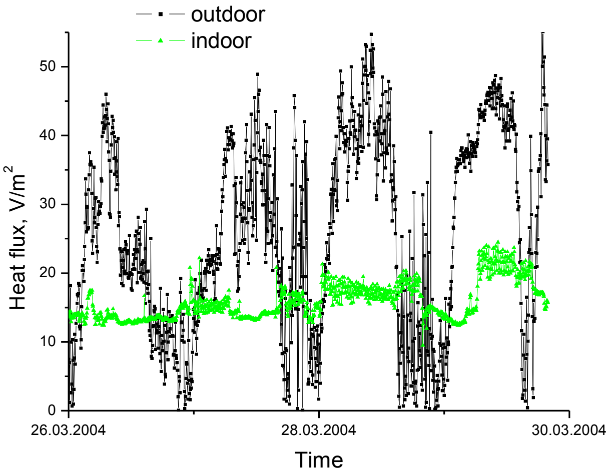

**Fig. 11. Heat flux time series.**

## CONCLUSIONS

Hence it can be stated that the suggested physical model of the freezing front and dew point calculation has been verified experimentally. Within the current article the Stephan's problem of the freezing pane propagation during liquid-solid phase transformations inside multilayer objects is discussed. The analytical solution is possible only for a limited set of bodies' shapes and boundary conditions. In practice for a calculation of the current coordinate of the freezing plane movement inside we consider a multilayer object of materials, heterogeneous by heat engineering characteristics. The dependencies of media temperature and surface heat emission factors on time are also given.

**Fig. 12. Dew point and freezing front coordinate time dynamics.**

The problem is solved numerically and is based on the heat conductivity and moisture transfer equations integration. For to solve this problem of a nonstationary heat conductivity the phase transformation is taken into account by means of a sharp jump of the specific heat capacity of the material near one’s temperature.

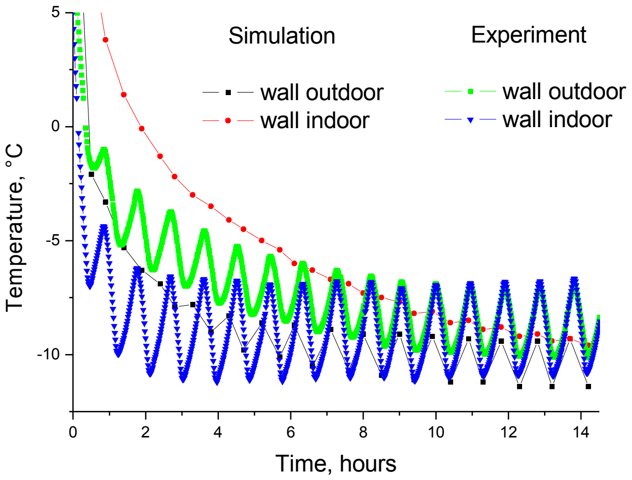

**Fig. 13. The experimentally measured temperature time series and the ones calculated using heat flux time series.**

At the external and internal wall surfaces of the total set of the boundary conditions is given. The examples of the numerical calculations of the freezing pane propagation are given for multilayer constructions. Also an algorithm of current dew point location determination is developed for multilayer objects.

The optimal technology of the current position of freezing front and dew point definition inside a multilayer building envelopes has been created. The main laws of the process have been received and recommendations for the defects elimination and adverse conditions are given. The research is based on the theoretical and experimental investigations and practice of the buildings’ thermal nondestructive testing.

For the survey simplification a PC program with a reporting ability has been created. The program carries out modeling tasks. During the processing thermal and moisture processes inside the multilayered structures are simulated. The program allows calculating the current positions of freezing front and dew point inside a multilayer building envelopes.

The method described above is developed by Technological institute of energetic investigations, diagnostic and nondestructive testing “WEMO”. This method was used for inspection of more than 300 buildings by the Moscow Government request. Corresponding technique have been certified by “State Standard” of Russian Federation and agreed with Department of Power Engineering of Russian Federation and “State City Technical Supervision”.

## REFERENCES

[i] Luikov A.V., Pergamon, Oxford, 1966, Heat and Mass Transfer in Capillary Porous Bodies.

[ii] Yao L.S., Prusa J., 1989, Melting and freezing, Adv. Heat Transfer 19, pp.1–95.

[iii] Pehovich A.I., Zhidkih V.M., 1976, Calculation of the thermal conditions of the solids, 352 pp.

[iv] Parfentieva N.A., Samarin O.D., 2002, About the oscillations of the freezing front in the enclosures and the Stefan problem calculation, Construction materials, the equipment, technologies of XXI century.-№11, pp.46-47.

[v] Prusakov G.M., 1993, Mathematical models by PC calculation, pp.144.

[vi] Leontiev A.I., 1979, Heat-mass exchange theory, pp.495.