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COMPUTATIONAL THERMOGRAPHY: NUMERICAL MODELING OF THE THERMAL REGIMES OF BUILDING STRUCTURES

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We consider numerical methods of simulating thermal regimes of building structures that make it possible to create optimum structures as regards power consumption by using more accurate calculations than those available in existing construction specifications and regulations. Possible means of reducing energy expenditures for formation of an optimum microclimate in living quarters are described.

At the present time ecological problems have become very pressing for the Republic of Belarus and require immediate solution. One of these, which arose as a result of the rapid development of power engineering, is associated with the increase in the content of carbon dioxide in the atmosphere attributed to the combustion of fossil fuels (on the average 2.15 thousand tons of carbon dioxide is released annually per 1 MW of the installed capacity of a heat and electric power plant). Radiative properties of emissions are responsible for the appearance of the greenhouse effect in the earth's atmosphere. The continuing growth in power consumption is largely dictated by the use of intensive technologies in industry and by appreciable expenditures of energy for public and household services, with the fraction of the latter becoming higher due to a decline in production. Heating, ventilation, and air conditioning for housing facilities in the Republic of Belarus consume up to 43% of the total energy used by public and household services. In 1985 this amounted to 0.65 ton of equivalent fuel per man or 0.042 ton/m^2 of residential accomodation (for comparison, in the U.S. the latter quantity is equal to $\sim$0.03 ton/m^2). Appreciable expenditure of energy occurs not only because of climatic conditions (the heating period lasts from 175 to 200 calendar days), but also because of insufficient (2–4-fold worse than in the U.S.) heat insulation properties of the structures erected. In this case, a typical single-story house loses 20% of its heat through the floor, 25% through the walls, 20% windows, 13% ventilation, and 22% through the roof. A multistory house loses no more than 6% of its heat through the floor, 30% through the windows, 17% through ventilation, 7% through the roof, and 40% through the walls. At the present time, nearly 0.068 ton/m^2 is spent annually for heating, ventilation, and air conditioning of public buildings, 0.19 ton/man for lighting and electric devices, 0.16 ton/man for passenger transport, 0.16 ton/man for cooking [1]. An analysis of consumption of energy resources shows that if the present tendencies persist unchanged, their consumption in Belarus will increase from 5.4 ton/man in 1990 to 6.3 ton/man in 2010.

Evidently one of the ways of reducing energy consumption is its optimization by using advances in econometrics, utilization of the energy of low-potential heat sources, and development of alternative, ecologically clean sources of electric and thermal energy. According to present-day estimates, realization of the optimum technologies for heating houses would make it possible to reduce energy expenditures in the nonindustrial sphere by 5–20% [2, 3]. Recent investigations showed high efficiency for "passive" technologies for energy saving that use, for example, the heat-accumulating capabilities of houses themselves. In such cases energy expenditures for heating during the winter can be lowered by 30%.

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A most characteristic example is provided by advances made in increasing the quality of heat insulation for windows, since heat insulation for the overwhelming majority of windows is insufficient. Single-layer glazing transmits considerable amounts of heat (a typical value of resistance to heat transfer is $R \cong 0.176\ K \cdot m^2/W$), due to which additional expenditures for sustaining a comfortable temperature levelcomprise 25% of all the expenditures for heating. Windows with double-layer glazing such as "thermopane" (a unit made of two layers of glass with a 6 mm air gap) are more efficient ($R \cong 0.35\ K \cdot m^2/W$). New double-layer multiple glass units with a polymer coating on the inner side of the glass (the radiation coefficient is $\varepsilon \cong 0.01-0.3$) provide a resistance to heat transfer of $R \cong 0.53\ K \cdot m^2/W$, while filling the gap between the the glass with argon gives $R \cong 0.7\ K \cdot m^2/W$. In "superwindows" the space between the glass is evacuated or filled with aerogel, thus ensuring a resistance to heat transfer of $R \cong 1.8\ K \cdot m^2/W$ ($3.3\ K \cdot m^2/W$ for the best specimens with a cost of up to 150% of the cost of ordinary glazing). To lower heat losses in "optimum houses" it is also necessary to improve heat insulation of the outer surfaces of the walls by applying heat-insulating coatings (then the resistance of the walls to heat transfer amounts to $4.2\ K \cdot m^2/W$ at a standard value of $1.9\ K \cdot m^2/W$) [4].

Another example of efficient technical devices for energy saving is heat accumulators that operate on the principle of rapid accumulation of thermal energy in a thermally insulated high-temperature "core," which, in cooling off, maintains a constant temperature (a lower one than that of the core) for a long time on the surface of an air radiator that heats a room. The use of heat pipes with built-in heat flux regulators in such constructions makes it possible to regulate dynamically the microclimate in rooms and substantially reduce nonproductive losses of heat for "overheating" a room when traditional heaters are used. Moreover, when heat "accumulators" are used with electric heaters, they improve the economics and performance in the operation of power networks, since they provide they make it possible to displace the maximum of the consumption of electric energy for heating to night hours and ensure ecologically clean conditions (due to maintenance of the temperature of the heat exchange surface of the heat accumulator at a level of less than 80°C the burn-out of oxygen and the burning of dust are prevented). Simultaneously, expenditures for the creation and operation of lines of district heating are reduced [5].

Analyzing the foregoing facts and existing tendencies in modern civil engineering, we can make the following conclusions:

One can attain high economic efficiency for energy saving technologies in the nonindustrial sphere only by ensuring a high degree of heat insulation of walls, floors, and ceilings and replacing conventional window glazing by two-layer multiple glass units with a polymer coating that reflects thermal radiation. An additional decrease in energy expenditures is possible as a result of forced circulation of warm air in a room by efficient ventilation systems.

In regions with a low residential density (in rural districts) it is economically advisable to use "heat" accumulators with electric heating to heat houses. In this case, the use of heaters that employ heat pipes and heat flux regulators is most promising. Since electric energy for "charging" accumulators can be consumed at night, daytime peak loads on power networks can be decreased considerably.

Installation of economical fluorescent lights with a reflecting coating, use of compact sources of local lighting, and maintenance of the optimum regime of operation of systems for heating, ventilation, and lighting are additional measures that make it possible to decrease the expenditure of electric energy by decreasing overall energy expenditures [6].

For selecting optimum energy-saving measures in constructing new and using existing residential and industrial buildings and optimizing the microclimate and thermal regime of rooms, the authors of the present work developed and investigated a numerical model of a house that implements new algorithms for thermal calculation of enclosing building structures.

There were good reasons for such investigations, since the construction specifications and regulations (SNiP) [7] presently required in the design of buildings and constructions recommend a procedure of heat calculations (of the stationary and dynamic thermal distribution in enclosing structures [8–11]) that is not free from drawbacks, many of which were noted long ago by A. V. Luikov [12].

First of all, this results from insufficient metrological study and from the use of absolete or insufficiently clearly defined terms in the text of the SNiP.

Second, the SNiP incorporate reference data on the thermophysical properties of building materials that were obtained in the range of room temperatures. The extensive use of building materials whose thermophysical properties change greatly with temperature leads to the appearance of errors in heat engineering calculations.

Third, unsteady-state temperature regimes are calculated with the use of terminology from "heat assimilation" theory introduced by O. E. Vlasov, which was criticized with good reason by A. V. Luikov and his pupils as lacking sufficient rigor and substantiation [12, 13]. To calculate multilayered walls by the technique suggested in the SNiP, it is necessary that R $\cong$ 1; for any i-th and j-th layer the ratio $(\lambda_i c_i \gamma_i)^{0.5} (\lambda_j c_j \gamma_j)^{-0.5}$ should be close to unity. Moreover, in physical meaning the quantity "coefficient of heat assimilation of a material" S (which characterizes the thermal inertia of the material) is determined only for a homogeneous material of a one-layer wall with a harmonic law of change of the external temperature:

$$S = (\lambda c \rho \omega)^{-1} = c\rho \, (aw)^{-1} . \tag{1}$$

Therefore, it is possible to state that for real conditions (multilayer walls and a nonharmonic character of the change in external conditions) calculations made by the technique of the SNiP are of the nature of estimates.

Moreover, the information contained in the SNiP has not been systematized and requires the use of additional literature for performing calculations [14]. As a result, this technique for calculations is admissible only for a limited number of materials under stationary "typical" conditions. Criticism is also engendered by the fact that the presence of air layers in real multilayer structures and the heat capacity and "thermal inertia" of the internal structures of a building are also not taken into account, although they may be sufficiently massive to play the role of a kind of "passive accumulator," making it possible to decrease expenditures for heating rooms.

In the opinion of the present authors, an alternative approach is to convert from the simplest empirical relations to the use of numerical models of unsteady-state thermal processes in the SNiP, since by now the necessary computing technique (personal computers) has come to be used extensively by design and building organizations, and modern numerical methods make it possible to perform calculations of the thermal regimes of buildings with high accuracy.

In conducting numerical modeling, the present authors used difference equations of energy balance in a one-dimensional formulation. After input of information on the thermophysical characteristics of all the materials used in building the structure investigated, a time step for the calculations was selected that was fairly small compared to the duration of the process (periodic heating-cooling of the structure during 24 hours, etc.). Then, geometric dimensions and boundary conditions were determined for each room for identical multilayered walls (external enclosing structures, internal walls, floors, ceilings, fillings of openings) that enclose the room, and an iterative cycle was performed that consisted in calculation of the nonstationary temperature distribution in all of the multilayered walls with account for the well-known law of change of the parameters of the atmosphere on the outer sides of the walls. After determination of the inner surface temperature of the walls, the heat flux "into" the room from each wall was determined and the air temperature in the room was calculated with account for the action of internal heat sources (heaters, equipment, the presence of people). Then, from the known air temperature inside the room and with account for the change in the air temperature on the external surfaces of the walls, a new nonstationary temperature distribution in the wall was calculated (as an initial approximation use was made of the temperature distribution in the multilayered wall obtained in the preceding step), etc.

To determine the nonstationary temperature distribution in multilayered walls, energy balance equations in implicit form were used. It was assumed that for each internal node the energy equation has the form

$$(1 + 2\,\mathrm{Fo})\, T_0^{t+\Delta t} - \mathrm{Fo}\, (T_1^{t+\Delta t} + T_2^{t+\Delta t}) - T_0^t = 0 , \tag{2}$$

where $\mathrm{Fo} = \alpha(\Delta t)/(\Delta x^2)$. For boundary nodes

$$(1 + 2\,\mathrm{Fo})\,(1 + \mathrm{Bi})\, T_0^{t+\Delta t} - 2\,\mathrm{Fo}\, (T_1^{t+\Delta t} + \mathrm{Bi}\, T_\infty) - T_0^t = 0 , \tag{3}$$

where $\mathrm{Bi} = h_c \Delta x / k$.

To calculate convective heat transfer it was assumed that due to the small difference in temperature between the wall T_w and the medium ($T_w = (0.5-3)T_\infty$) the thermophysical properties of the medium change insignificantly, and this permits one to use the Grashof number for determining the value of the heat transfer coefficient for a plane vertical surface of height l under boundary conditions of the first kind (constant temperature). In this case [15–17]

$$\mathrm{Nu} = [0.845 + (0.387\,\mathrm{Ra}_l^{1/6})/(1 + (0.492/\mathrm{Pr})^{9/16})^{8/27}\,]^2\,, \tag{4}$$

$$\mathrm{Ra}_l = \mathrm{Gr}_l\,\mathrm{Pr} = g\beta\,\overline{T}\,l^3\nu^{-2}\,\mathrm{Pr}\,, \tag{5}$$

with the governing temperature

$$\overline{T} = T_w - 0.38\,(T_w - T_\infty)\,. \tag{6}$$

The coefficient of heat transfer from the surface is determined as

$$h_c = \mathrm{Nu}\,\lambda\,l^{-1}\,, \tag{7}$$

accurate to 5–7%.

For surfaces with boundary conditions of the second kind (a constant flux q), the modified number was used:

$$\mathrm{Gr}_l = g\beta\,q\,l^4\nu^{-2}\lambda^{-1}\,. \tag{8}$$

For horizontal surfaces of area s that face upward, the characteristic temperature is determined by the expression $\overline{T} = 0.5(T_w - T_\infty)$, and the characteristic length is $l = s/p$.

The value of Nu averaged over the surface is determined as a function of on the value of the Rayleigh number

$$\text{at}\quad \mathrm{Ra}_l = 1\ldots 200 \quad \overline{\mathrm{Nu}} = 0.96\,\mathrm{Ra}_l^{1/6}\,,$$

$$\text{at}\quad \mathrm{Ra}_l = 200\ldots 8\cdot 10^6 \quad \overline{\mathrm{Nu}} = 0.54\,\mathrm{Ra}_l^{1/4}\,,$$

$$\text{at}\quad \mathrm{Ra}_l = 8\cdot 10^6\ldots 3\cdot 10^{10} \quad \overline{\mathrm{Nu}} = 0.15\,\mathrm{Ra}_l^{1/3}\,.$$

For central and edge regions, respectively,

$$\mathrm{Nu}_{max} = 0.120\cdot \mathrm{Gr}_x^{1/3}\,, \quad \mathrm{Nu}_{min} = 0.465\cdot \mathrm{Gr}_x^{1/5}\,. \tag{9}$$

When a surface faced downward, its characteristic size was taken to be equal to the width of the surface (i.e., to the minimum dimension for a rectangular surface) and the mean value of the heat transfer coefficient was determined in accordance with [18] at $\overline{\mathrm{Nu}} = 3.88 + 0.077\cdot \mathrm{Gr}_l^{1/3}$. Within the range $\mathrm{Gr}_l = 1-5\cdot 10^7$, the accuracy of the calculations amounted to 5%.

The value of the convective heat flux from a plane external surface immersed in a laminar air flow with the temperature T_∞ per unit area [18] is

$$q/s = 0.33kx^{-1}\,\mathrm{Re}_x^{0.5}\,\mathrm{Pr}^{0.33}\,(T_\infty - T_s) = 0.33\mathrm{Nu}_x\,kx^{-1}\,(T_\infty - T_s)\,, \tag{10}$$

and the local value of the Nusselt number corresponds to the combination

$$\mathrm{Nu}_x = 0.33\,\mathrm{Re}_x^{0.5}\,\mathrm{Pr}^{0.33}\,, \tag{11}$$

where $\mathrm{Re}_L = \rho v_\infty l \mu^{-1}$.

In the case of turbulent flow, the mean heat transfer coefficient of a plane surface of length l can be determined as $\mathrm{Nu}_L = 0.036\mathrm{Pr}^{0.33}\mathrm{Re}_L^{0.8}$.

Use of the foregoing relations in the calculations instead of tabulated values recommended in the SNiP makes it possible to increase considerably the accuracy of the calculations and reduce nonproductive expenditures of materials and energy in construction and operation of buildings.

NOTATION

R, thermal resistance to heat transfer; λ_i, thermal conductivity; c_i, heat capacity; γ_i, moisture content; i, number of a layer; S, thermal inertia of the material; ρ, density of the substance; ω, frequency of harmonic vibrations; t, time; Fo, Fourier number; α, thermal diffusivity; Δt, time step; Δx, spatial step; Bi, Biot number; h_c, coefficient of convective heat transfer; k, thermal conductivity; T_∞, ambient temperature; T_w, wall temperature; Nu, Nusselt number; Ra_l, Rayleigh number; Gr_l, Grashof number; Pr, Prandtl number; g, free fall acceleration; β, coefficient of thermal volumetric expansion of air; l, characteristic length; ν, coefficient of kinematic viscosity of air; $\overline{T}$, determining temperature; λ, thermal conductivity of the material; q, heat flux; s, area of the heat transfer surface; p, perimeter of the heat transfer surface; v_∞, free stream velocity; μ, air viscosity.

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