Buildings energy consumption modeling methods

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Abstract. The tasks of improving energy efficiency are one of the main parts of the project in the process of its implementation. The present paper discusses methods of mathematical modeling of heat transferring processes taking into account climatic factors of the city of Turkestan of the Republic of Kazakhstan. Using a one-dimensional model of the equations of heat conduction, a nonlinear equation is compiled regarding the temperature of the material on an open surface. Methods for solving the nonlinear equation are applied, numerical calculations are carried out. The accuracy of the obtained mathematical methods should increase with the use of computer modeling and the improvement of mathematical devices of calculations, which requires further study of the obtained calculations. The results of numerical calculations are presented in graphical form. The analysis of various modeling methods helps in choosing the right solutions for a particular case. Nowadays, environmental problems, climate change, more than ever, require modern tools and technologies to improve the energy efficiency of buildings, such as energy modeling, mathematical modeling of the microclimate.

Key words: heat transferring, BEM, big data, numerical methods, program, energy consumption analysis.

1 Introduction

An imperative prerequisite for modern designing is the creation and maintenance of favorable conditions for a person in the premises [1]. Without building a three-dimensional model, the issues of optimal heat transfer control are erroneous [2].

Solar radiation is one of the main factors affecting the thermal regime of a building. The introduction of an intelligent heat consumption management system improves energy efficiency while maintaining optimal indoor climate conditions [2].

BEM (Building Energy Modeling) – modeling the energy consumption of a building. This is a series of engineering calculations that allows to predict energy consumption throughout the year, as a result, to predict the payback of design decisions. To model the energy consumption of a building, a mathematical model is required [3,4].

The mathematical model will describe its operation in conditions as close to real as possible, but only if the four main groups of factors are correctly taken into account: weather data, the geometry of the building and its surroundings, internal parameters and models of systems and equipment [5,6].

Modern sciences and technologies have a great practical importance in the energy sector and in industrial technological processes. For example, the calculation of building envelopes under environmental conditions. This technology is of particular interest [7].

Input data:
\begin{itemize}
  \item object of study: residential building;
\end{itemize}
• study period: February;
• location of the object of study: Turkestan city.

Modeling was carried out under insolation conditions characteristic of Turkestan. Vertical surfaces of different spatial orientations are characterized by the following values of the daily average surface density of solar radiation flux:
- South – 2214.29 W·h/m²;
- West – 892.85 W·h/m²;
- East – 892.85 W·h/m²;
- North – 428.57 W·h/m².

The heat input from solar radiation was chosen as the main disturbing factor. Other weather conditions are characterized by constant values:
- outdoor air temperature \( T_{out} = -21 \)°C;
- wind speed \( v = 5.2 \) m/s;
- wind direction – from North to South.

2 Materials and methods

The mathematical model of heat transfer due to conductivity is the following heat transfer equation [7]:

\[
pC \frac{dT}{dt} - \nabla \cdot (k \nabla T) = Q,
\]

where \( T \) – temperature; \( p \)– density; \( C \) – heat capacity; \( k \) – coefficient of thermal conductivity; \( Q \) – absorbed heat.

For a stationary problem, the temperature does not change in time and the first term disappears. In the case of heat flux entering the system, the condition has the form:

\[
\vec{n} \cdot (k \nabla T) = q_0 + h(T_{int} - T) + C_{const}(T_{amb}^4 - T^4),
\]

where the right side characterizes the heat flux that the system exchanges with the environment [7].

The term \( C_{const}(T_{amb}^4 - T^4) \) simulates the transfer of heat to the environment by radiation. Here is the temperature of environmental radiation, which may differ from \( T_{inf} \). \( C_{const} \) is the product of the surface emissivity \( \varepsilon \) to the Stefan-Boltzmann constant \( \sigma = 5.669 \times 10^{-8} \text{Wt}/(\text{m}^2 \cdot \text{K}^4) \) with the same dimension as the dimension of the Stefan Boltzmann constant:

\[
C_{const} = \varepsilon \sigma.
\]

In the one-dimensional case, the stationary process of heat transfer is described by the following differential equation [8-10]:

\[
C_p \frac{\partial u}{\partial t} = \frac{\partial}{\partial x} \left( k \frac{\partial u}{\partial x} \right).
\]

If \( u(x,t) = u(x) \), and \( k = \text{const} \), then:

\[
k \frac{d^2 u}{dx^2} = 0.
\]

For Eq. (1), the following boundary conditions are set:

\[
k \frac{du}{dx} \bigg|_{x=0} = h(u - u_\infty) \bigg|_{x=0} + \varepsilon\sigma(u^4 - u_\infty^4),
\]

\[
u \bigg|_{x=t} = \bar{u}.
\]

After some transformations, the following algebraic equation is derived from Eq. (1)-(3):

\[
u(0) + \frac{h}{k} u(0) + \frac{\varepsilon\sigma}{k} u^4(0) = A,
\]

where

\[
A = \bar{u} + \frac{\varepsilon\sigma}{k} u_\infty^4 + \frac{h}{k} u_\infty.
\]

To find the roots of the equation Eq. (8) we introduce the function:

\[
f(y) = \left(1 + \frac{h}{k}\right) y + \frac{\varepsilon\sigma}{k} y^4 - A.
\]
The root of the equation Eq. (10) is determined by the iterative method (Newton's method). A special place in the application of the Newton method is occupied by finding the initial approximation of the iterative method [11-13]. For this, the equation $f'(y) = 0$ is solved and found the root of this equation:

$$\gamma_* = -\left(\frac{k + hl}{4\epsilon_\sigma l}\right)^{\frac{1}{3}} = -\frac{3}{k4\epsilon_\sigma l}.$$  

(11)

Further considerations show that:

$$y_0 = \gamma_* = -\frac{3}{4} (1 + \frac{hl}{k})\sqrt{\frac{k + hl}{k}} - A.$$  

(12)

The method of finding the root $y_k$: to find the root of the equation $f(y) = 0$, we separate the root $y_k$.

Calculating:

$$f(-y_0) = -(1 + \frac{hl}{k})y_* + \frac{\epsilon_\sigma l}{k}y_*^4 - A = -2(1 + \frac{hl}{k})y_* + \left(1 + \frac{hl}{k}\right)y_* + \frac{\epsilon_\sigma l}{k}y_*^4 - A = -2\left(1 + \frac{hl}{k}\right)y_* > 0.$$  

(13)

The last inequality indicates that the root $y_k$ lies on the interval $(0, -y_*]$. The second derivative of the function $f(y)$:

$$f''(y) = \frac{12\epsilon_\sigma l}{k}y^2 > 0.$$  

(14)

I.e. the graph of the function $f(y)$ is concave. As the initial approximation of the function, we take $y_0 = -\gamma_*$. Because at this point $f(-\gamma_*) < f''(\gamma_*) > 0$.

Newton's method for the equations $f(y) = 0$ is written as:

$$y_{n+1} = y_n - \frac{f(y_n)}{f'(y_n)}, n = 0,1,...$$  

(15)

The dependence of the number of iterations on the accuracy is monotonic.

The finite element method is widely used to solve heat transfer problems. Thus, numerical methods are generally applied in the following cases:

- to obtain approximate solutions of equations that cannot be solved analytically;
- to obtain a simple solution in case of a large number of different conditions;
- to verify the correctness of the analytical solution.

The finite difference method is a well-known and simplest interpolation method. Its essence lies in replacing the differential coefficients of the equation with difference coefficients, which allows us to reduce the solution of the differential equation to the solution of its difference analogue, i.e., to construct its finite-difference scheme [14, 15].

In an ordinary differential equation:

$$u'(x) = 3u(x + 2),$$  

(16)

by replacing the derivative with a finite difference:

$$\frac{u(x + \Delta x) - u(x)}{\Delta x} \approx u'(x),$$  

(17)

where $\Delta x$ – increment in $x$, we get the approximated form:

$$u(x + \Delta x) = u(x) + \Delta x(3u(x) + 2).$$  

(18)

The last expression is called the finite-difference equation, and its solution corresponds to the approximate solution of the initial differential equation. Given $u(x)$, starting from the first point $x = 0$ under the initial condition, when $u(0) = 0$ the values at the next point $u(x + h)$ and so on.

3 Results and discussion

Modeling can be carried out using partial differential equations using the Matlab package.

Obviously, in the framework of one article it is impossible to describe all current existing methods for modeling the energy efficiency of buildings [16, 17]. In further studies, it is planned to use one of the various modern methods of working with big data of neural networks in the Matlab software.
package, as applied to the heat transfer process based on mathematical modeling. As it's known, neural networks are frequently used to create models for forecasting, as well as a kind of deep learning [18-21].

Studies of insolation processes characteristic of the winter (February) conditions of Turkestan city were carried out. Mathematical simulation results are presented. The obtained mathematical methods made it possible to study the processes of heat exchange with the environment.

In a basis of the mathematical model of the stationary process of heat transfer in a homogeneous material, a nonlinear algebraic equation is compiled regarding the temperature of the material on an open surface. A study of the algebraic equation, as a result of which the root of the equation is separated. Numerical calculations are carried out. Calculations show that the Newton method gives good convergence.

Hence, the continuation of work at the present time should be expanded and aimed at finding effective business models.

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