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V. V. BILIAIEVA[1*], S. A. SHCHERBYNA[2]

[1*]Dep. of Energy Systems and Energy Management, Ukrainian State University of Science and Technologies, SEI DMI, Nauky Ave., 4, Dnipro, Ukraine, 49010, tel. +38 (095) 101 19 78, e-mail vikabelyaeva604@gmail.com, ORCID 0000-0003-2399-3124
[2]Dep. of Energy Systems and Energy Management, Ukrainian State University of Science and Technologies, SEI DMI, Nauky Ave., 4, Dnipro, Ukraine, 49010, tel. +38 (050) 362 77 89, e-mail s.a.shcherbyna@gmail.com, ORCID 0009-0004-7593-8631

Numerical Models in Applied Problems of Heat and Mass Transfer

Purpose. The problems of farm ventilation, prediction of CO concentration fields inside farms, prediction of artificial soil heating in greenhouses are considered. To solve a complex of such problems, it is necessary to have specialized mathematical models, oriented towards users in design organizations. Development of numerical models for solving heat and mass transfer problems for agricultural facilities (farms, greenhouses). **Methodology.** To solve the problem of ventilation of the working room (determination of the air flow velocity field in the room), a mathematical model of the motion of a vortex-free flow of an inviscid fluid (Laplace equation for the velocity potential) is used. Numerical integration of the modeling equation is carried out using two schemes: a locally one-dimensional scheme and a conditional approximation scheme. The G. Marchuk model is used to model the mass transfer process. Splitting schemes are used for numerical integration of the modeling equation. Two numerical models are built to analyze thermal fields in a stationary environment: a two-dimensional energy equation and a one-dimensional energy equation. Two difference schemes are used for numerical integration of the two-dimensional energy equation: a conditional approximation scheme and an explicit finite-difference scheme. An implicit splitting scheme is used to solve the one-dimensional energy equation. **Findings.** The software implementation of the developed numerical models has been carried out. The results of computational experiments are presented. **Originality.** Effective mathematical models and computer codes have been developed for solving problems of aerodynamics and mass transfer in the working space, as well as the process of heat conduction in a stationary environment. The created numerical models belong to the class of "diagnostic models", that is, computer codes that implement the developed numerical models make it possible to quickly obtain estimated data on thermal or concentration fields in the study area. **Practical value.** The created computer codes can be used to analyze thermal and concentration fields in agricultural premises (greenhouses, farms) to analyze the efficiency of energy systems and ensure the necessary ventilation and heating modes of the environment.

Key words: heat and mass transfer; soil heating; room ventilation; energy saving; mathematical modeling

Introduction

Heat supply of agricultural facilities is a very important task. Heat must provide the necessary air conditions on farms, small enterprises engaged in the processing of agricultural products, in greenhouses. Thanks to economical, resource-saving heating modes, it is possible to reduce the cost of many types of agricultural products. When considering the problems of this class, two classes of tasks can be distinguished - this is the task of ventilation of working premises, in order to remove harmful substances contained in the air of premises, as well as artificial heating of the soil in greenhouses. Ventilation of agricultural premises is a complex task, as it is necessary to take into account a significant number of factors that affect the formation of concentration fields of harmful substances. To ensure the required air quality in working premises, at the stage of designing the ventilation system, it is necessary to have specialized mathematical models.

For successful plant growth in cultivation facilities, especially during the cold season, it is very important to maintain a stable temperature [2, 6–11]. Insufficient heat supply can lead to a slowdown and reduction in growth.

To scientifically substantiate the parameters of the greenhouse heating system, it is necessary to solve a set of important problems. Particularly important problems include the problem of rational heating of the soil in the greenhouse [11]. This is due to the fact that the root system of plants must be in a certain temperature range. Maintaining this temperature range allows for a positive impact on yield. On the other hand, a rational mode of heating the soil in the greenhouse allows for a reduction in the energy consumption of the enterprise

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and a reduction in the cost of production. To substantiate the heating mode, it is necessary to have special mathematical models and calculation methods. In this regard, an important scientific problem is the development of methods for calculating the multifactor process of soil heating for choosing an energy-saving heating mode.

Purpose

Development of numerical models for solving heat and mass transfer problems for agricultural facilities (farms, greenhouses).

Methodology

When solving heat and mass transfer problems, it is necessary to determine two possible scenarios:

1. Scenario № 1: heat transfer (mass transfer) process in the absence of medium movement – for example, heating of soil in greenhouses with artificial heating.

2. Scenario № 2: the process of heat transfer (mass transfer) in a moving medium – for example, artificial heating of air in greenhouses.

Therefore, when developing numerical models for the second scenario, it is necessary to add hydroaerodynamic equations to the modeling equations of heat and mass transfer. Let us consider the modeling equations for solving problems of this class. It should be emphasized that hydrodynamic models are the foundation for creating methods for calculating ventilation of agricultural premises.

Hydroaerodynamics model. To describe the motion of an air or liquid medium, it is proposed to use an inviscid fluid model. If the vortex process is neglected, the modeling equation has the form:

$$\frac{\partial P^2}{\partial x^2}+\frac{\partial P^2}{\partial y^2}=0. \qquad (1)$$

where P – speed potential.

The components of the air flow velocity vector are related to the velocity potential by the following dependencies:

$$u=\frac{\partial P}{\partial x}, v=\frac{\partial P}{\partial y}.$$

The boundary conditions for equation (1) are considered in the works of Loytsyansky.

For the numerical solution of the modeling equation (1), the method of establishing the solution in time is used. To use this method, the equation for the velocity potential is reduced to an «evolutionary» form:

$$\frac{\partial P}{\partial t}=\frac{\partial^2 P}{\partial x^2}+\frac{\partial^2 P}{\partial y^2}, \qquad (2)$$

where t – fictitious time.

Next, a locally one-dimensional difference scheme is constructed. For this, the coordinate splitting of the equation (2) is carried out:

$$\frac{\partial P}{\partial t}=\frac{\partial^2 P}{\partial x^2}, \qquad (3)$$

$$\frac{\partial P}{\partial t}=\frac{\partial^2 P}{\partial y^2}. \qquad (4)$$

Next, a finite-difference scheme is constructed for equations (3) and (4):

$$P_{i,j}^{n+1}=P_{i,j}^{n}+Vt\frac{P_{i+1,j}^{n}-P_{i,j}^{n}}{\Delta x^2}+Vt\frac{-P_{i,j}^{n}+P_{i-1,j}^{n}}{\Delta x^2}. \qquad (5)$$

$$P_{i,j}^{n+1}=P_{i,j}^{n}+Vt\frac{P_{i,j+1}^{n}-P_{i,j}^{n}}{\Delta y^2}+Vt\frac{-P_{i,j}^{n}+P_{i,j-1}^{n}}{\Delta y^2}. \qquad (6)$$

As can be seen, for the numerical integration of equations (3) and (4) an explicit difference scheme is used, which enables simple software implementation of the constructed numerical model.

Cyclic calculation based on dependencies (5), (6) ends when the condition is met:

$$\left|P_{i,j}^{n+1}-P_{i,j}^{n}\right|\le \varepsilon,$$

where ε – small number (for example, $\varepsilon = 0,001$); n – iteration number.

The components of the flow velocity vector are calculated as follows:

$$u_{i,j}=\frac{P_{i,j}-P_{i-1,j}}{\Delta x}, v_{i,j}=\frac{P_{i,j}-P_{i,j-1}}{\Delta y}.$$

When performing calculations based on the finite-difference scheme (5), (6), it is necessary to use a small-time step, which is associated with the stability of the difference schemes. Therefore, another numerical model was constructed to solve equation (2). The difference equations for the numerical solution of equation (2) are as follows:

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$$\frac{P_{i,j}^{n+\frac{1}{2}} - P_{i,j}^{n}}{\Delta t} = \left[\frac{-P_{i,j}^{n+\frac{1}{2}} + P_{i-1,j}^{n+\frac{1}{2}}}{\Delta x^2}\right] + \left[\frac{-P_{i,j}^{n+\frac{1}{2}} + P_{i,j-1}^{n+\frac{1}{2}}}{\Delta y^2}\right],$$

$$\frac{P_{i,j}^{n+1} - P_{i,j}^{n+\frac{1}{2}}}{\Delta t} = \left[\frac{P_{i+1,j}^{n+1} - P_{i,j}^{n+1}}{\Delta x^2}\right] + \left[\frac{P_{i,j+1}^{n+1} - P_{i,j}^{n+1}}{\Delta y^2}\right].$$

This difference scheme is absolutely stable and allows for simple software implementation.

The considered mathematical models were developed for truss ventilation problems.

Mass transfer model. To solve the problem of mass transfer in a moving medium, the following equation is used (G. Marchuk's model):

$$\frac{\partial C}{\partial t} + \frac{\partial uC}{\partial x} + \frac{\partial vC}{\partial y} = \frac{\partial}{\partial x}\left(\mu_x \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu_y \frac{\partial C}{\partial y}\right) + Q_i\delta(x - x_i)\delta(y - y_i), \quad (7)$$

where C – impurity concentration in a moving medium; u, v – components of the flow velocity vector; t – time; μ_x, μ_y – diffusion coefficients; $\delta(x_i, y_i)$ – Dirac delta function; Q – intensity of impurity emission into the environment.

The boundary conditions for equation (7) are considered in [3].

The solution of the modeling equation (7) is based on its physical splitting. The splitting is carried out as follows:

$$\frac{\partial C}{\partial t} + \frac{\partial uC}{\partial x} + \frac{\partial vC}{\partial y} = 0, \quad (8)$$

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left(\mu_x \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu_y \frac{\partial C}{\partial y}\right), \quad (9)$$

$$\frac{\partial C}{\partial t} = Q_i\delta(x - x_i)\delta(y - y_i). \quad (10)$$

The numerical solution of equation (8) is carried out using the alternating triangular finite-difference scheme. The solution of equation (9) is carried out numerically using the method of A.A. Samarsky.

To solve equation (10), the Euler method is used.

This model, together with the developed numerical aerodynamic model, is focused on predicting *CO* levels on farms (*CO* emissions from animals).

Heat and mass transfer model. In the absence of medium movement, the process of heat conduction within the medium is modeled by the following equation [1, 5]:

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(a_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(a_y \frac{\partial T}{\partial y}\right), \quad (11)$$

where T – environment temperature; $a = \left(a_x, a_y\right)$ – known thermal conductivity coefficients; x, y – Cartesian coordinates; t – time.

To solve equation (11), the following boundary conditions can most often be set: a «thermally insulated» boundary, a boundary condition of the first kind – a known temperature value at the boundary; a boundary condition of the second kind – a known heat flux at the boundary. For the time t = 0, a known temperature distribution in the calculation domain is given.

Two difference schemes are used for numerical integration. The first difference scheme is the explicit scheme [4]:

$$T_{i,j}^{n+1} = T_{i,j}^{n} + \Delta t \frac{T_{i+1,j}^{n} - 2T_{i,j}^{n} + T_{i,j}^{n}}{\Delta x^2} a_x + \Delta t \frac{T_{i,j+1}^{n} - 2T_{i,j}^{n} + T_{i,j-1}^{n}}{\Delta y^2} a_y.$$

The second scheme is the conditional approximation scheme. This scheme is two-step and has the form [4]:

$$\frac{T_{i,j}^{n+\frac{1}{2}} - T_{i,j}^{n}}{\Delta t} = \left[a_x \frac{-T_{i,j}^{n+\frac{1}{2}} + T_{i-1,j}^{n+\frac{1}{2}}}{\Delta x^2}\right] + \left[a_y \frac{-T_{i,j}^{n+\frac{1}{2}} + T_{i,j-1}^{n+\frac{1}{2}}}{\Delta y^2}\right],$$

$$\frac{T_{i,j}^{n+1} - T_{i,j}^{n+\frac{1}{2}}}{\Delta t} = \left[a_x \frac{T_{i+1,j}^{n+1} - T_{i,j}^{n+1}}{\Delta x^2}\right] + \left[a_y \frac{T_{i,j+1}^{n+1} - T_{i,j}^{n+1}}{\Delta y^2}\right],$$

A feature of the conditional approximation scheme is that the unknown temperature value can be found using an explicit formula. Developed computer code.

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In the case where a one-dimensional heat conduction process is considered, the modeling equation has the form [1, 5]:

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(a \ \frac{\partial T}{\partial x}\right), \qquad (12)$$

where T – soil temperature; a – thermal conductivity coefficient; x – the Cartesian coordinate; t – time.

The boundary conditions for the modeling equation (1) are as follows (Fig. 6):

1. At $x = 0$, the given temperature is $T_s = 20\ ^{\circ}\mathrm{C}$, which is maintained constant (boundary condition of the first kind).

2. At the end of the calculation area, the condition of a «thermally insulated» wall is implemented.

At the initial moment of time, it is assumed that the temperature in the calculation region is known $T_0 = 20\ ^{\circ}\mathrm{C}$.

Numerical models. For numerical integration of the modeling equation (1), a total approximation scheme is used. This scheme has the form of a two-step splitting:

– first step:

$$\frac{T_i^{n+\frac{1}{2}} - T_i^n}{\Delta t} = \left[a_x \frac{-T_i^{n+\frac{1}{2}} + T_{i-1}^{n+\frac{1}{2}}}{\Delta x^2} \right];$$

– second step:

$$\frac{T_i^{n+1} - T_i^{n+\frac{1}{2}}}{\Delta t} = \left[a_x \frac{T_{i+1}^{n+1} - T_i^{n+1}}{\Delta x^2} \right].$$

The unknown temperature value inside the soil at each step of the decomposition is determined by an explicit "running" calculation formula.

The software implementation of the developed mathematical model was carried out, and the «SOIL–1» program was developed.

The developed numerical models are focused on predicting temperatures inside greenhouses, in particular, in the soil of greenhouses during its artificial heating. These models can be used to select an energy-saving mode of artificial soil heating in greenhouses.

For numerical integration of the Laplace equation for the velocity potential, an explicit scheme is used. Equation (2) was reduced to the «nonstationary» form:

$$\frac{\partial P}{\partial t} = \frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2}, \qquad (6)$$

where t – fictitious time.

To conduct computational experiments, a software implementation of the constructed numerical model was carried out in the FORTRAN language.

Findings

The figures below show the solution of two model problems. The first problem is the ventilation of a mini-farm, where three animals are located. Fig. 1 shows the air pollution zone (CO concentration field) during ventilation of the farm. The movement of the air flow is shown by «arrows». It can be seen that the developed numerical model makes it possible to determine the regularities of the formation of pollution areas.

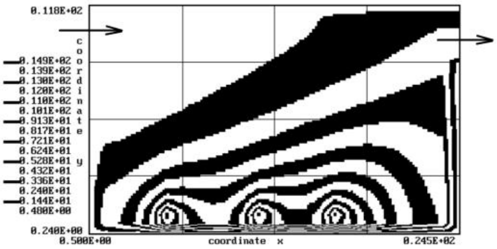

Fig. 1. CO concentration contours centered on mini farms

As can be seen from Fig. 1, pollution areas with a significant gradient of CO concentration are formed near the animals. The pollution areas have the shape of a «circle», which is explained by the fact that where the animals are located, the air flow speed is low, and the formation of the pollution area is greatly influenced by diffusion. The calculation time using the constructed model is 3 s.

Fig. 2 shows the solution to the second model problem – determining the temperature field in the soil (greenhouse) during its artificial heating. Four heating elements are located in the middle of the soil, where a constant temperature of +35 ^{0}C is maintained. The positions of these heating elements are shown by a «circle» in Fig. 2. The temperature field formed under the action of these heating elements is shown in Fig. 2.

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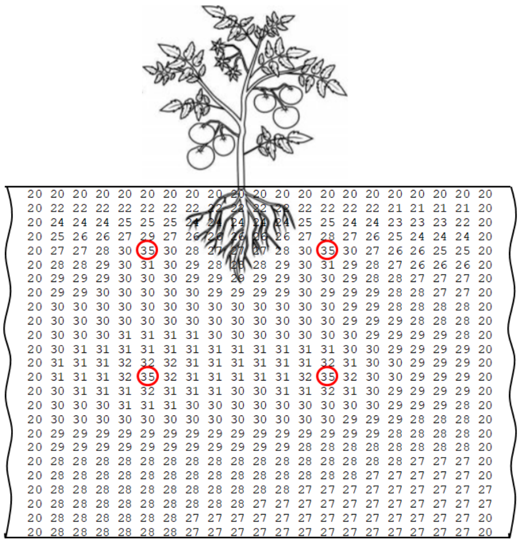

Fig. 2. Temperature field inside the soil during artificial heating

As can be seen from Fig. 2, the use of heating elements allows you to form a temperature field in the area of the root system in the range of 24 ˚C – 26 ˚C.

Note that the calculation time was 3 s.

Originality and practical value

The construction of a complex of numerical models that make it possible to determine the dynamics of heat and mass transfer processes and aerodynamics is considered.

Computer codes have been developed to solve problems of aerodynamics and mass transfer in a working space, as well as the process of heat conduction in a stationary environment.

The created numerical models belong to the class of «diagnostic models», that is, computer codes that implement the developed numerical models make it possible to quickly obtain estimated data related to thermal or concentration fields in the study area.

Conclusions

1. An effective aerodynamic model has been constructed to determine the air flow velocity field in a ventilated room.

2. A numerical mass transfer model has been developed to analyze indoor CO concentration fields.

3. Two numerical models have been developed to analyze the process of artificial soil heating.

4. A computational experiment was conducted, confirming the effectiveness of the developed numerical models.

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В. В. БІЛЯЄВА[1*], С. А. ЩЕРБИНА[2]

[1*]Каф. енергетичних систем та енергоменеджменту, Український державний університет науки і технологій, ННІ ДМІ, пр. Науки, 4, Дніпро, Україна, 49010, тел. +38 (095) 101 19 78, ел. пошта vikabelyaeva604@gmail.com, ORCID 0000-0003-2399-3124
[2]Каф. енергетичних систем та енергоменеджменту, Український державний університет науки і технологій, ННІ ДМІ, пр. Науки, 4, Дніпро, Україна, 49010, тел. +38 (050) 362 77 89, ел. пошта s.a.shcherbyna@gmail.com, ORCID 0009-0004-7593-8631

Чисельні моделі в прикладних задачах тепломасопереносу

Мета. Розглянуто задачі вентиляції ферм, прогнозування концентраційних полів СО всередині ферм, прогнозування штучного нагріву ґрунту в теплицях. Для рішення комплексу таких задач потрібно мати спеціалізовані математичні моделі, орієнтоване на користувачів в проектних організаціях. Розробка чисельних моделей для рішення задач тепломасопереносу для об'єктів сільського господарства (ферми, теплиці). **Методика.** Для рішення задачі вентиляції робочого приміщення (визначення поля швидкості повітряного потоку в приміщенні) використовується математична модель руху безвихрового потоку нев'язкої рідини (рівняння Лапласу для потенціалу швидкості). Чисельне інтегрування моделюючого рівняння здійснюється за допомогою двох схем: локально- одновимірної схеми та схеми умовної апроксимації. Для моделювання процесу масопереносу використовується модель Г. Марчука. Для чисельного інтегрування моделюючого рівняння використовуються схеми розщеплення. Для аналізу теплових полів в нерухомому середовище побудовані дві чисельні моделі: двовимірне рівняння енергії та одновимірне рівняння енергії. Для чисельного інтегрування двовимірного рівняння енергії використовуються дві різницеві схеми: схема умовної апроксимації та явна кінцево-різницева схема. Для рішення одновимірного рівняння енергії використовується неявна схема розщеплення. **Результати.** Здійснена програмна реалізація розроблених чисельних моделей. Наведені результати обчислювальних експериментів. **Наукова новизна.** Розроблені ефективні математичні моделі та комп'ютерні коди для розв'язку задач аеродинаміки та масопереносу в робочому приміщенні, а також процесу теплопровідності в нерухомому середовищі. Створені чисельні моделі відносяться до класу «diagnostic models», тобто, комп'ютерні коди, що реалізують розроблені чисельні моделі, дають можливість оперативно отримати оціночні дані щодо теплових або концентраційних полів в області дослідження. **Практична значимість** Створені комп'ютерні коди можуть бути використані для аналізу теплових та концентраційних полів в сільгосп приміщеннях (теплиці, ферми) для аналізу ефективності роботи енергетичних систем та забезпечення потрібних режимів вентиляції та нагріву середовища.

Ключові слова: тепломасоперенос; нагрівання ґрунту; вентиляція приміщення; енергозбереження; математичне моделювання

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