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Mathematical modeling of carbon dioxide transfer in a local work zone during operation of a radiant heating system

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Abstract. Mathematical modeling of heat transfer and carbon dioxide diffusion processes in a closed room with a working gas infrared emitter and air exchange system was performed. The distribution of CO_2 produced by burning natural gas in the emitter and generated by an additional source was taken into account. Temperature fields, flow lines and CO_2 concentration values were obtained at different air flow rates. The operating parameters of the systems for creating scheduled thermal conditions and air exchange were analyzed.

1 Introduction

Providing the required air temperature in local working areas is possible with the use of a gas infrared emitter (GIE) [1, 2]. The open design of the GIE is more efficient [3, 4]. Due to open combustion, higher temperatures are achieved on the radiating surface of the GIE, thereby increasing the energy emitted by it. But as has already been established [5, 6], there is a need to use an air exchange system to maintain the specified values of CO_2 concentrations in the air emitted during open combustion of gas in the gas emitter.

It was previously established [7] that when the GIE and the air exchange system work together, large-scale circulation flows are formed in the room, which intensively mix the air. At the same time, part of the air heated and contaminated with combustion products (mainly CO_2) from the GIE enters the local working area, increasing the temperature and CO_2 concentration in it.

The use of enclosing structures that prevent CO_2 from entering the local work zone and the removal of warm air from it would allow more efficient use of gas emitters in creating comfortable conditions for workers in local work zones [8]. However, isolating the work zone from the circulation currents in the room leads to the formation of stagnant zones in it. Moreover, if a production process with the release of anthropogenic gas is taking place in the local zone, the use of enclosing structures can lead to a significant increase in the concentration of anthropogenic gas in this zone. Supplying fresh air from the air exchange system with a certain flow rate to such zones would allow maintaining the concentration of CO_2 and the temperature in them at the regulatory level. Studies of the effect of the

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operating conditions of the air exchange system on the air temperature and the concentration of CO_2 in local work zones with a source of anthropogenic gas generation and local enclosing structures during the joint operation of the air exchange system and the gas infrared emitter have not yet been conducted.

The aim of this work is mathematical modeling of heat transfer and diffusion processes of carbon dioxide in a local working area limited by additional enclosing structures in a large-sized room during CO_2 generation by technological processes.

2 Mathematical statement and solution method

The theoretical analysis of heat and mass transfer processes was carried out by numerical modeling. The problem in the conditions under consideration was solved in a two-dimensional formulation (see figure 1).

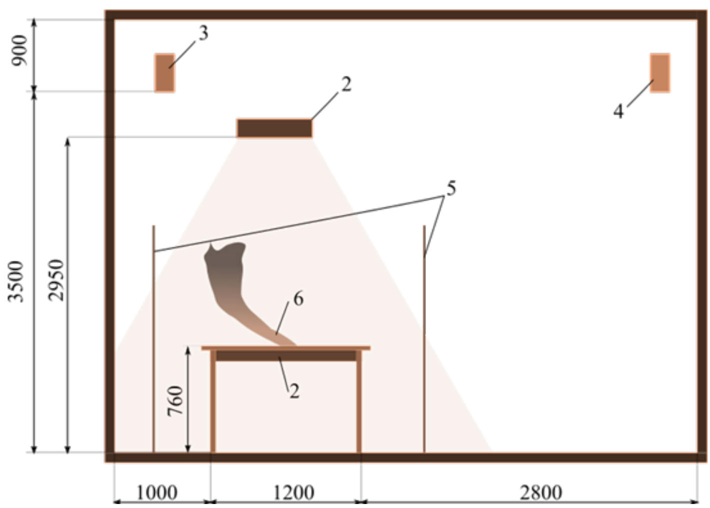


Fig. 1. Solution area: 1 – horizontal panel simulating equipment, 2 – gas infrared emitter, 3, 4 – areas of air inflow and outflow of the air exchange system, respectively, 5 – enclosing structures, 6 – source of anthropogenic gas.

Determination of the main parameters of heat and air mass transfer makes it possible to simulate the formation of the CO_2 concentration field. For this purpose, the assumption of a binary diffusion process in the air – carbon dioxide system is used within the model using Fick's law. Mathematical modeling of the processes of convective-conductive heat transfer and diffusion in the solution area of the problem was carried out using the calculation modules of the COMSOL Multiphysics package: "The Heat Transfer in Fluids Interface", "The Turbulent Flow, k-ε Interface", the module "Transport of Concentrated Species" by the finite element method on a triangular adaptive mesh with a minimum and maximum edge size of 0.00156 m and 0.348 m, respectively. The element sizes were obtained by analyzing the solution for internal convergence. The parameters of the radiative heat flow during modeling of the GIE operation were calculated by the "Surface-to-Surface Radiation" module within the zonal model using average angular coefficients [9]. For the equations of motion, traditional boundary conditions are used: no-slip conditions on solid boundaries, the average flow rate normal velocity component on the injection surface, and the value of the pressure outside the room on the outflow surface. On the gas-solid wall interfaces, conjugation conditions were specified, and due to the small time range, adiabatic conditions were used on the outer surfaces of the solution region. When formulating the heat flow on the interface, the radiation component is taken into account. A steady-state temperature of 800 ºC was set on the radiating lower surface of the GIE. The initial temperature and the temperature of the supply air were taken to be equal to 7 ºC. It is considered that the CO_2 pollution influx is localized on the upper surface of the GIE and in the center of the upper surface of the horizontal panel. The CO_2 influx from the GIE was determined by the power and the used combustible gas and in this case was $3.155 \cdot 10^{-5}$ kg/s. The power of the pollution source in the center of the horizontal panel was taken to be equal to half the flow from the GIE. The impermeability condition is set on the gas-solid wall interface. The level of carbon dioxide pollution upon entering the room corresponds to the initial level in the room (400 ppm), and upon expiration it is taken to be equal to the pollution level in the immediate vicinity of device 4 (Fig. 1).

The main parameters of the room and the GIE were taken to be similar to those used in the authors' previous studies, for example, [7, 8], and corresponded to real objects.

3 Results and discussions

As the analysis of the results of numerical modeling shows, a quasi-stationary hydrodynamic flow pattern is established approximately 40-60 minutes after the start of the heating system operation and is largely determined by the operating parameters of the systems for creating regulated thermal conditions and air exchange.

Figures 2-4 show the results of numerical modeling of the processes of heat transfer and diffusion of carbon dioxide in a room with a CO_2 generation source and enclosing structures in the local work zone at air flow rates in the air exchange system of 0.01, 0.03, 0.07 kg/s and a system operating time of 60 min.

Under conditions of a small air inflow from the air exchange system (G = 0.01 kg/s, Fig. 2), the incoming air, mixing with heated and polluted air from the GIE, enters the local work zone limited by enclosing structures, lowering the air temperature in it to 22 °C. The concentration of CO_2 in the local work zone at a height of 1.5 - 1.7 meters (the breathing area of the worker) is on average 1600 ppm, which is above the standard [10, 11].

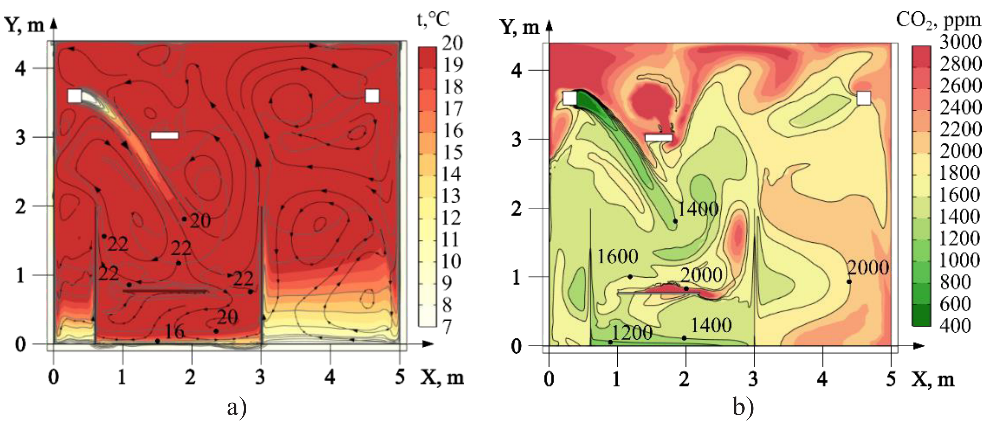
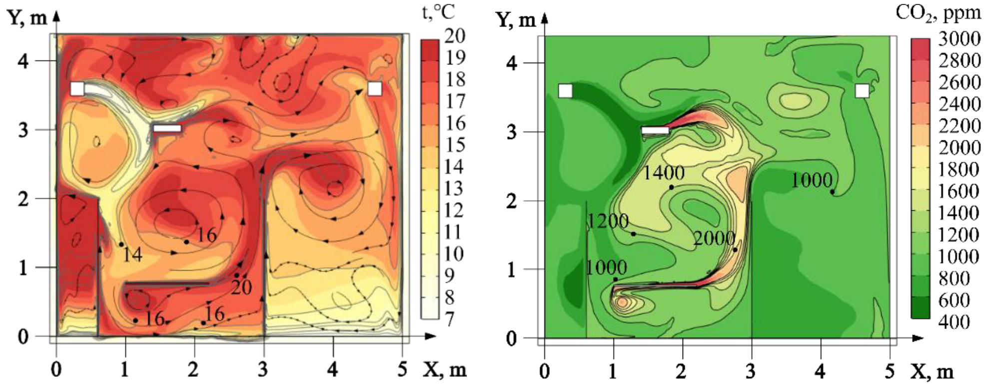


Fig. 2. Temperature field and air flow lines (a), CO_2 concentration field (b), formed by the 60th minute of GIE operation at a blown air flow rate of 0.01 kg/s.

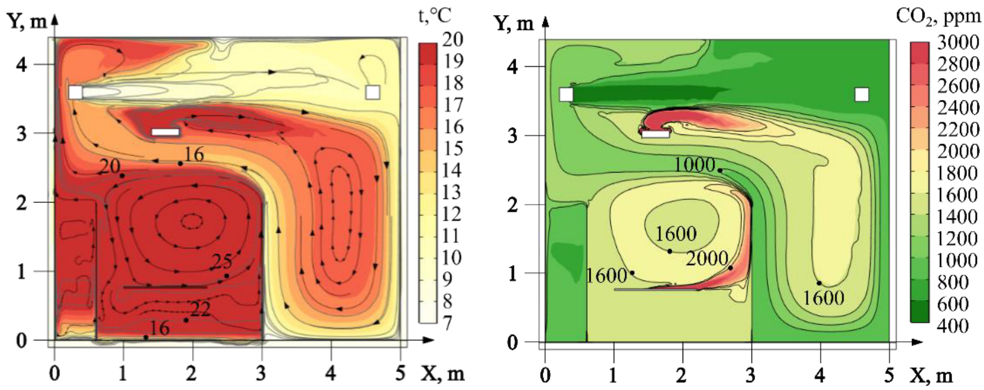
When the supply air flow rate increases to 0.03 kg/s (Fig. 3), the incoming air flow from the air exchange system enters the GIE and is divided into two flows – lower and upper. The lower supply air flow enters the local working area, lowering the temperature in it to 16 °C (Fig. 3a). At the same time, the CO_2 concentration in the local working area at a height of 1.5 – 1.7 meters decreases to the standard 1200 ppm (Fig. 3b). The upper air flow forms a circulation vortex in the room, equalizing the CO_2 concentration in the air to 2000 ppm. Enclosing structures prevent this polluted air from entering the local working area.



a) b)

Fig. 3. Temperature field and air flow lines (a), CO2 concentration field (b), formed by the 60th minute of GIE operation at a blown air flow rate of 0.03 kg/s.

With an air exchange system flow rate of 0.07 kg/s, the supply air enters only the upper part of the room (Fig. 4). An extensive circulation vortex is formed throughout the room with a decrease in air temperature to 16 °C (Fig. 4a) and CO_2 concentration to 1600 ppm (Fig. 4b). In the enclosed local work zone, the air temperature increases to 25 °C, but the CO_2 concentration also increases to 1600 ppm.



a) b)

Fig. 4. Temperature field and air flow lines (a), CO_2 concentration field (b), formed by the 60th minute of GIE operation at a blown air flow rate of 0.07 kg/s.

4 Conclusion

Based on the results of mathematical modeling, it can be concluded that it is advisable to use local enclosing structures when a gas infrared emitter, a ventilation system and a carbon dioxide generation source operate together to ensure efficient air heating and create comfortable working conditions for workers in local work areas.

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