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NUMERICAL AND PHYSICAL MODELING OF THE THERMAL REGIME IN A METRO TRACK TUNNEL WITH FIRE IN A MOVING TRAIN CARRIAGE

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Results of the numerical solution using the factorized finite-volume method of Favr-averaged three-dimensional nonstationary Navier–Stokes and energy equations that are closed by a high-Reynolds dissipation turbulence model are compared with experimental data on the evolution of the thermal regime in a metro tunnel with the development of fire in a moving carriage.

Numerical modeling of the development of fire and the motion of smoke is of importance in the designing and expert examination of metro objects [1]. The models are based on the system of Navier–Stokes equations for subsonic turbulent flows of a multicomponent gas in the presence of a dispersed admixture (smoke). It should be noted that the considered unsteady processes are very intricate and mathematical models that describe them need a thorough testing. Therefore, the performed comprehensive calculational and experimental study of the heat and mass transfer in a tunnel with a moving burning carriage has aimed primarily at estimating the adequacy of the developed computational complex.

Physical experiments were carried out on carriages of the E series installed in a full-scale tunnel model of a rectangular cross section that measured 4.6 × 4.1 m and was 38 m long. The tunnel walls were fabricated from concrete blocks of the FBS 24.4.6-T brand. Ferroconcrete plates of the IP1-1 brand were used as a cover. In the tunnel walls, 1.2 × 1.2 m viewing windows were located at a height of 1.2 m, with four windows on each side of the tunnel, that were rigged with folding metal shutters. At one of the tunnel ends, a ventilation device was placed, which induced the required air blow in the tunnel. Figure 1 shows a diagram of the carriage position in the tunnel and the sections in which the temperatures were measured.

The carriage interior was finished with standard lining materials:

DBSP TU 6-05-1305-77 plastic (ceiling and walls);

FSF TU 6516-89 plywood and TU 21-29-104-83 alkyd linoleum (floor);

TU 38-10616-81 foam rubber and TU 17-21-561-84 vinylis leather (seats).

The total fire load reduced to the floor area was 47 $kg \cdot m^{-2}$.

The fire source was kerosene-impregnated rags distributed uniformly over the surface of the carriage floor, which practically precluded the stage of fire propagation over the carriage and produced a maximum possible thermal regime in the combustion of a single carriage. In the experiments, the local temperatures of the gas flows in the tunnel and of heated surfaces of the latter were determined. Hot junctions of the thermocouples that measured the temperature of heated surfaces of the enclosing structures were immured to a depth of 1–2 mm along a length of about 150 mm. The temperatures were measured using Chromel-Alumel thermocouples with 0.7-mm-diam. thermoelectrodes, whose signal was recorded by KSP-4 potentiometers.

Prior to the fire experiments, the mean air velocity in the fourth section of the tunnel was measured by an ASO-3 vane anemometer. Two experiments were conducted with mean velocities of the air flows equal to 1.2 and 1.7 $m \cdot sec^{-1}$.

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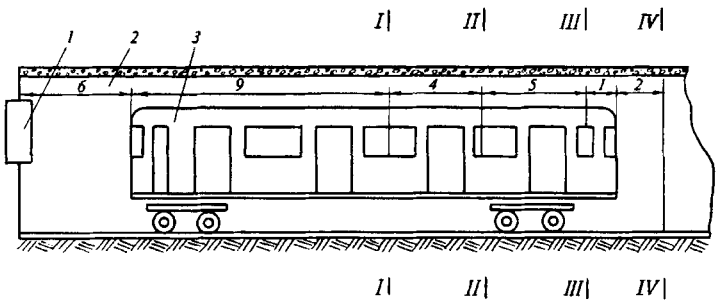

Fig. 1. Diagram of the carriage position in the model of a track tunnel: 1) ventilation device; 2) tunnel model (dimensions in meters); 3) test carriage; *I-IV*) tunnel sections in which thermocouples were placed.

A mathematical model of the gas-mixture motion is based on the system of complete Favr-averaged, three-dimensional, nonstationary Navier–Stokes equations supplemented with equations for the laws of conservation of individual gas components and energy with allowance for the turbulent character the mixture flow on the whole. The model is applied to calculating the motion of smoke, i.e., of the set of gaseous products of the combustion of organic materials, in which solid and liquid microparticles are scattered. The presence of such microparticles is neglected in the current work, since the combustion itself with the corresponding heat release is disregarded. This approach is used in a number of similar works, specifically, in [2].

A characteristic feature of the adopted model is the assumption that the gas density is dependent on the mixture temperature and composition but is independent of variations of the pressure field on the background of the assigned level of static pressure. For fairly low Mach numbers, this assumption is quite justified, and, as a result, there is no need for a very laborious resolution of acoustic processes that are not essential to this problem.

The turbulence is modeled on the basis of the standard high-Reynolds version of the k–ε model that is modified for taking into account the effect of the lift force, stratification, and streamline curvature [3]. Equations of the two-parametric dissipation model include the Kolmogorov–Prandtl formula for turbulent viscosity with a correction function dependent on the turbulent Richardson number and the equations of transfer of the kinetic energy of turbulent pulsations and its dissipation rate.

Within the framework of the standard k–ε model, the boundary conditions on solid surfaces are specified, assuming a universal logarithmic velocity profile to take place in the turbulent boundary layer.

The aerosol is modeled assuming that the only condensed component in the flow is free carbon in the form of soot. This is valid for flame combustion of a number of solid combustibles such as dry wood, polyvinylchloride, rubber, cellular polystyrene, and foamed polyurethane [4], and also liquids and gaseous hydrocarbons. The state of the aerosol is described by two basic parameters: mass fraction of free condensed carbon and specific concentration of particles (number of particles in 1 kg of the mixture). The admixture particles are treated as fractal aggregates (flakes). Here, the particle coagulation is taken into account.

The radiative heat transfer is modeled on the assumption that a major contribution to this process is made by soot, whereas the radiation, scattering, and absorption of gaseous products (CO_2 and H_2O) can be disregarded. The absorption coefficient of the aerosol is calculated in the Rayleigh limit of the Mie theory. The radiation scattering is neglected, which is also valid in the limit of small particles.

The problem is solved using the finite-volume method within the framework of the concept of splitting by physical processes. The transport equations, which are written in delta form on an unbiased nonuniform grid, are solved with the aid of fully implicit finite-difference schemes [5]. A calculating procedure of the SIMPLEC type is used for correcting the pressure in the approximation of low Mach numbers. An approach is applied [6] that is based on multiblock grids with an overlap, with the set of grids including simple-topology grids in each block. The procedure of global iterations draws on a piecewise-linear interpolation of the characteristics in the zones of overlapping of the calculational grids. Convective terms in the explicit part of the transfer equations are digitized with the aid of a counterflow scheme with quadratic interpolation.

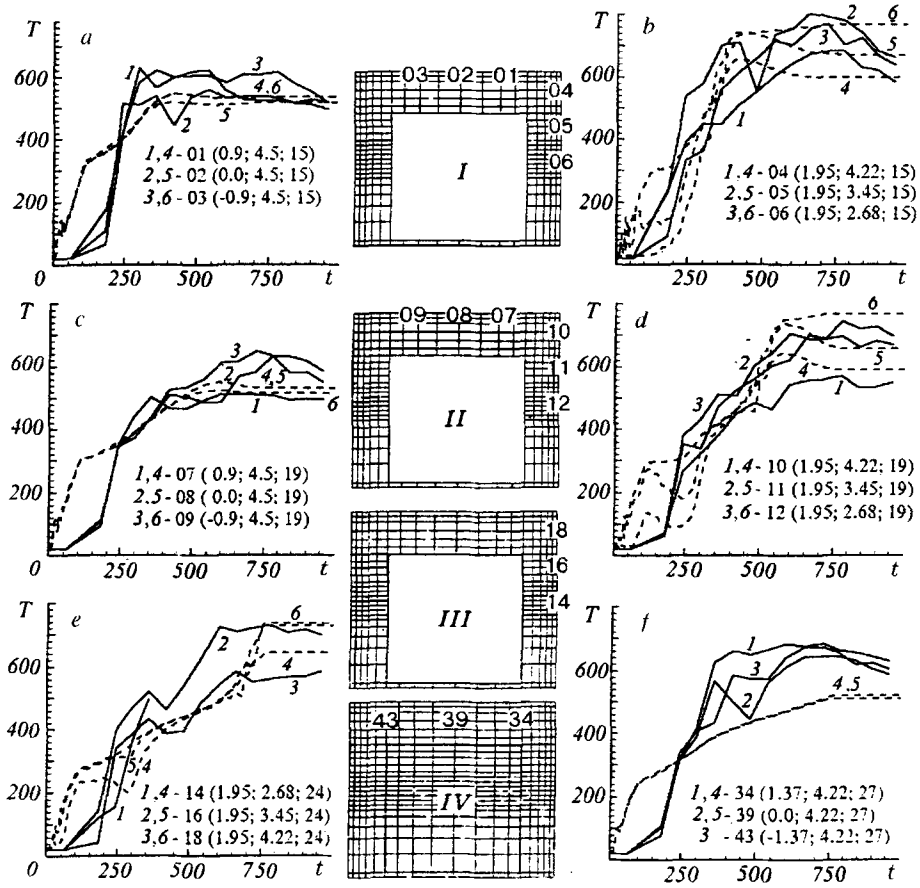

Fig. 2. Experimental (continuous curves 1-2) and calculated (dashed curves 4-6) time (sec) dependences of temperature (°C) at various points of the tunnel sections: *I* (a, b); *II* (c, d); *III* (e), and *IV* (f). The points are numbered, and their position is designated in meters and is written in brackets: the longitudinal and vertical coordinates measured from the middle of the carriage section and the distance of the section from the beginning of the carriage, respectively.

At the initial instant, a uniform gas flow through the inlet section of the tunnel with a mean velocity of 1.2 m/sec is assumed. At the same time, the gas that represents combustion products begins to be injected through side walls of the carriage. The injection proceeds through the slit with a height of 0.4 m that is located at a distance of 0.58 m from the carriage top, which approximately conforms to the level of the window top. Simultaneously, air suction is taken to proceed through the slit of the same height, which is located directly below the first one. The combustion is assumed to start in the carriage forepart. The initial length of the slit is set equal to zero. The velocity of propagation of the flame front is taken to be 0.025 m/sec. The parameters of the outflowing gas are temperature, 1123 K and mass flow per unit length of the slit, 2.73 $m^3/(m \cdot sec)$, and the composition is O_2, 23%, C, 0.285%, CO, 0.1423%, and the rest is nitrogen. The outflow velocity here is 6.825 m/sec. The suction rate is calculated at each instant so that the ratio of mass flows through the outlet and inlet slits is equal to 0.93 (which corresponds to the physical experiment). The parameters of the outflowing gas are assumed to be time-invariable. A constant pressure is specified at the outlet boundary (the outflow into the atmosphere). The tunnel walls are regarded as heat-insulated.

A comparative analysis of time variations of the calculated and experimental temperature distributions in the selected tunnel sections demonstrates their quite acceptable agreement, specifically, as to the rate of

change and maximum temperature level, which is indicative of the adequacy of the developed computational complex (Fig. 2). It should be noted that the differences, which take place in the initial period of development of the process, are linked with disregard for the actual ignition phase, characterized primarily by a certain time delay in the establishment of the assigned specific flow of the outflowing combustion products. The explosive development of the process is implemented in the calculational model. However, the revealed agreement of the calculated and experimental rates of temperature rise indicates its independence of the initial phase of the process and the predominance of a flow mechanism in the formation of the thermal regime in the metro track tunnel. The insignificant discrepancy in the behavior of the calculated and experimental curves for the time dependence of temperature with $t > 700$ sec (a fall in the experiments and attaining the asymptotics in the calculations) can be attributed to a decrease in the actual specific flow of the combustion products in the carriage forepart.

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