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STATISTICAL MODELING OF THERMAL-RADIATION TRANSFER IN NATURAL-CONVECTION TURBULENT DIFFUSION FLAMES. 3. FLAME ABOVE THE SURFACE OF LIQUID FUEL

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Results of numerical modeling of natural-convection turbulent diffusion flames above the surface of liquid fuel have been presented. The rate of burning (evaporation) of the fuel was determined as a function of the incident radiation heat flux, which in turn depended on the amount of fuel entering the flame zone. In so doing, feedback in which thermal radiation is of primary importance was closed. Radiation transfer was modeled by the statistical method.

Introduction. Reservoirs of hydrocarbon fuels, transportation facilities, cisterns, tankers, oil-extraction platforms, and oil-refinement and chemical enterprises provide examples of objects where fires caused by the combustion of readily inflammable fluids are possible. In emergency spillage on such objects there form natural-convection turbulent diffusion flames above the surface of a liquid fuel. As a result of their investigation, a great body of experimental data in a wide range of fuel-surface sizes has been accumulated. It has been found that the evaporation rate of a liquid fuel is determined by convective heat supply in the case of small surfaces D (diameter of a reservoir, a burner, or spillage), and by the radiation flux from the flame zone at large D ($D > 0.2$ m). Of considerable practical interest is the latter case where the radiation flux predominates in the thermal balance on the fuel surface.

With increase in the size of the fuel surface D and corresponding growth of the height and width of the flame, an increasingly larger portion of the intrinsic radiation of the flame is absorbed by combustion products, i.e., transition from the optically transparent flame to an optically dense flame occurs. As is shown by experiments, at the same time, the dependence of the mass rate of burning $\dot{m}_{\text{fuel}}$ on D reaches saturation. A great many results of measurement of the mass rate of burning of condensed fuels from unit area of the surface for different size of the fuel surface are generalized in [2]. The obtained empirical relations have the form

$$\dot{m}_{\text{fuel}} = \dot{m}_{\text{fuel}\infty} \left[1 - \exp\left(-k_\beta D\right)\right] . \tag{1}$$

However, natural-convection turbulent diffusion flames above the surface of a liquid fuel are still a difficult object for numerical modeling. Despite the abundance of works devoted to simplified approaches, only in some of them was an attempt to calculate the mass rate of combustion made (see, e.g., [5]). We note that the model must be applicable to burning liquids with a surface size from tens of centimeters to several meters. This range, which is of practical importance, involves both optically transparent and dense flames. Solution of the indicated problem requires an efficient algorithm of calculation of thermal-radiation transfer from combustion products to the fuel surface.

In the present work, for calculation of radiation transfer we use the statistical method presented in [6] together with description of the turbulence and combustion models. We note that the model of [6] was tested in calculations of flames above a gas burner with a specified constant flow rate of the fuel $\dot{m}_{\text{fuel}}$ [7]. In contrast to [7], in the present work the rate of burning (gasification) of the fuel was determined as a function of the incident radiation heat flux, which in turn depends on $\dot{m}_{\text{fuel}}$. This means the closing of a positive feedback in the system fuel flow–flame–thermal radiation–fuel gasification which provides a rise and propagation of fire. It should be noted that the indicated feedback is disregarded in most modern works.

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In what follows, we consider combustion in motionless air and in the presence of a side wind. Calculations are made depending on the size of the fuel surface and the wind velocity.

Problem Formulation and Boundary Conditions. It is assumed that the liquid fuel (acetone with a standard enthalpy of formation of −218.5 kJ/mole) is in a round reservoir of diameter D; the fuel surface is kept at the floor level. It is known that under the conditions of fully developed combustion the temperature of the liquid surface is close to the boiling temperature T_b [1]. In this case, the partial pressure of the fuel vapor is equal to atmospheric pressure and the mass fraction is equal to unity. The heat (convection and radiation) flux $q_{fuel}(x, y)$ received by the fuel surface is expended in heating the liquid from the initial temperature T_0 to the boiling temperature T_b and in evaporating the liquid at T_b. In this case, the enthalpy of the unit mass of the liquid changes by a value $\Delta h_{vap}(T_0)$ (enthalpy of evaporation of the fuel at the initial temperature T_0). The balances of heat and mass take the form

$$q_{fuel}(x, y) = \dot{m}_{fuel}(x, y)\,\Delta h_{vap}(T_0)\,, \tag{2}$$

$$\dot{m}_{fuel}(x, y) = \rho_{fuel}(T_b)\,w_{fuel}(x, y)\,. \tag{3}$$

Thus, in the case considered where the liquid surface has a boiling temperature, the evaporation rate is determined by the received heat flux and is independent of mass exchange near the surface. Correspondingly, the relations

$$w_{fuel}(x, y) = \frac{q_{fuel}(x, y)}{\rho_{fuel}(T_b)\,\Delta h_{vap}(T_0)}\,, \quad T_{fuel} = T_b\,, \quad Y_{fuel} = 1\,.$$

are used as the boundary conditions for the normal velocity, the temperature, and the mass fraction of the fuel on the liquid surface. The following dependence of the enthalpy of evaporation on the temperature was used in calculations:

$$\Delta h_{vap}(T) = \frac{A}{M_{fuel}} \exp\left(-\alpha \frac{T}{T_c}\right)\left(1 - \frac{T}{T_c}\right)^{\beta}\,,$$

where A = 46.95 kJ/mole, $\alpha = \beta = 0.2826$, T_c = 508.2 K [8], and M_{fuel} = 0.05808 kg/mole for acetone. The difference $\Delta h_{vap}(T_0) - \Delta h_{vap}(T_b)$ corresponds to the heat expended in warming-up the liquid from the initial temperature to the boiling temperature. At the temperature of boiling of acetone T_b = 329.3 K [8], we have $\Delta h_{vap}(T_b)$ = 501 kJ/kg.

A detailed description of the model, the boundary conditions, and the numerical method is given in [6, 7].

Calculation Results. *Combustion in the absence of a side wind*. Calculation of a stationary flame above the fuel surface in motionless air was made for reservoirs with diameters D = 0.15, 0.3, 0.6, and 1.2 m. For D = 0.15 and 0.3 m, the computational region had horizontal dimensions 1.2 m and height 1.5 m. For D = 0.6 and 1.2 m, the dimensions of the regions were 2.4 × 2.4 × 3.0 m and 4.8 × 4.8 × 6.0 m respectively. The grid consisted of 102,400 meshes (40 × 40 × 64).

As for flames above a gas burner [7], the effective absorptivity of the flame ε_f was determined by the statistical method. The effective optical thickness of the flame τ_f was obtained from the relation $\varepsilon_f = 1 - \exp(-\tau_f)$. For the above-indicated diameters of the reservoir the values of τ_f were 0.37, 0.7, 1.1, and 1.6 respectively. Thus, both optically transparent and optically dense flames were considered. Stationary fields of temperature, velocity, and divergence of the radiation heat flux $\partial q_j^r / \partial x_j$ for the flame above the reservoir of diameter D = 0.3 m are given in Fig. 1. Figure 2 shows the profiles of the heat flux at the floor level (coincides with the fuel surface) for D = 0.15 and 0.3 m.

We note that the result of calculation of $\dot{m}_{fuel}$ is very sensitive to the emissivity of the fuel surface (it was assumed that the absorptivity and the radiating capacity of the surface are the same). By virtue of the lack of experimental data, the numerical value of the emissivity (0.4) was selected so as to obtain the best agreement of the calculated and measured rates of burning. Comparison for the results for acetone depending on the size of the fuel surface is given in Fig. 3. The range of variation of $\dot{m}_{fuel}$ is shown in the figure in accordance with the generalized formula (1), where $\dot{m}_{fuel} = 0.04 \pm 0.003$ kg/(m^2·sec) and $k_\beta = 1.9 \pm 0.3$ 1/m for acetone [2]. It should be noted that we succeeded in obtaining good agreement of the calculated and experimental values of the burning rate. This indicates the adequacy of the model used and, first of all, of the method of calculation of thermal-radiation transfer.

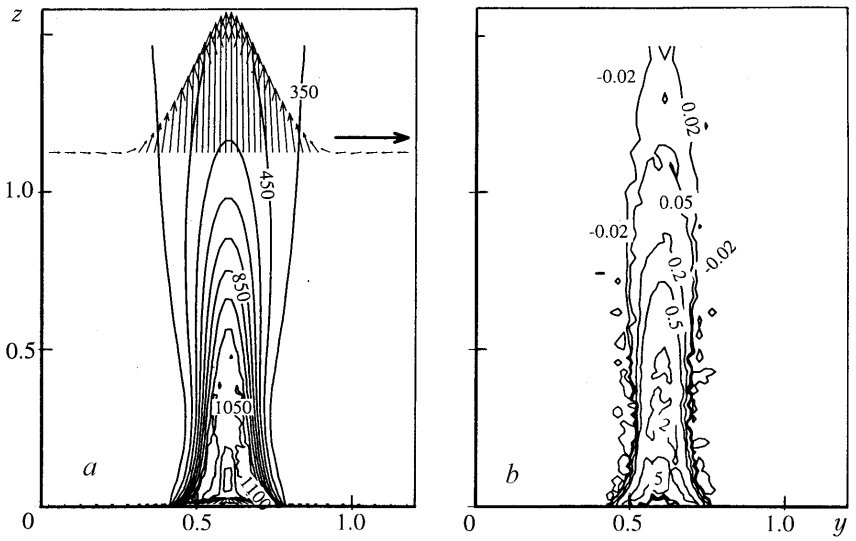

Fig. 1. Stationary torch of a turbulent flame above the surface of acetone in air (D = 0.3 m). Fields in the symmetry plane of the torch: a) temperature and velocity at a height of 1.12 m (length of the horizontal arrow corresponds to 2 m/sec); b) divergence of the radiation heat flux $\partial q_j^r/\partial x_j$. y, z, m; T, K (a); $\partial q_j^r/\partial x_j$, MW/m^3 (b).

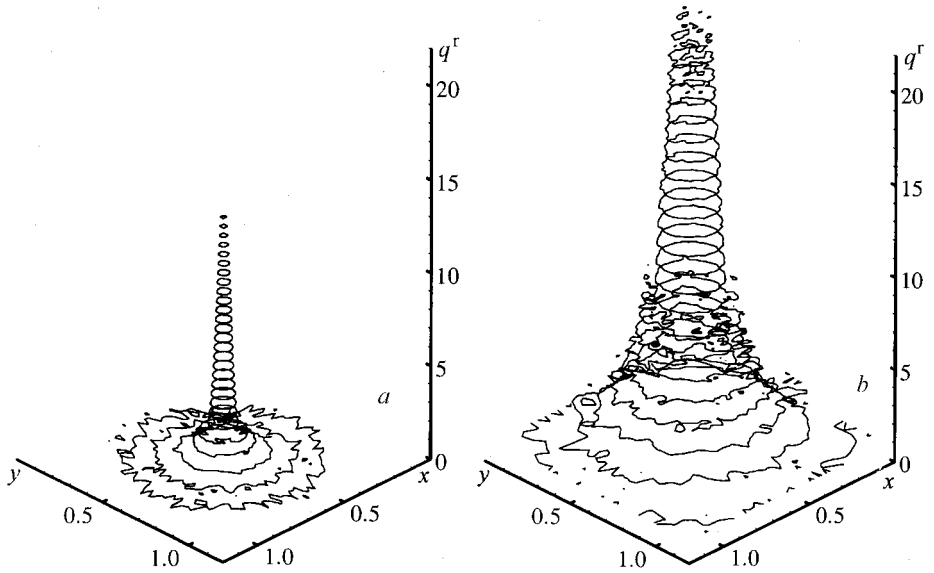

Fig. 2. Radiation heat flux from the flame, which is incident on the surface of the fuel (acetone): a) D = 0.15; b) 0.3 m. x, y, m; q^r, kW/m^2.

Combustion under the conditions of a side wind. A side wind considerably changes the shape of the flame and its temperature and radiated power. This was shown, in particular, in [9, 10], where in modeling the torch formed by a fuel jet with a constant flow rate the radiation fluxes from the torch were calculated. In a more recent work [11], inclination of the flame by wind was studied numerically in a two-dimensional plane flow. In this case, the radiation fluxes were calculated after the calculation of the nonradiating flame. Thus, in [9–11], the fuel flow rate was not related to the incident radiation flux and the feedback indicated above was not considered. It was found in the experiments on combustion of fluids [1] that not only does the side wind change the shape and temperature of the flame but it can also cause an increase in the rate of burning from a unit area of the fuel surface due to intensification of radiation. The same conclusion was drawn in [12] on the basis of two-dimensional modeling of a linear site of combustion where the rate of burning depended on the incident radiation flux (which was determined by the method of

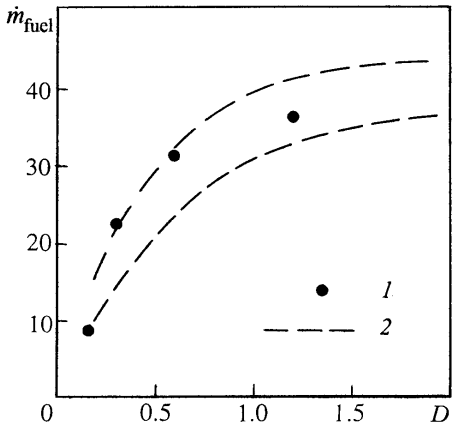

Fig. 3. Dependence of the mass rate of burning of acetone $\dot{m}_{fuel}$ on the size of the fuel surface D: 1) calculation by the present model; 2) range of results of measurements from the data of [2]. $\dot{m}_{fuel}$, g/(m^2·sec); D, m.

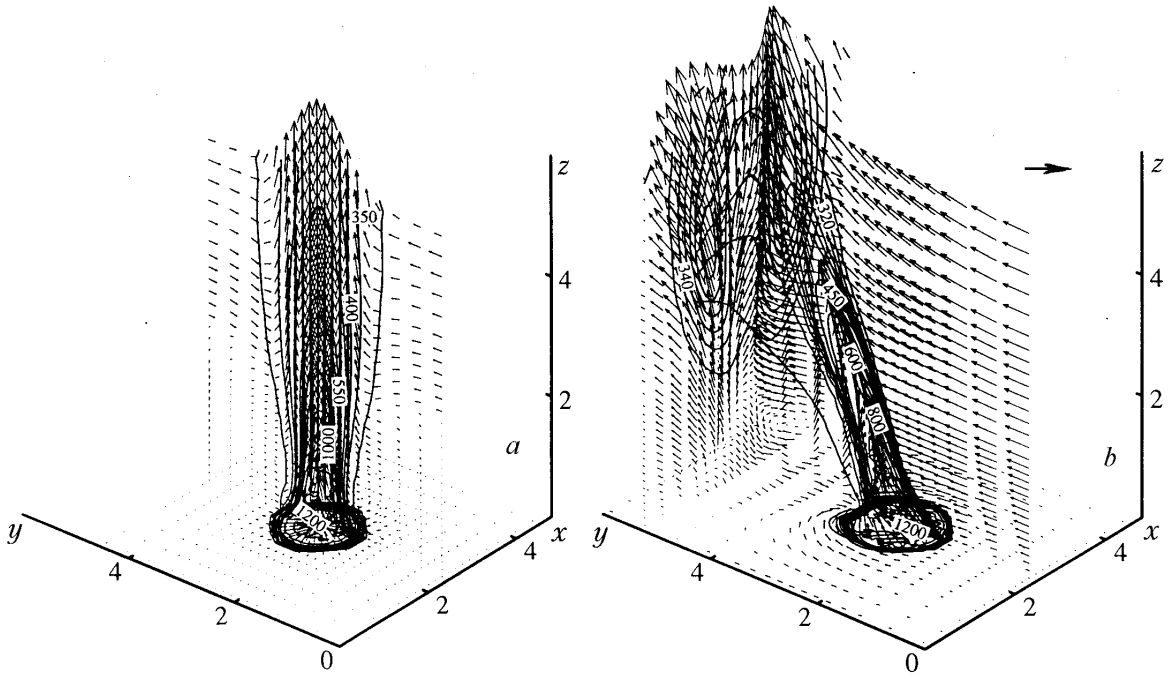

Fig. 4. Stationary fields of the mean velocity and the temperature in the torch of a turbulent flame above the acetone surface (D = 1.2 m) in air: a) motionless air; b) side wind 2 m/sec (length of the horizontal arrow in the upper right-hand corner corresponds to 2 m/sec). T, K; x, y, z, m.

discrete coordinates). In the present work, the combustion of an evaporating fluid under the conditions of a side wind was considered in a three-dimensional formulation and with account for relation (2)–(3) between the rate of burning and the radiation flux. Radiation transfer was modeled by the statistical method [6].

Calculations of flames above the surface of liquid acetone were made for three reservoirs with diameters D = 0.3, 0.6, and 1.2. The computational region used above for the flame in motionless air was extended by 1/3 in the leeward direction and the number of control volumes increased to 122,880 (40 × 48 × 64). The side wind was modeled by the velocity profile $v(z) = V_{wind}[1 - \exp(-z/z_{b.l}]$, $u = w = 0$ being used as the boundary condition at $y = 0$. The height of the "boundary layer" above the floor level was taken to be equal to $z_{b.l}$ = 1 m. Stationary flames were calculated for the velocity of the oncoming flow V_{wind} from 0 to 6 m/sec. Figure 4 shows stationary fields of the mean velocity and temperature in the flame above the reservoir of diameter D = 1.2 m which were obtained in the

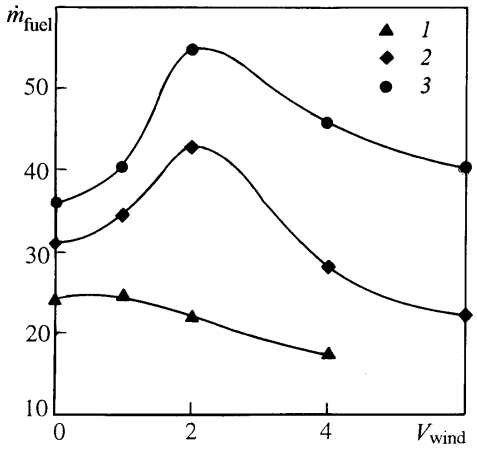

Fig. 5. Calculated dependences of the rate of burning of acetone $\dot{m}_{fuel}$ on the velocity of side wind V_{wind}: 1) D = 0.3; 2) 0.6; 3) 1.2 m. $\dot{m}_{fuel}$, g/(m^2·sec); V_{wind}, m/sec.

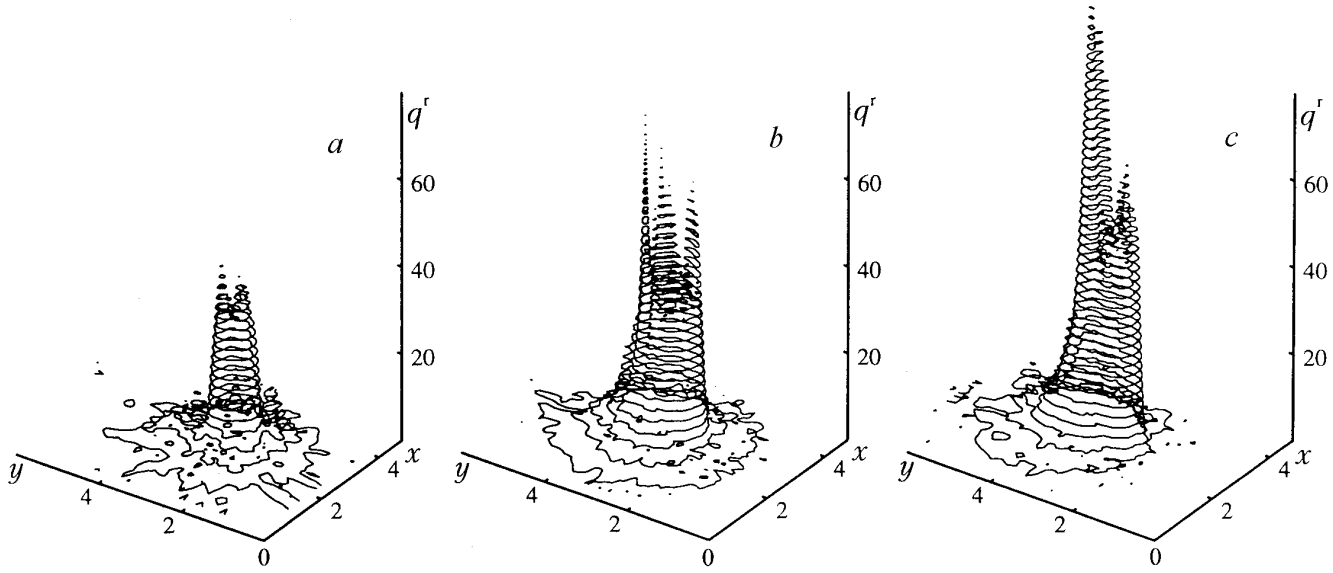

Fig. 6. Radiation heat flux q^r from the flame, which is incident on the surface of the fuel (acetone, D = 1.2 m) under the conditions of a side wind: a) V_{wind} = 1; b) 2; c) 4 m/sec. q^r = kW/m^2; V_{wind}, m/sec.

absence of wind (V_{wind} = 0) and under the conditions of a side wind (V_{wind} = 2 m/sec). We note that for the wind-inclined flame the model predicts separation of the torch into two vortex flows with opposite twisting. A similar structure of the torch was observed in the experiments with jets in a cross flow and in numerical modeling (see, e.g., [10]).

The results of the effect of a side wind on the flame depends on the size of the reservoir and the wind velocity. In particular, cold air, penetrating to the combustion zone, can decrease its temperature and, consequently, the radiated power. This takes place if additional oxygen is not used in the reaction, i.e., if the concentration of oxygen in most of the flame zone is higher than the stoichiometric concentration. Such is the case for well-ventilated flames of small size. However, a vast fuel-rich and oxygen-depleted region exists in flames above large reservoirs. In this case, wind-caused intensification of the capture of air by the flame approximates the concentration of oxygen in the flame zone to the stoichiometric concentration. This increases the flame temperature and the radiated power.

Another factor which affects the rate of gasification of the fuel is the amount of emitted energy which reaches the fuel surface. It depends on the shape of the flame and the angle of its inclination, i.e., on the wind velocity. The more the flame is deflected from the vertical, the larger the portion of emitted energy incident on the surface beyond

the fuel material. As a result of the effect of the indicated factors, the dependence of the burning rate and, consequently, the thermal power of the flame on the velocity of a side wind can be nonmonotonic.

The above considerations explain the dependence of the burning rate on the wind strength that was obtained in calculations (see Fig. 5). Indeed, for reservoirs of large diameter (0.6 m or larger), an increase in the wind velocity from 0 to 2 m/sec leads to an increase in the concentration of oxygen in the fuel-rich flame zone, which results in an increase in the flame temperature and the power of thermal radiation. The thus-caused intensification of the radiation flux incident on the fuel surface leads to a considerable increase in the burning rate $\dot{m}_{\text{fuel}}$ (up to 60% for D = 1.2 m). The profiles of the incident radiation fluxes for three velocities of side wind are given in Fig. 6. It is well seen that as the wind velocity increases, the indicated flux increases and its maximum shifts in the leeward direction. However, at a large wind velocity, an increase in the inclination of the flame results in a decrease in the burning rate due to the fact that, despite the temperature growth, an increasingly larger portion of the emitted energy is redistributed beyond the fuel surface.

In the case of reservoirs with a diameter 0.3 m or smaller, a side wind at a small velocity does not cause an appreciable increase in the burning rate and decreases it substantially if the wind velocity is large (Fig. 5). This is associated with the fact that the additional amount of air brought by the wind serves as an inert diluent, decreasing the flame temperature.

We note that stalling of the flame takes place at a large wind velocity [1]. In considering this effect, one should allow for the effect of extinguishing in the combustion model. Moreover, participation of the reservoir walls in the heat-exchange process should be taken into account. In the present work, where prominence is given to modeling of thermal-radiation transfer, the indicated effects were not analyzed.

CONCLUSIONS

Calculation of flames above the surface of liquid acetone in motionless air gave a burning rate which is in good agreement with experimental data obtained at different diameters of the reservoir, i.e., for both optically thin and thick flames. This indicates the adequacy of the model applied and of the method of calculation of thermal-radiation transfer used in it.

Calculation of flames above the surface of liquid acetone under the conditions of a side wind showed a nonmonotonic dependence of the burning rate on the wind velocity (the character of this dependence was strongly related to the size of the flame, i.e., the reservoir diameter). Substantial increase in the burning rate with increase in the wind velocity to a certain value at which the burning rate reached a maximum was observed for flames above rather large reservoirs. This occurred due to the increase in the concentration of oxygen in the fuel-rich flame zone, which resulted in an increase in the temperature and the radiated power. Further increase in the velocity of the side wind led to a decrease in the burning rate, despite the radiation enhancement. This is associated with the redistribution of the heat flux, emitted by the inclined flame, beyond the fuel surface. In flames above small reservoirs, a side wind decreased the flame temperature and the burning rate, since the additional oxidizer brought by the wind was not used in the reaction but served as an inert diluent.

The experience gained in modeling of thermal-radiation transfer in natural-convection turbulent diffusion flames has shown that the statistical method successfully combines reliability of the results and computational efficiency.

NOTATION

D, characteristic dimension (diameter) of the reservoir, the burner, or the spillage, m; $\dot{m}_{\text{fuel}}$, rate of removal of the fuel mass from a unit area of the surface (burning rate), kg/(m^2·sec); $\dot{m}_{\text{fuel}\infty}$, mass rate of burning when $D \to \infty$, kg/(m^2·sec); M_{fuel}, molar mass of the fuel, kg/mole; k_β, effective coefficient of absorption, 1/m; q_{fuel}, total heat flux received by the fuel surface, W/m^2; q^{r}, radiation heat flux, W/m^2; T_{b}, temperature of boiling of the fuel, K; T_{c}, critical temperature of the fuel, K; T_0, initial temperature of the fuel and temperature of the surrounding air, K; u, v, and w, projections of velocity on the axes x, y, and z; V_{wind}, wind velocity, m/sec; w_{fuel}, vapor velocity near the fuel surface, m/sec; x_j, coordinate corresponding to the axis j, m; x, y, z, space coordinates, m; Y_{fuel}, mass fraction of the fuel;

$z_{b.l}$, height of the boundary layer in the velocity profile of a side wind, m; α and β, parameters for the temperature dependence of the evaporation heat; ε_f, radiating capacity of the flame; Δh_{vap}, enthalpy of evaporation of unit mass, J/kg; ρ_{fuel}, partial density of the fuel vapor, kg/m^3; τ_f, optical density of the flame. Sub- and superscripts: b, boiling; b.l, boundary layer in the velocity of side wind; c, critical; fuel, fuel; f, flame zone; vap, evaporation; wind, side wind; 0, surrounding air; r, radiation.

REFERENCES

1. V. I. Blinov and G. N. Khudyakov, *Diffusion Combustion of Fluids* [in Russian], Moscow (1961).
2. V. Babrauskas, *Fire Technol.*, **19**, No. 4, 251–261 (1983).
3. K. S. Mudan and P. A. Croce, in: *SFPE Handbook of Fire Protection Engineering*, 2nd edn., NFPA, Quincy, MA (1995), pp. 3-197–3-240.
4. P. Joulain, in: *Proc. 27th Int. Symp. on Combustion*, The Combustion Institute, Pittsburgh (1998), pp. 2691–2706.
5. K. C. Adiga, D. E. Ramaker, P. A. Tatem, and F. W. Williams, in: *Proc. 2nd Int. Symp. IAFSS "Fire Safety Science"* (1989), pp. 241–250.
6. A. Yu. Snegirev, *Inzh.-Fiz. Zh.*, **76**, No. 2, 48–56 (2003).
7. A. Yu. Snegirev, *Inzh.-Fiz. Zh.*, **76**, No. 2, 57–65 (2003).
8. V. Majer V. and Svoboda, *Enthalpies of Vaporization of Organic Compounds: A Critical Review and Data Compilation*, Oxford (1985).
9. S. Galant, D. Grouset, G. Martinez, P. Micheau, and J. B. Allemand, in: *Proc. 20th Int. Symp. on Combustion*, The Combustion Institute, Pittsburgh (1984), pp. 531–540.
10. M. Fairweather, W. P. Jones, and R. P. Lindstedt, *Combust. Flame*, **89**, 45–63 (1992).
11. X. L. Zhang, J. P. Vantelon, J. M. Most, and A. Hodin, *Combust. Sci. Technol.*, **124**, 17–33 (1997).
12. B. Porterie, D. Morvan, J. C. Loraud, and M. Larini, *Phys. Fluids*, **12**, No. 7, 1762–1782 (2000).