Journal of Engineering Physics and Thermophysics, Vol. 82, No. 3, 2009

HEAT AND MASS TRANSFER IN HOT-PARTICLE-INDUCED IGNITION OF A LIQUID-FUEL VAPOR ENTERING THE AMBIENT AIR FROM THE SURFACE OF FABRIC IMPREGNATED WITH THE FUEL

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UDC 536.468

A study has been made of the regularities of heat and mass transfer in the ignition of a mixture of an oxidant and a liquid-fuel vapor entering the ambient air from the surface of a portion of fabric impregnated with a fire-hazardous fluid. The dependences of the ignition-delay time on the initial temperature of the particle and the volume fraction of the fluid in the fabric material have been established. Investigations have been performed for three popular fabrics (wool, silk, and linen) and three typical fire-hazardous fluids (gasoline, kerosene, and diesel fuel).

Keywords: *heat and mass transfer, ignition, impregnated fabric, liquid fuel, hot particle.*

Introduction. To clean contaminated portions of weldable structures and surfaces of engines of transport facilities and construction equipment of combustible materials and lubricants one uses pieces of fabrics fully or partially impregnated with gasoline, kerosene, diesel fuel, transformer oil, and other fire-hazardous fluids.

When maintenance and civil-engineering works are performed much attention is given to accident prevention. But the probability that the fuel vapor entering the ambient air from the surface of fabric impregnated with fire-hazardous fluids will ignite is not envisaged and not described in any standard documents. The reason is the absence of results of theoretical and experimental investigations of the problem. Besides, the probability that the fabric material directly, not only the liquid fuel, will ignite is higher under certain conditions.

An analysis of the investigated mechanisms of ignition of fuel-vapor mixtures shows a number of problems in developing the general theory of ignition for fluids similar to [1]. Until the present time, no theoretical foundations of heat- and mass-transfer processes in the ignition of the fuel vapor entering the ignition zone from the surface of fabric impregnated with fire-hazardous fluids have been developed. We only know of the results of a few investigations of the processes of ignition of the vapor of liquid fuels in the ambient air [2–4], on whose basis a mathematical apparatus for studying the investigated process can be created.

This work seeks to numerically investigate the regularities of heat and mass transfer in the ignition of a mixture of air and the liquid-fuel vapor coming from the surface of fabric impregnated with fire-hazardous fluid.

Formulation of the Problem. We consider the system particle–fabric impregnated with liquid fuel–air (Fig. 1). The liquid fuel whose volume fraction is known is contained in the fabric at the initial instant of time. On arrival of a particle heated to a high temperature at the fabric surface, the rigid skeleton and the fluid filling the pores are heated. As a result the components of the liquid fuel begin to evaporate. The generated fuel vapor mixes with the oxidant in the ambient air. The mixture of the fuel vapor and the oxidant is heated due to the particle's heat. Once the critical temperature of the mixture and concentration of the fuel in it have been reached, ignition conditions are realized. The intensity of the ignition process under study is determined by the intensity of the processes of heat and mass transfer in the system in question (Fig. 1) and by the heat content of the ignition source and the volume fraction of the components of the liquid fuel in the fabric.

Wool, linen, and silk fabrics enjoy wide use. In this connection, in modeling the process under study, realization of ignition conditions in the system in question (Fig. 1) is of the greatest interest as applied to these fabrics and typical fire-hazardous fluids (gasoline, kerosene, diesel fuel). A single steel particle that is heated to high temperatures and that represents a droplet of a melt coated with crystallized material is considered as the ignition source.

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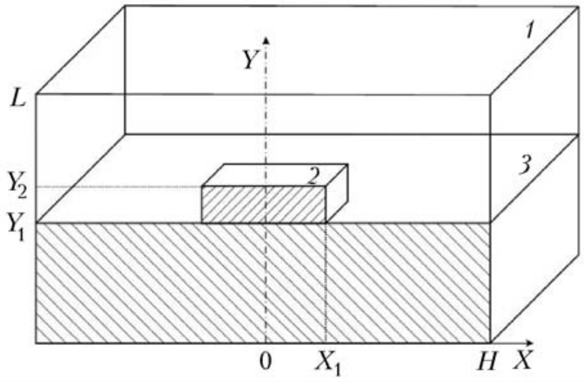

Fig. 1. Diagram of the domain of solution of the problem at the initial instant of time ($\tau = 0$) (a) and at $0 < \tau < \tau_d$ (b): 1) air; 2) particle; 3) fabric impregnated with liquid fuel.

Numerical solution of the ignition problem is performed under the following assumptions:

1. Evaporation of the fuel produces one substance with known characteristics. When the kinetic parameters of ignition of liquid substances are determined experimentally one usually seeks the effective values of the activation energy E and the pre-exponential factor k_0. Realization of one "effective" reaction involving one fuel is assumed.

2. The thermophysical characteristics of the particle material, the fluid, the fabric, and the air are temperature-independent. These parameters vary in a fairly wide temperature range only slightly [6–8].

3. The possible imperfection of thermal contact at the particle–fabric boundary (deformation of the contacting surfaces of the fabric and the particle upon their interaction) is disregarded. The processes of ignition of liquid fuels are quite rapid, whereas the falling velocities of particles are small in real applications. Therefore, we consider the inertial settling of the hot particle in which the contact surfaces are not deformed.

As the ignition conditions, we assume that [4] a) the heat released by the chemical reaction of the fuel vapor with the oxidant is larger than the heat transferred from the source of heating of the vapor-gas mixture; b) the temperature of the vapor-gas mixture exceeds the initial temperature of the heating source.

Mathematical Model. A system of differential equations describing the process under study involves the equations of motion, continuity, energy, heat conduction, and diffusion with allowance for the release of heat by the chemical reaction of the fuel vapor with the oxidant in the gaseous phase and as a result of the particle crystallization in the solid phase

$$X_1/L < X < H/L\,, \quad Y_1/L < Y < Y_2/L\,; \quad 0 < X < H/L\,, \quad Y_2/L < Y < 1$$

$$\frac{1}{\mathrm{Sh}}\frac{\partial \Omega}{\partial \tau} + U\frac{\partial \Omega}{\partial X} + V\frac{\partial \Omega}{\partial Y} = \frac{1}{\mathrm{Re}}\left(\frac{\partial^2 \Omega}{\partial X^2} + \frac{\partial^2 \Omega}{\partial Y^2}\right) + \frac{\mathrm{Gr}}{\mathrm{Re}^2}\frac{\partial \Theta}{\partial X}\,, \tag{1}$$

$$\frac{\partial^2 \Psi}{\partial X^2} + \frac{\partial^2 \Psi}{\partial Y^2} = \Omega\,, \tag{2}$$

$$\frac{1}{\mathrm{Sh}}\frac{\partial \Theta_5}{\partial \tau} + U\frac{\partial \Theta_5}{\partial X} + V\frac{\partial \Theta_5}{\partial Y} = \frac{1}{\mathrm{RePr}}\left(\frac{\partial^2 \Theta_5}{\partial X^2} + \frac{\partial^2 \Theta_5}{\partial Y^2}\right) + \frac{Q_o W_o H}{\rho_5 C_5 \Delta T V_s}\,, \tag{3}$$

$$\frac{1}{\mathrm{Sh}}\frac{\partial C_f}{\partial \tau} + U\frac{\partial C_f}{\partial X} + V\frac{\partial C_f}{\partial Y} = \frac{1}{\mathrm{ReSc}}\left(\frac{\partial^2 C_f}{\partial X^2} + \frac{\partial^2 C_f}{\partial Y^2}\right) - \frac{H W_o}{\rho_5 V_s}\,; \tag{4}$$

$$0 < X < X_1/L\,,\;\; Y_1/L < Y < Y_2/L$$

$$\frac{1}{\mathrm{Fo}_2}\frac{\partial \Theta_2}{\partial \tau} = \frac{\partial^2 \Theta_2}{\partial X^2} + \frac{\partial^2 \Theta_2}{\partial Y^2} + \frac{W_c Q_c H}{L_p \Delta T \lambda_2}\,; \tag{5}$$

$$0 < X < H/L\,,\;\; 0 < Y < Y_1/L$$

$$\frac{1}{\mathrm{Fo}_3}\frac{\partial \Theta_3}{\partial \tau} = \frac{\partial^2 \Theta_3}{\partial X^2} + \frac{\partial^2 \Theta_3}{\partial Y^2}\,. \tag{6}$$

The initial conditions ($\tau = 0$)

$$\Theta_3 = \Theta_0 \;\text{ for }\; 0 < X < H/L\,,\;\; 0 < Y < Y_1/L\,; \tag{7}$$

$$\Theta_2 = \Theta_p \;\text{ for }\; 0 < X < X_1/L\,,\;\; Y_1/L < Y < Y_2/L\,; \tag{8}$$

$$\Theta_1 = \Theta_0\,,\;\; C_f = 0\,,\;\; \Psi = 0\,,\;\; \Omega = 0 \;\text{ for }\; X_1/L < X < H/L\,,\;\; Y_1/L < Y < Y_2/L\,;\;\; 0 < X < H/L\,,$$

$$Y_2/L < Y < H/L\,. \tag{9}$$

The boundary conditions ($0 < \tau < \tau_3$ are as follows: at the particle–vapor-gas mixture boundary ($Y = Y_2/L$, $0 < X < X_1/L$ and $X = X_1/L$, $Y_1/L < Y < Y_2/L$), we specify boundary conditions of the fourth kind for the energy and heat-conduction equations and the conditions of equality of the corresponding functions to zero for the diffusion and Poisson equations and for the equation of motion; at the vapor-gas mixture–fabric boundary ($Y = Y_1/L$, $X_2/L < X < H/L$), we specify boundary conditions of the fourth kind with allowance for the evaporation of the components of the fluid from the fabric surface for the energy equation, and boundary conditions of the second kind for the diffusion and Poisson equations and the equation of motion; at the particle –fabric boundary ($Y = Y_1/L$, $0 < X < X_1/L$), we specify boundary conditions of the fourth kind for the heat-conduction equation; the condition of equality of the corresponding functions to zero is specified for all the equations on the axis of symmetry and at the boundaries ($Y = 0$, $Y = 1$, $0 < X < H/L$ and $X = H/L$, $0 < Y < 1$).

The thermophysical characteristics of the fabric impregnated with liquid fuel are determined from the formulas $\lambda_3 = \lambda_{31}(1 - \varphi_{32}) + \lambda_{32}\varphi_{32}$, $C_3 = C_{31}(1 - \varphi_{32}) + C_{32}\varphi_{32}$, and $\rho_3 = \rho_{31}(1 - \varphi_{32}) + \rho_{32}\varphi_{32}$.

The volume fractions of the components of the vapor-gas mixture are computed from their mass concentrations in the mixture from the expressions $\varphi_4 = \dfrac{\dfrac{C_f}{\rho_4}}{\dfrac{C_f}{\rho_4} + \dfrac{1 - C_f}{\rho_1}}$, $\varphi_4 + \varphi_1 = 1$. The thermophysical characteristics of the mixture of the fuel vapor with the oxidant in air are determined from the expressions $\lambda_5 = \lambda_1\varphi_1 + \lambda_4\varphi_4$, $C_5 = C_1\varphi_1 + C_4\varphi_4$, and $\rho_5 = \rho_1\varphi_1 + \rho_4\varphi_4$.

To compute the oxidation rate of the flammable fluid in air we use the expression [9] $W_o = k_0(1 - C_f)^{m_1} \times C_f^{m_2}\rho_5 \exp\left[-\dfrac{E}{RT_5}\right]$. The mass velocity of crystallization of the particle is calculated from the formula $W_c = V_c\rho_2$.

The linear velocity of crystallization of the particle is determined at each time step from the following expression: $V_c = \dfrac{\delta(X, Y, \tau + \Delta\tau) + \delta(X, Y, \tau)}{\Delta\tau}$. The diffusion coefficients of the liquid-fuel vapor and the kinematic viscosities of the vapor-gas mixtures are computed in accordance with the propositions of [3].

Method of Solution and Initial Data. The system of differential equations describing heat- and mass-transfer processes in ignition, by a single hot particle, of the fuel vapor that escapes from the surface of fabric impregnated with liquid fuel (1)–(6) with the corresponding initial and boundary conditions is solved by the finite-difference method [10]. The difference analogs of the differential equations (1)–(6) are solved by the locally one-dimensional method [10]. The system of one-dimensional difference equations is solved by the running method with an implicit four-point difference scheme [10]. The iteration method [11] is employed for solution of nonlinear one-dimensional difference equations. The substantial nonlinearity and unsteadiness of the process under study are noteworthy. In this connection, a nonuniform time step and an irregular grid are established in the numerical solution.

Theoretical investigation of the process of ignition in the system in question (Fig. 1) is performed for the following values of the thermophysical and thermochemical characteristics of the interacting substances [6–8, 12, 13]:

air: C_1 = 1190 J/(kg·K), ρ_1 = 1.161 kg/m^3, and λ_1 = 0.026 W/(m·K);

steel: C_2 = 470 J/(kg·K), ρ_2 = 7831 kg/m^3, λ_2 = 49 W/(m·K), and Q_c = 205 kJ/kg;

gasoline: C_{32} = 2060 J/(kg·K), ρ_{32} = 751 kg/m^3, λ_{32} = 0.116 W/(m·K), C_4 = 2280 J/(kg·K), ρ_4 = 2.5 kg/m^3, λ_4 = 0.027 W/(m·K), Q_o = 45 MJ/kg, E = 130 kJ/mole, $k_0 = 7 \cdot 10^6$ sec^{-1}, M = 100 kg/kmole, Q_e = 29.4 kJ/kg, and β = 0.0012 K^{-1};

kerosene: C_{32} = 2190 J/(kg·K), ρ_{32} = 885 kg/m^3, λ_{32} = 0.117 W/(m·K), C_4 = 2370 J/(kg·K), ρ_4 = 2.8 kg/m^3, λ_4 = 0.028 W/(m·K), Q_o = 43.8 MJ/kg, E = 190 kJ/mole, $k_0 = 7 \cdot 10^7$ sec^{-1}, M = 166.2 kg/kmole, Q_e = 26.1 kJ/kg, and β = 0.00096 K^{-1};

diesel fuel: C_{32} = 2980 J/(kg·K), ρ_{32} = 887.7 kg/m^3, λ_{32} = 0.1169 W/(m·K), C_4 = 3230 J/(kg·K), ρ_4 = 3.1 kg/m^3, λ_4 = 0.029 W/(m·K), Q_o = 42 MJ/kg, E = 250 kJ/mole, $k_0 = 9 \cdot 10^8$ sec^{-1}, M = 150 kg/kmole, Q_e = 25 kJ/kg, and β = 0.0009 K^{-1};

silk: C_{31} = 1386 J/(kg·K), ρ_{31} = 1560 kg/m^3, and λ_{31} = 0.060 W/(m·K);

wool: C_{31} = 1721 J/(kg·K), ρ_{31} = 1320 kg/m^3, and λ_{31} = 0.052 W/(m·K);

linen: C_{31} = 1580 J/(kg·K), ρ_{31} = 1500 kg/m^3, and λ_{31} = 0.088 W/(m·K).

On passage to dimensionless variables we use L, V_s, t_s, and T_s as the scale quantities. The results of the performed numerical investigations are illustrated at T_s = 1000 K, the dimensions of the solution domain $L = 20 \cdot 10^{-3}$ m and $H = 10 \cdot 10^{-3}$ m, and the dimensions of the particle $L_p = 1 \cdot 10^{-3}$ m and $H_p = 4 \cdot 10^{-3}$ m.

The convection rate of the fuel vapor near the fluid surface is determined from the formula [14] $V_s = \sqrt{g\beta\Delta TL}$.

The maximum possible real time of delay of ignition in the system in question (Fig. 1) t_s = 5 sec is selected as the time scale.

Investigation Results. As a result of the numerical modeling of the process under study we have established the dependence of the delay time of ignition of the vapor of typical liquid fuel, i.e., gasoline, on the initial temperature of a steel particle for a fixed volume fraction of the gasoline in wool fabric impregnated with it (Table 1).

Analyzing the resulting dependence of τ_d on the initial temperature of the steel particle, we can infer that at $\Theta_p = 2$, the value of τ_d is virtually half as high as the analogous index for $\Theta_p = 1$. It is seen from Table 1 that for $\varphi_{32} = 0.15$, a very high temperature of the ignition source $\Theta_p = 0.95$ is inadequate to realize ignition conditions.

It is well known [3] that ignition of a vapor-gas mixture by a single high-temperature particle is possible for a concentration of the fuel in the mixture of the order of 10–15%. This result shows that a relatively low content of the fuel is sufficient to realize the conditions of ignition of the vapor-gas mixture. It can be inferred that the volume fraction of the liquid fuel φ_{32} is one basic parameter determining the characteristics of ignition.

Table 2 gives the dependence of the delay time of ignition of the mixture of air with the vapor of a widely used fuel, i.e., kerosene, entering the gas phase above the particle from the surface of wool fabric impregnated with it.

Table 2 demonstrates the substantial influence of the volume fraction of the components of the liquid fuel in the fabric on the characteristics of ignition in the system in question (Fig. 1). The ignition-delay time as a function of the volume fraction φ_{32} derives from the fact that when the concentrations of the liquid fuels in the fabric are low the fluid evaporates less intensely, a smaller amount of the fuel vapor diffuses into the ambient air, and the concentration of the fuel in the vapor-gas mixture above the particle decreases, which causes the ignition-delay time to increase, whereas for $\varphi_{32} = 0.08$, no ignition conditions are realized at all.

TABLE 1. Ignition-Delay Times in the System Steel Particle–Wool Fabric–Gasoline–Air as Functions of Θ_p for $\varphi_{32} = 0.15$

Θ_p, K	2	1.8	1.6	1.5	1.4	1.2	1	0.95
τ_d	0.343	0.369	0.454	0.504	0.553	0.665	0.787	No ignition

TABLE 2. Ignition-Delay Times in the System Steel Particle–Wool Fabric–Kerosene–Air as Functions of φ_{32} at $\Theta_p = 1.5$

φ_{32}	0.2	0.18	0.16	0.15	0.14	0.12	0.1	0.08
τ_d	0.378	0.423	0.483	0.537	0.559	0.618	0.726	No ignition

TABLE 3. Ignition-Delay Times in the System Steel Particle–Fabric–Liquid Fuel–Air τ_d Depending on the Type of Fabric and Fuel for $\Theta_p = 1.5$ and $\varphi_{32} = 0.15$

Fuel	Fabric material		
	linen	silk	wool
Gasoline	0.441	0.469	0.504
Kerosene	0.468	0.497	0.537
Disel fuel	0.505	0.523	0.581

Table 3 gives results of numerical modeling of the process under study for a few kinds of typical liquid fuels (gasoline, kerosene, diesel fuel) and fabrics (wool, silk, linen).

An analysis of numerical τ_d values (Table 3) shows that ignition conditions are realized for different combinations of liquid fuels and fabric materials. The resulting differences of the ignition-delay times for the selected liquid fuels and fabric materials are attributed to the difference in their thermophysical and thermochemical characteristics.

Figure 2a and b gives the temperature field and the position of the characteristic isotherms in the system (Fig. 1) at the instant of ignition in the interaction of a metal particle with the surface of fabric impregnated with liquid fuel. It is seen that the warmup zone of the fabric is much larger than the analogous parameter for the case of interaction between the fluid and the hot particle [3]. The temperature of the fabric impregnated with the fluid near the lower particle surface reaches much higher values than the analogous indices in ignition of fluids.

The dimensions of the warmup zone can change substantially depending on the fabric and its porosity and on the relative content of the components of the liquid fuel in it. In particular, when the pores of a condensed solid phase (fabric) are filled with the liquid-fuel components the probability of intense evaporation near the particle-fabric boundary is high. Under certain conditions (at high Θ_p and φ_{32}), this can lead to ignition of the vapor-gas mixture in the pores or on the surface of the fabric.

Figure 2c shows a typical concentration field, from which it is clear that the fuel concentration is maximum at the evaporation boundary. The nonuniform reduction in the concentration with distance from the fluid surface is noticeable. The reason is that most of the fuel vapor enters the ambient air near the high-temperature particle due to intense evaporation in this region. The fuel vapor ascending along the lateral faces of the particle is additionally heated by the heat of the ignition source. Once the upper bound has been reached, the flows of the fuel vapor combine. This causes the concentration of the fuel vapor in the air and the temperature in the vapor-gas mixture near the particle to increase. Therefore, in the system in question (Fig. 1), the ignition of the vapor-gas mixture occurs near the upper bound of the particle in the region of the axis of symmetry (Fig. 2a).

Figure 2d and e gives the position of the isolines of the stream function and the vorticity-vector field at the instant of ignition. An analysis of the isolines of the stream function shows that the fuel vapor, in motion from the surface of the fabric impregnated with fire-hazardous fluid, produces nonuniform ascending flows. The basic vorticity contour near the upper bound of the particle and the additional contour near the lateral faces of the particle are clearly seen (Fig. 2e). The obtained result is attributed to the fact that vapor flows moving with a high velocity near the lateral particle faces are formed due to the intense evaporation of the components of the fluid. Once the upper bound of the particle has been reached, part of the vapor continues to move in the direction opposite to the normal to the evaporation surface. The other part of the vapor moves in the direction of the axis of symmetry of the particle above its surface, which is caused by molecular diffusion due to the nonuniform distribution of the fuel concentration in the

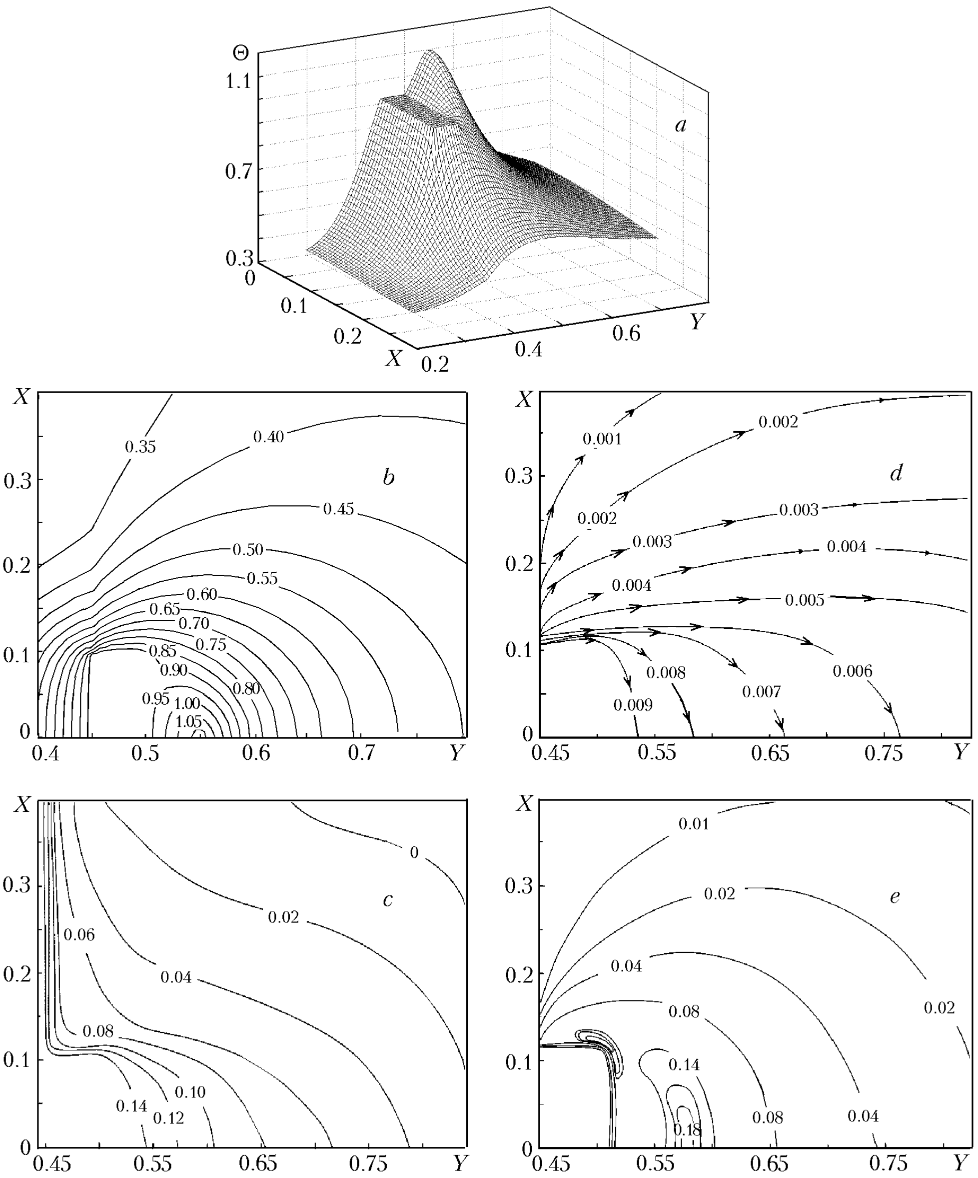

Fig. 2. Temperature field (a), isotherms of Θ (b), field of fuel concentrations C_f (c), isolines of stream function Ψ (d), and field of vorticity vector **Ω** (e) in the system steel particle–wool fabric impregnated with gasoline–air at the instant of ignition (τ_d = 0.787) for Θ_p = 1 and φ_{32} = 0.15.

gas region and by natural convection due to the heat fluxes from the surface of the heat-release source. The vapor moves from the other lateral face of the particle analogously to the motion of this part of the vapor flows. The flows moving in opposite directions combine to form vortex structures. A few circulation flows whose formation is attributable to the action of the hot particle and its finite dimensions are seen in Fig. 2e. It is noteworthy that the formation of vortices at the heat-release source is the most intense due to the intensification of the processes of transfer at the heated portion. Depending on the temperature and dimensions of the particle the contours of circulation flows can substantially change compared to those presented in Fig. 2e. The reason is that a sharp inhomogeneity of the temperatures and hydrodynamic parameters is observed in the presence of a particle heated to high temperatures in the system in question (Fig. 1). Under such conditions, the velocity and direction of the vapor flows are influenced by the lifting and body forces and by the viscous-friction forces in the vapor-gas mixture.

CONCLUSIONS

1. The basic factors determining the intensity of the ignition process under study are the initial temperature of the particle and the volume fraction of the components of the liquid fuel in the fabric.

2. The ignition zone of the vapor-gas mixture under the considered conditions is in the gas region above the particle in the region of the axis of symmetry.

3. The conditions of ignition of the vapor-gas mixture are realized for a number of popular fabrics and typical liquid fuels.

4. The obtained numerical results of theoretical modeling make it possible to explain the mechanism of widespread inflammations during welding and other works in the immediate vicinity of the portions of evaporation of flammable fluids.

5. The presented mathematical model of ignition can be used for further basic research into the heat- and mass-transfer processes in the ignition of mixtures of air with the vapor of liquid fuels by single particles of different physical natures that are heated to high temperatures.

This work was carried out with financial support of the Russian Foundation for Basic Research (code of the project 06-08-00366-a).

NOTATION

C, specific heat, J/(kg·K); C_f, concentration of the liquid-fuel vapor ($0 < C_f < 1$); E, activation energy, kJ/mole; Fo, Fourier number; g, free-fall acceleration, m/sec^2; Gr, Grashof number; H, characteristic dimension of the solution domain along the X axis, m; H_p, characteristic dimension of the particle along the X axis, m; k_0, pre-exponential factor, sec^{-1}; L, characteristic dimension of the solution domain along the Y axis, m; L_p, characteristic dimension of the particle along the Y axis, m; M, molecular weight, kg/mole; m_1 and m_2, constants; Pr, Prandtl number; Q_e, thermal effect of evaporation of the fluid, kJ/kg; Q_c, thermal effect of crystallization of the heating source, kJ/kg; Q_o, thermal effect of the oxidation reaction, MJ/kg; R, universal gas constant, J/(mole·K); Re, Reynolds number; Sc, Schmidt number; Sh, Strouhal number; T, temperature, K; T_s, temperature scale, K; ΔT, temperature difference ($\Delta T = T_s - T_0$), K; t_s, time scale, sec; U, dimensionless component of the fuel-vapor velocity in the projection onto the X axis; V, dimensionless component of the fuel-vapor velocity in the projection onto the Y axis; V_s, scale of the convection rate of the fuel vapor near the fluid surface, m/sec; V_c, linear velocity of crystallization of the particle, m/sec; W_c, mass velocity of crystallization of the particle, kg/(m^2·sec); W_o, mass rate of oxidation of the fuel vapor, kg/(m^3·sec); X, Y, dimensionless analogs of the coordinates of the Cartesian coordinate system; β, volumetric expansion coefficient, K^{-1}; $\delta(X, Y, \tau + \Delta\tau)$ and $\delta(X, Y, \tau)$, distances from the lower bound of the particle to the crystallization front at the $(\tau + \Delta\tau)$th and τth time step, m; Θ, dimensionless temperature; Θ_p, initial particle temperature; λ, thermal conductivity, W/(m·K); ρ, density, kg/m^3; τ, dimensionless time; τ_d, dimensionless ignition-delay time; φ, volume fraction; Ω, dimensionless analog of the vorticity vector; Ψ, dimensionless analog of the stream function. Subscripts: 0, initial instant of time; 1, air; 2, parameters in the particle; 3, fabric impregnated with flammable fluid; 31, fabric material; 32, components of the liquid fuel; 4, liquid-fuel vapor; 5, vapor-gas mixture; f, fuel; d, delay; e, evaporation; c, crystallization; s, scale; o, oxidation; p, particle.

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