

DISTINCTIVE FEATURES OF THE GAS-PHASE IGNITION OF A MIXTURE OF A KEROSENE VAPOR AND AIR BY A STEEL WIRE HEATED TO HIGH TEMPERATURES

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The process of ignition of a mixture of air and a kerosene vapor by a steel wire heated to high temperatures has been modeled numerically. The investigations have been carried out on a model allowing for the combination of heat- and mass-transfer processes (evaporation of the flammable liquid, diffusion and convection of the fuel vapor in air, heat conduction, and oxidation of the fuel vapor in air). The values of the delay time of ignition of the vapor-gas mixture have been determined and the scale of influence of the initial temperature and dimensions of the wire, the distance between the heating source and the kerosene surface, and the temperature and humidity of air on the inertia of the ignition process have been established.

Keywords: steel wire, vapor-gas mixture, kerosene, gas-phase ignition, ignition-delay time.

Introduction. It is well known [1–3] that minor and major failures in energy-supply systems are responsible for many fires. As a rule, in such cases we have overheating, carbonization, melting, and smoldering of the coatings of electric cables, which consequently impacts directly on conducting elements. The latter in turn gives rise to conductor portions heated to high temperatures, which become ignition sources on contact with combustibles [2].

The processes of electric-spark ignition of solid (e.g., wood) and liquid (hydrocarbon fuels) condensed substances have been thoroughly studied [4, 5]. The processes of ignition of mixtures of a liquid-combustible vapor and air by electric-current conductors heated to high temperatures (more than 900 K) remain less well understood. Investigation of such processes is reduced to an analysis of the conditions of thermal interaction between small-size heated bodies (e.g., incandescent wires and metal rods) and vapor-gas mixtures.

The present work seeks to numerically investigate the gas-phase ignition of a mixture of a vapor of typical flammable liquid and air by a steel wire heated to high temperatures within the framework of a model that allows for the combination of physicochemical processes in the small vicinity of the wire and the liquid surface (evaporation of the liquid combustible to absorb energy, diffusion and convection of the fuel vapor, heat conduction, and the reaction of oxidation of the fuel vapor in air to release heat.)

Formulation of the Problem. We consider the system heated wire–flammable liquid–vapor-gas mixture (Fig. 1). A typical liquid fuel with stable properties and well-studied characteristics, i.e., kerosene, is selected as a combustible. We consider the following stages of the ignition process. At an ambient-air temperature of 270–310 K, we have the evaporation of kerosene spread over the surface of a solid body (e.g., a concrete coating). The fuel vapor mixes, due to diffusion and convection, with air containing a certain fraction of steam. This produces a mixture of the fuel vapor, water, and air above the liquid-fuel surface. After a certain time interval, the vapor masses reach the wire heated to a high temperature (more than 900 K) and located at a certain distance from the surface of the flammable liquid $d_{w,liq}$. Investigations are performed for steel wires spread wide apart. The vapor-gas mixture is heated by the wire energy and, once the temperatures and concentrations of the fuel vapor in the mixture sufficient for ignition have been attained, inflammation occurs.

We consider a wire whose one dimension substantially exceeds the other two dimensions ($l_w = 0.002$ m and $h_w = 0.001$ m). Regions of dimensions $l = 0.02$ m and $h = 0.01$ m are separated in kerosene and air. The kerosene-film thickness l_1 is taken to be 0.007 m. The problem is solved in dimensionless variables in the axisymmetric formulation.

The parameters l_w , h_w , l_1 , $l_{w,liq}$, l , and h correspond to dimensionless (Fig. 1) analogs L_w , H_w , L_1 , $L_{w,liq}$, L , and H ($L_w = Y_3 - Y_2$, $H_w = X_1$, $L_1 = Y_1$, and $L_{w,liq} = Y_2 - Y_1$).

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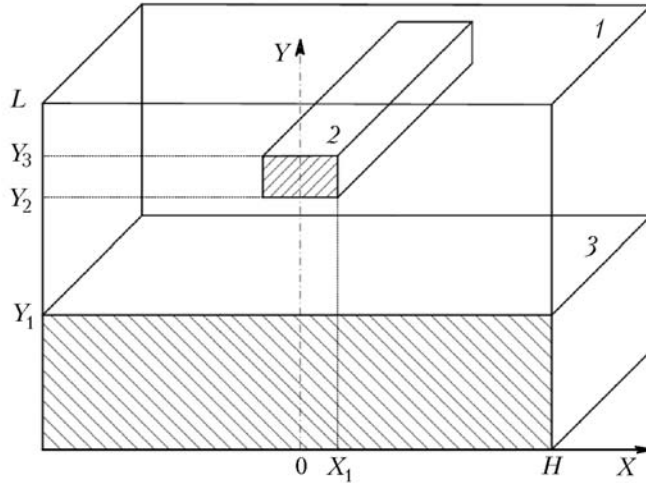


Fig. 1. Diagram of the solution domain of the problem: 1) vapor-gas mixture; 2) steel wire; 3) kerosene.

Modeling is performed under the following assumptions:

1. Evaporation of the liquid fuel produces one substance with known characteristics. Such an approach is traditionally used in solving problems of ignition of condensed substances [6, 7].

2. Possible processes of burnout of the liquid fuel are disregarded.

We take the traditional ignition conditions [6]: (1) the heat released as a result of the chemical reaction of ignition of the fuel vapor in air is larger than the heat transferred from the heated wire to the vapor-gas mixture; (2) the temperature of the vapor-gas mixture is higher than the initial temperature of the heating source.

Numerical modeling of the process of ignition in the system (Fig. 1) characterized by the parameters $0 < X < H$ and $Y_1 < Y < Y_2$, $X_1 < X < H$ and $Y_2 < Y < Y_3$, and $0 < X < H$ and $Y_3 < Y < L$ is reduced to solution, for $0 < \tau < \tau_d$, of a system of nonlinear differential equations of the form [8–10]:

the Poisson equation

$$\frac{\partial^2 \Psi}{\partial X^2} + \frac{\partial^2 \Psi}{\partial Y^2} = \Omega; \quad (1)$$

the equation of motion of the vapor-gas mixture

$$\frac{1}{Sh} \frac{\partial \Omega}{\partial \tau} + U \frac{\partial \Omega}{\partial X} + V \frac{\partial \Omega}{\partial Y} = \frac{1}{Re_1} \left[\frac{\partial^2 \Omega}{\partial X^2} + \frac{\partial^2 \Omega}{\partial Y^2} \right] + \frac{Gr_1}{Re_1^2} \frac{\partial \Theta_1}{\partial X}; \quad (2)$$

the energy equation

$$\frac{1}{Sh} \frac{\partial \Theta_1}{\partial \tau} + U \frac{\partial \Theta_1}{\partial X} + V \frac{\partial \Theta_1}{\partial Y} = \frac{1}{Re_1 Pr_1} \left[\frac{\partial^2 \Theta_1}{\partial X^2} + \frac{\partial^2 \Theta_1}{\partial Y^2} \right] + \frac{Q_o W_o l}{\rho_1(T) C_1(T) \Delta T V_{sc}}; \quad (3)$$

the equation of diffusion of the fuel vapor in air

$$\frac{1}{Sh} \frac{\partial C_f}{\partial \tau} + U \frac{\partial C_f}{\partial X} + V \frac{\partial C_f}{\partial Y} = \frac{1}{Re_{13} Sc_{13}} \left[\frac{\partial^2 C_f}{\partial X^2} + \frac{\partial^2 C_f}{\partial Y^2} \right] + \frac{l W_o}{\rho_{13}(T) V_{sc}}; \quad (4)$$

the equation of diffusion of the steam in air

$$\frac{1}{Sh} \frac{\partial C_{\text{wat}}}{\partial \tau} + U \frac{\partial C_{\text{wat}}}{\partial X} + V \frac{\partial C_{\text{wat}}}{\partial Y} = \frac{1}{Re_{12} Sc_{12}} \left[\frac{\partial^2 C_{\text{wat}}}{\partial X^2} + \frac{\partial^2 C_{\text{wat}}}{\partial Y^2} \right]; \quad (5)$$

the balance equation

$$C_{\text{wat}} + C_f + C_o = 1; \quad (6)$$

the heat-conduction equation for the wire

$$0 < X < X_1, \quad Y_2 < Y < Y_3, \quad \frac{1}{Fo_2} \frac{\partial \Theta_2}{\partial \tau} = \frac{\partial^2 \Theta_2}{\partial X^2} + \frac{\partial^2 \Theta_2}{\partial Y^2}; \quad (7)$$

the heat-conduction equation for the liquid

$$0 < X < H, \quad 0 < Y < Y_1, \quad \frac{1}{Fo_3} \frac{\partial \Theta_3}{\partial \tau} = \frac{\partial^2 \Theta_3}{\partial X^2} + \frac{\partial^2 \Theta_3}{\partial Y^2}. \quad (8)$$

It should be noted that unlike the mathematical models of [11, 12], the system of equations (1)–(8) allows for the content of the steam in the vapor-gas mixture. This system corresponds to the initial conditions ($\tau = 0$):

$$\Theta = \Theta_w \quad \text{for } 0 < X < X_1, \quad Y_2 < Y < Y_3; \quad \Theta = \Theta_0 \quad \text{for } 0 < X < H, \quad 0 < Y < Y_1;$$

$$\Omega = 0, \quad \Psi = 0, \quad C_f = 0, \quad C_{\text{wat}} = C_{\text{wat}0}, \quad \Theta = \Theta_{\text{amb}} \quad \text{for } 0 < X < H, \quad Y_1 < Y < Y_2;$$

$$X_1 < X < H, \quad Y_2 < Y < Y_3, \quad 0 < X < H, \quad Y_3 < Y < L.$$

The boundary conditions ($0 < \tau < \tau_d$) correspond to the model presented in [11].

The thermophysical characteristics of the vapor-gas mixture as of a heterogeneous system containing fuel vapor, steam, and air are calculated from the formula

$$\lambda_1(T) = \lambda_{11}(T) \phi_{11} + \lambda_{12}(T) \phi_{12} + \lambda_{13}(T) \phi_{13}, \quad C_1(T) = C_{11}(T) \phi_{11} + C_{12}(T) \phi_{12} + C_{13}(T) \phi_{13},$$

$$\rho_1(T) = \rho_{11}(T) \phi_{11} + \rho_{12}(T) \phi_{12} + \rho_{13}(T) \phi_{13}.$$

The volume fractions of the components of the vapor-gas mixture are computed from their mass concentrations from the expressions

$$\phi_{11} = \frac{\frac{C_o}{\rho_{11}(T)}}{\frac{C_o}{\rho_{11}(T)} + \frac{C_{\text{wat}}}{\rho_{12}(T)} + \frac{C_f}{\rho_{13}(T)}}, \quad \phi_{12} = \frac{\frac{C_{\text{wat}}}{\rho_{12}(T)}}{\frac{C_o}{\rho_{11}(T)} + \frac{C_{\text{wat}}}{\rho_{12}(T)} + \frac{C_f}{\rho_{13}(T)}}, \quad \phi_{11} + \phi_{12} + \phi_{13} = 1.$$

To compute the rate of oxidation of the fuel vapor in air W_o and the velocity of convection of the fuel near the kerosene-evaporation boundary V_{sc} we use the expressions of [11].

Method of Solution and Initial Data. The algorithm of solution of the system of differential equations (1)–(8) with corresponding initial and boundary conditions has been given in [11]. The reliability of the obtained results is determined by checking the conservatism of the difference scheme whose algorithm has been presented in [12]. To pass to dimensionless variables we use $T_{sc} = 1000$ K, $l = 0.02$ m, and $t_{sc} = 1$ sec as the scale quantities.

Numerical modeling of the investigated process of ignition is performed for the following values of the characteristics of the interacting substances and the heat- and mass-transfer conditions [13–17]: $\Theta_0 = 0.3$, $\Theta_w = 1.3$, $L_w =$

TABLE 1. Ignition-Delay Times as Functions of Θ_w for $L_w = 0.1$, $H_w = 0.05$, $L_{w.liq} = 0.35$, $\Theta_{amb} = 0.308$, and $C_{wat0} = 0.1$

Θ_w	1.4	1.35	1.30	1.25	1.20	1.15	1.10	1.05	1.00	0.95
τ_d	0.552	0.567	0.613	0.669	0.771	0.872	0.991	1.135	1.346	No ignition

TABLE 2. Ignition-Delay Times as Functions of L_w and H_w at $\Theta_w = 1.25$, $L_{w.liq} = 0.35$, $\Theta_{amb} = 0.308$, and $C_{wat0} = 0.1$

L_w	0.250	0.200	0.150	0.100	0.050
H_w	0.125	0.100	0.075	0.050	0.025
τ_d	0.581	0.598	0.623	0.669	No ignition

TABLE 3. Ignition-Delay Times as Functions of $L_{w.liq}$ for $L_w = 0.1$, $H_w = 0.05$, $\Theta_w = 1.25$, $\Theta_{amb} = 0.308$, and $C_{wat0} = 0.1$

$L_{w.liq}$	0.25	0.35	0.50	0.65	0.75
τ_d	0.426	0.669	1.035	1.494	No ignition

TABLE 4. Ignition-Delay Times as Functions of Θ_{amb} for $L_w = 0.1$, $H_w = 0.05$, $\Theta_w = 1.25$, $L_{w.liq} = 0.35$, and $C_{wat0} = 0.1$

Θ_{amb}	0.308	0.303	0.298	0.293	0.288	0.283	0.278
τ_d	0.669	0.676	0.692	0.708	0.747	0.851	No ignition

TABLE 5. Ignition-Delay Times as Functions of C_{wat0} for $L_w = 0.1$, $H_w = 0.05$, $\Theta_w = 1.25$, $L_{w.liq} = 0.35$, and $\Theta_{amb} = 0.308$

C_{wat0}	0	0.10	0.20	0.30	0.40	0.50
τ_d	0.653	0.669	0.695	0.741	0.829	No ignition

0.1, $H_w = 0.05$, $\Theta_{amb} = 0.308$, $C_{wat0} = 0$, $L_{w.liq} = 0.35$, $Q_o = 45$ MJ/kg, $E = 193.7$ kJ/mole, and $k_0 = 7 \cdot 10^7$ sec⁻¹. The thermophysical characteristics of kerosene and its vapor, air, the steam, and the steel wire have been presented in [14–17].

Investigation Results. The basic parameter of the ignition source in the considered system of the interacting substances (Fig. 1) is its energy content (heat content). It is determined by the temperature, dimensions, and thermo-physical properties of the source material. Tables 1 and 2 give results of a numerical analysis of the scale of influence of the initial temperature and dimensions of the wire on the inertia of the ignition process. Investigations have been performed at initial wire temperatures Θ_w lower than the melting temperature of steel ($\Theta_m = 1.45$ – 1.55) [17].

From Tables 1 and 2, it is clear that ignition conditions are realized in a fairly wide range of variation in Θ_w , L_w , and H_w . The obtained dependences of τ_d on the initial temperature and dimensions of the wire enable us to evaluate the inertia of the processes of ignition of mixtures of a liquid-fuel vapor and air by heating sources of small dimensions. The increase in τ_d with decrease in Θ_w , L_w , and H_w is caused by the decrease in the energy content of the warmed-up wire.

The inertia of the process under study is by far dependent not only on the characteristics of the heating source but also on the conditions of thermal interaction of the wire with the vapor-gas mixture. Table 3 gives the ignition-delay time as a function of the distance between the steel wire and the surface of the evaporated kerosene $L_{w.liq}$. It is clear from the table that the inertia of the ignition process is sharply diminished with $L_{w.liq}$. Thus, e.g., the τ_d values differ virtually three times for $L_{w.liq} = 0.25$ and 0.50 . The reason is that the mass of the fuel vapor flowing past the heating source increases as the heated wire approaches the kerosene surface. However, no ignition conditions are realized for $L_{w.liq} = 0.75$ and other adequate parameters of the process. It should be noted that ignition is also possible for $L_{w.liq} > 0.75$, as the wire's energy content increases due to the high values of Θ_w , L_w , and H_w .

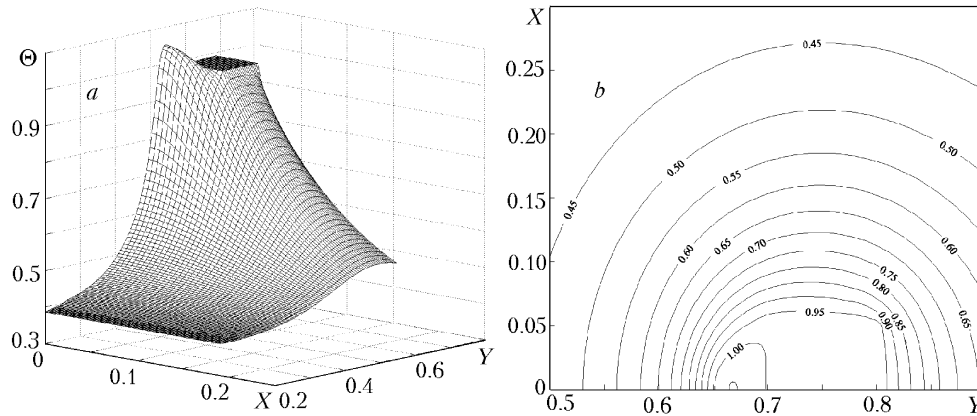


Fig. 2. Temperature field (a) and the Θ isotherms (b) at the instant of ignition ($\tau_d = 1.346$) for $L_w = 0.1$, $H_w = 0.05$, $\Theta_w = 1.0$, $L_{w.liq} = 0.35$, $\Theta_{amb} = 0.308$, and $C_{wat0} = 0$.

An analysis is made of the scale of influence of the temperature Θ_{amb} and humidity C_{wat0} of air in which the kerosene vapor oxidizes (Tables 4 and 5). From Table 4, it is clear that ignition conditions are realized even at relatively low air temperatures ($\Theta_{amb} = 0.283$). A pronounced nonlinear dependence of τ_d on Θ_{amb} is noteworthy.

Both the increase in the air humidity C_{wat0} and the decrease in Θ_{amb} lead to a nonuniform increase in τ_d (Table 5). It should be noted that the possibility of igniting the vapor-gas mixture is preserved even at a high initial air humidity ($C_{wat0} \leq 0.3$). As the initial wire temperature increases to $\Theta_w = 1.4$, the C_{wat0} range in which ignition conditions are realized increases to $C_{wat0} \leq 0.50$.

Figure 2 gives the temperature field and the position of the characteristic isotherms in the considered system of the interacting substances at the instant of ignition to illustrate results of the performed numerical modeling. In Fig. 2a, it is seen that the ignition zone is above the heated wire in the gas region. This result is in good qualitative agreement with the data [4] of experimental investigation of the process of ignition of moving gas mixtures by high-temperature metal spheres and rods. The location of the ignition zone above the wire can be explained as follows. In the system in question, the kerosene vapor is formed uniformly over the entire surface as a result of phase transition. Thereafter the vapor diffuses into the ambient air and mixes with it. A vapor-gas mixture with a high content of the kerosene vapor but having a temperature insufficient for ignition is formed. When the incandescent wire appears in the gas region above the kerosene- evaporation surface, vortices of the vapor-gas flows are formed near the lower surface of the heating source. As a result the number of heated vapor masses under the wire increases and the temperature of the vapor-gas mixture grows. Under these conditions, the rate of the reaction of oxidation of the fuel vapor sharply increases, and ignition of the vapor-gas mixture in the immediate vicinity of the lower face of the wire occurs (Fig. 2a). The obtained result enables us to single out the basic distinctive features of the conditions of ignition of flammable liquids in the presence of direct thermal contact with the heating source [12] and when it is located at a certain distance from the evaporation boundary. In the first case the stages of warming up of the liquid and the conditions of thermal interaction of the heating source with the liquid (e.g., the presence of a vapor gap between the source and the inflammable liquid substance, the immersion of the source in the liquid) are determining. In the second case the inertia of the ignition process is mainly determined by the time of warming up of the vapor-gas mixture.

The small dimensions of the ignition zone and its relatively small remoteness from the surface of the incandescent wire are noteworthy (Fig. 2b). The dimensions of this zone are much smaller than the area of the spread liquid fuel and the heated wire.

CONCLUSIONS

1. We have investigated the combination of interrelated processes of heat and mass transfer with phase transformations and chemical reactions in ignition of a mixture of typical combustible and air by a small-size wire heated to high temperatures.

2. We have established the ranges of variation in the determining parameters (Θ_w , L_w , H_w , Θ_{amb} , and C_{wat0}) of the ignition process and have separated their limiting values for which no ignition conditions are realized.

3. We have established the location of the zone of ignition of the vapor-gas mixture near the lower face of the incandescent wire. The dimensions of this zone and the distance between it and the heating source have been determined.

4. Analysis of the obtained results has shown that most of the ignition-delay time is accounted for by the warmup time of the vapor-gas mixture, which is mainly characterized by the intensity of the diffusion and convection of the fuel vapor in air. The convective transfer of the fuel vapor in the oxidant medium makes the entire ignition process under study much more complicated and, as a consequence, influences the ignition-delay time on a larger scale than the diffusion process does.

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NOTATION

C , specific heat, J/(kg·K); C_{wat} , mass concentration of the steam; C_{wat0} , initial mass concentration of the steam; C_f , mass concentration of the fuel in the mixture; C_o , mass concentration of air; E , activation energy, kJ/mole; Fo , Fourier number; Gr , Grashof number; h , dimension of the solution domain along the x axis, m; h_w , dimension of the wire along the x axis, m; k_0 , preexponential factor, sec^{-1} ; l , dimension of the solution domain along the y axis, m; l_w , dimension of the wire along the y axis, m; $l_{w.liq}$, distance from the wire to the kerosene surface, m; l_1 , kerosene-film thickness, m; Pr , Prandtl number; Q_o , thermal effect of the oxidation reaction, MJ/kg; Re , Reynolds number; Sc , Schmidt number; Sh , Strouhal number; T , temperature, K; ΔT , temperature difference ($\Delta T = T_{sc} - T_0$), K; T_{sc} , temperature scale, K; t_{sc} , 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_{sc} , scale of velocity of the fuel-vapor convection near the liquid surface, m/sec; W_o , mass velocity (rate) of oxidation of the fuel vapor, $\text{kg}/(\text{m}^3 \cdot \text{sec})$; X , Y , dimensionless analogs of the coordinates of the Cartesian coordinate system x , y ; Θ , dimensionless temperature; Θ_0 , dimensionless initial kerosene temperature; Θ_{amb} , dimensionless initial ambient air temperature; Θ_w , dimensionless initial wire temperature; Θ_m , dimensionless melting temperature; Ψ , dimensionless analog of the stream function; Ω , dimensionless analog of the vorticity vector; λ , thermal conductivity, W/(m·K); ρ , density, kg/m^3 ; τ , dimensionless time; τ_d , dimensionless ignition-delay time; ϕ , volume fraction. Subscripts: 0, initial instant of time; 1, vapor-gas mixture; 2, wire; 3, kerosene; 11, air; 12, steam (water vapor); 13, fuel vapor; wat, water; f, fuel; d, delay; sc, scale; o, oxidation; amb, ambient air; w, wire; w.liq, wire and liquid; m, melting.

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