

Research Article

Mathematical Modeling of Heat and Mass Transfer Processes with Chemical Reaction at Polymeric Material Ignition by Several Small-Size Hot Particles

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Numerical research of interconnected heat and mass transfer processes in the “two hot particles—polymeric material—air” system was executed. The joint effect of several local heat sources on the main integrated characteristic of ignition process (ignition delay time) was established. Two ignition models characterized by the relative positioning of hot particles on a polymeric material surface were revealed. Besides, there were established characteristics of local heat sources and the distance between them ($700\text{ K} < T_p < 1150\text{ K}$ and $L > 1.5$ or $T_p > 1150\text{ K}$ and $0.25 < L < 1.5$) when regularities of heat and mass transfer processes in the “two hot particles—polymeric material—air” system are similar to regularities of heat and mass transfer processes in the “single hot particle—polymeric material—air” system.

1. Introduction

In recent years, polymeric materials (polymethyl methacrylate, polystyrene, polyethylene, etc.) have been widely adopted in various industries as decorative and constructive elements. Polymeric material products are very susceptible to thermal effects [1–4] even at rather low outside temperature ($T \approx 400\text{--}600\text{ K}$). Under conditions of some technological processes (at increased ambient temperature) strength characteristics are changed, melting occurs, dangerous carcinogens and are emitted. Possible temperatures of technological processes for power production can reach more than 1000 K . Under such conditions, the probability of local power sources (metal and nonmetallic particles warmed to high temperature with sizes about several millimeters) formation is high [5–9].

The numerical research results [10, 11] were obtained for thermal conduction and thermal convection processes during a polymeric material ignition by a single metal particle heated to high temperature. Established theoretical consequences can be used for developing guidelines and methods to reduce the flammability, ignition preventing, and

subsequent stages of polymeric material combustion processes. However, in practice, several (two, three, etc.) small-size particles heated to high temperature can cause fires. Ignition conditions and heat transfer characteristics may be different for the “single hot particle—polymeric material—air” system and the “two hot particles—polymeric material—air” system. For example, it is known that ignition delay time of solid condensed substance (composite propellant) at high concentration (large number per unit area surfaces) of hot particles in the gas stream equals the values of ignition delay time at condensed substance heating by a massive plate with constant (during ignition period) high temperature [5, 6]. Therefore, more detailed information about characteristics of physical and chemical processes at polymeric material heating by several hot particles is necessary for the development of relevant precautionary activities.

The purpose of the present study was to develop the mathematical model and analyze the characteristics of interconnected heat and mass transfer processes during interaction of two small-size metal particles heated to high temperatures with a polymeric material at the accounting

of thermal conduction in condensed substance and thermal decomposition of polymeric material, thermal convection, and diffusion and oxidation reaction in outside gas area.

2. Problem Statement

It was determined [12] that ignition conditions for liquid condensed substances are defined by the distance between two neighboring particles at the various quantities of hot particles (local heat sources) falling to the flammable material surface. Therefore, previous study results [12] were taken into account at the problem statement.

A scheme with two steel particles heated to high temperature in the parallelepiped shape (with the same sizes) situated on the surface of typical polymeric material, polymethyl methacrylate (PMMA), was chosen to simulate the conditions of hot particle flow interaction with polymeric material. We reasonably [12] used the “two hot particles—polymeric material—air” system (Figure 1) instead of the “several hot particles—polymeric material—air” system for heat and mass transfer process investigation. Areas with sizes x_L and y_L much larger than the sizes of hot particles x_p and y_p were allocated in polymeric material and air (Figure 1).

The rate of PMMA thermal decomposition process accelerated at polymeric material near-surface layer heating (at $0 < t < t_d$) by the heat of hot particles. Gaseous products of polymeric material pyrolysis mixed with an oxidizer (air) at the diffusion in outside gas area. The gas mixture was warmed by the thermal convection at its movement along lateral sides ($x = x_1, x = x_2, x = x_3, x = x_4$, and $y_1 < y < y_2$) of heat sources (Figure 1). The ignition occurred when the temperature and concentration of combustible component (PMMA gas) reached the critical values.

The assumptions for the problem statement of heat and mass transfer process include the following.

- (1) A gas substance with known kinetic parameters is formed as a result of PMMA thermal decomposition. The realization of only one “effective” oxidation reaction where one substance reacts was assumed.
- (2) A possible burning out of the polymeric material is not considered. It was found by the authors [12] that the burning out of substance near-surface layer has an insignificant effect on the ignition characteristics at local heating during short time period (less than 0.5 s).
- (3) Surfaces of hot particles and polymeric material ($x_1 < x < x_2, x_3 < x < x_4, y = y_1$) have ideal thermal contact. The possibility of gas gap formation is not considered.

Ignition conditions were taken into account [13].

- (1) The heat release from the oxidation reaction of PMMA gas is more than the heat consumed by both hot particles to the heating of polymeric material and gas mixture.
- (2) The temperature of gas area in a zone of intense exothermic reaction exceeds the initial temperature of local heat sources.

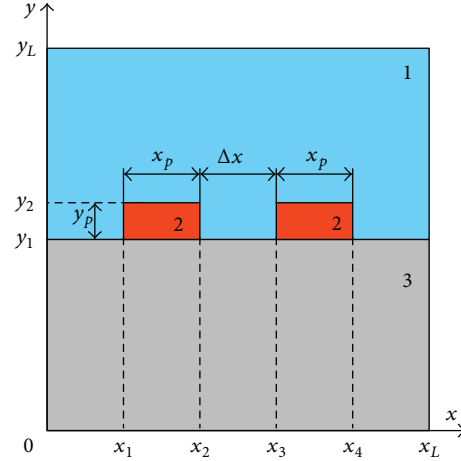


FIGURE 1: A scheme of the solution domain at $t = 0$: 1: oxidizer (gas mixture at $0 < t \leq t_d$); 2: hot particle; 3: polymeric material.

3. Mathematical Model and Solution Method

The mathematical model describes the interconnected processes of thermal conduction and thermal decomposition in a condensed substance and thermal convection and diffusion processes and oxidation reaction in the gas area are represented by the system of nonstationary partial differential equations ($0 < t < t_d$).

For gas mixture ($0 < x < x_1, x_2 < x < x_3, x_4 < x < x_L, y_1 < y < y_2; 0 < x < x_L, y_2 < y < y_L$), the following equations and conditions were implemented.

Poisson's equation:

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} = -\omega. \quad (1)$$

The equation of gas mixture movement:

$$\frac{\partial \omega}{\partial t} + u \frac{\partial \omega}{\partial x} + v \frac{\partial \omega}{\partial y} = v_1 \left(\frac{\partial^2 \omega}{\partial x^2} + \frac{\partial^2 \omega}{\partial y^2} \right) + \beta g \frac{\partial T_1}{\partial x}. \quad (2)$$

The thermal convection equation:

$$\rho_1 C_1 \left(\frac{\partial T_1}{\partial t} + u \frac{\partial T_1}{\partial x} + v \frac{\partial T_1}{\partial y} \right) = \lambda_1 \left(\frac{\partial^2 T_1}{\partial x^2} + \frac{\partial^2 T_1}{\partial y^2} \right) + Q_1 W_1. \quad (3)$$

The diffusion equation:

$$\rho_1 \left(\frac{\partial C_f}{\partial t} + u \frac{\partial C_f}{\partial x} + v \frac{\partial C_f}{\partial y} \right) = \rho_1 D_1 \left(\frac{\partial^2 T_1}{\partial x^2} + \frac{\partial^2 T_1}{\partial y^2} \right) - W_1. \quad (4)$$

The balance equation:

$$C_f + C_o = 1. \quad (5)$$

The heat balance equation for hot particles ($x_1 < x < x_2, x_3 < x < x_4, y_1 < y < y_2$):

$$\rho_2 C_2 \frac{\partial T_2}{\partial t} = \lambda_2 \left(\frac{\partial^2 T_2}{\partial x^2} + \frac{\partial^2 T_2}{\partial y^2} \right). \quad (6)$$

The heat balance equation for the polymeric material ($0 < x < x_L, 0 < y < y_1$):

$$\rho_3 C_3 \frac{\partial T_3}{\partial t} = \lambda_3 \left(\frac{\partial^2 T_3}{\partial x^2} + \frac{\partial^2 T_3}{\partial y^2} \right) - Q_3 W_3. \quad (7)$$

The initial conditions ($t = 0$):

$$\begin{aligned} T &= T_0 \quad \text{at } 0 < x < x_L, \quad 0 < y < y_1; \\ T &= T_p \quad \text{at } x_1 < x < x_2, \quad x_3 < x < x_4, \quad y_1 < y < y_2; \\ T &= T_0, \quad C_f = 0, \quad \psi = 0, \quad \omega = 0 \\ &\text{at } 0 < x < x_1, \quad x_2 < x < x_3, \quad x_4 < x < x_L, \quad y_1 < y < y_2; \\ &0 < x < x_L, \quad y_2 < y < y_L. \end{aligned} \quad (8)$$

The boundary conditions ($0 \leq t \leq t_d$):

$$\begin{aligned} x = 0, \quad x = x_L, \quad 0 < y < y_1: \quad \frac{\partial T_3}{\partial x} &= 0; \\ x = 0, \quad x = x_L, \quad y_1 < y < y_L: \\ \frac{\partial T_1}{\partial x} = 0, \quad \frac{\partial C_f}{\partial x} = 0, \quad \frac{\partial \psi}{\partial x} &= 0; \\ x = x_1, \quad x = x_3, \quad y_1 < y < y_2: \\ -\lambda_1 \frac{\partial T_1}{\partial x} = -\lambda_2 \frac{\partial T_2}{\partial x}, \quad T_1 = T_2, \quad \frac{\partial C_f}{\partial x} = 0, \quad \frac{\partial \psi}{\partial x} &= 0, \\ \psi &= 0; \\ x = x_2, \quad x = x_4, \quad y_1 < y < y_2: \\ -\lambda_2 \frac{\partial T_2}{\partial x} = -\lambda_1 \frac{\partial T_1}{\partial x}, \quad T_2 = T_1, \quad \frac{\partial C_f}{\partial x} = 0, \quad \frac{\partial \psi}{\partial x} &= 0, \\ \psi &= 0; \\ y = 0, \quad 0 < x < x_L: \quad \frac{\partial T_3}{\partial y} &= 0; \\ y = y_1, \quad 0 < x < x_1, \quad x_2 < x < x_3, \quad x_4 < x < x_L: \\ -\lambda_3 \frac{\partial T_3}{\partial y} = -\lambda_1 \frac{\partial T_1}{\partial y} + Q_1 W_1, \quad T_3 = T_1, \\ \rho_1 D_1 \frac{\partial C_f}{\partial y} = -W_3, \quad \frac{\partial \psi}{\partial y} &= 0; \\ y = y_1, \quad x_1 < x < x_2, \quad x_3 < x < x_4: \\ -\lambda_3 \frac{\partial T_3}{\partial y} = -\lambda_2 \frac{\partial T_2}{\partial y}, \quad T_3 = T_2; \\ y = y_2, \quad x_1 < x < x_2, \quad x_3 < x < x_4: \\ -\lambda_2 \frac{\partial T_2}{\partial y} = -\lambda_1 \frac{\partial T_1}{\partial y}, \quad T_2 = T_1, \quad \frac{\partial C_f}{\partial y} = 0, \\ \frac{\partial \psi}{\partial y} = 0, \quad \psi &= 0; \\ y = y_L, \quad 0 < x < x_L: \quad \frac{\partial T_1}{\partial y} = 0, \quad \frac{\partial C_f}{\partial y} = 0, \quad \frac{\partial \psi}{\partial y} &= 0. \end{aligned} \quad (9)$$

Stream function ψ and vortex velocity vector ω :

$$u = \frac{\partial \psi}{\partial y}, \quad v = -\frac{\partial \psi}{\partial x}, \quad \omega = \text{rot}_y \vec{v} = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}. \quad (10)$$

The mass rate of combustible gas mixture oxidation [14]:

$$W_1 = \rho_1 k_1^0 C_o^n C_f^m \exp\left(-\frac{E_1}{RT_1}\right), \quad (11)$$

where n and m are constants ($n = m = 1$).

The mass rate of polymeric material pyrolysis:

$$W_3 = \int_0^{y_1} \rho_3 k_3^0 \exp\left(-\frac{E_3}{RT_s}\right) dy. \quad (12)$$

The diffusion coefficient of polymeric material thermal decomposition products in a gas mixture:

$$D_1 = D_0 \left(\frac{T_1}{273} \right)^{1.7}. \quad (13)$$

Volume fractions of gas mixture components were determined by its dimensionless mass concentrations:

$$\varphi_f = \frac{C_f / \rho_f}{C_f / \rho_f + C_o / \rho_o}, \quad \varphi_o + \varphi_f = 1. \quad (14)$$

Thermophysical properties of gas mixture were defined as

$$\begin{aligned} \lambda_1 &= \lambda_f \varphi_f + \lambda_o \varphi_o, \\ C_1 &= C_f \varphi_f + C_o \varphi_o, \\ \rho_1 &= \rho_f \varphi_f + \rho_o \varphi_o. \end{aligned} \quad (15)$$

The system of (1)–(7) with the corresponding initial and boundary conditions was solved by the finite difference method. The equations of elliptic type (Poisson's and gas mixture movement) were solved by the alternating direction method. Difference analogues of heat balance and diffusion equations were solved by the locally one-dimensional method. A system of differential equations was solved by the iteration method and the sweep method at each iteration (for nonlinear equations), using the implicit four-point difference scheme.

In developing the algorithm for solving numerically the ignition problem, we used the elements of the algorithm developed for the numerical simulation of conjugate heat transfer processes at the local heating of an area with limited sizes [15]. To improve the accuracy of integrated characteristics computation, we used not less than 500 knots of difference grid for each coordinate and chose a short time step $\Delta t = 10^{-6}$ s. The verification of numerical research results was executed similar to [10, 11] by the test of conservation for the used difference scheme. The error of the energy conservation law in the solution area does not exceed 2.7% (Figure 1).

TABLE 1: Thermophysical properties of substances.

Substance	ρ , kg/m ³	C , J/(kg·K)	λ , W/(m·K)
Air	1.161	1190	0.026
Steel	7831	470	49
PMMA (solid)	1200	1466.5	0.19
PMMA (gas)	1.29	1005.6	0.025

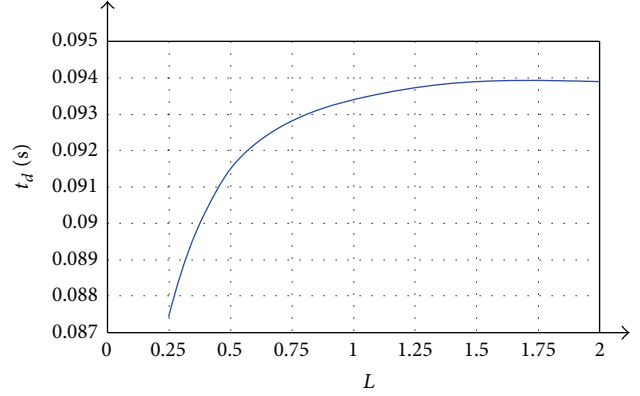
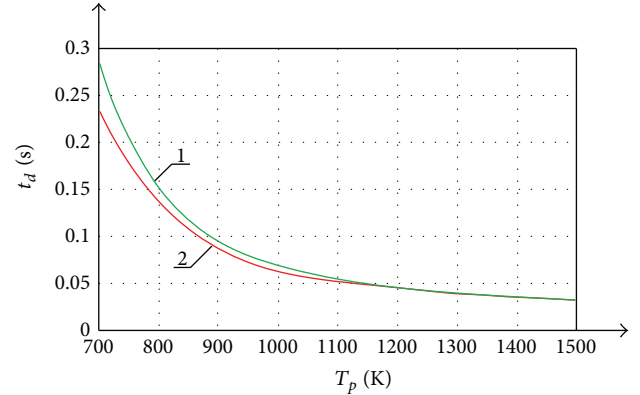
4. Results and Discussion

The numerical investigations were carried out for the following values of parameters [16–21]: the heat effect of oxidation reaction $Q_1 = 2.5 \times 10^7$ J/kg; the heat effect of PMMA thermal decomposition $Q_3 = 10^6$ J/kg; activation energy $E_1 = 0.125 \times 10^6$ J/mol, $E_3 = 0.13 \times 10^6$ J/mol; preexponential factor $k_1^0 = 10^{10}$ s⁻¹, $k_3^0 = 2.82 \times 10^9$ s⁻¹; the thermal expansion coefficient $\beta = 0.0009$ K⁻¹; the kinematic viscosity coefficient $\nu_1 = 1.4 \times 10^{-5}$ m²/s; the diffusion coefficient $D_0 = 8.12 \times 10^{-6}$ m²/s; the initial temperature of air and polymeric material $T_0 = 300$ K; temperature of PMMA pyrolysis beginning $T_s = 500$ K; hot particles sizes $x_p = 4 \times 10^{-3}$ m, $y_p = 2 \times 10^{-3}$ m; solution area sizes $x_L = 20 \times 10^{-3}$ m, $y_L = 20 \times 10^{-3}$ m. Thermophysical properties of the substances are presented in Table 1 (Figure 1) [16–19].

The purpose of interconnected heat and mass transfer process research at the ignition of polymeric material consisted of the investigation of the joint effect of several local heat sources on the main integrated characteristic: ignition delay time t_d (Figure 1). In previous studies [10, 11], for a single particle, it was established that the heat content of a local heat source (characterized by its initial temperature T_p) is the main factor determining t_d . It is also reasonable for two particles to carry out the analysis of the influence of the distance between heat sources Δx on ignition delay time (Figure 1). Therefore, the numerical investigation was executed by varying the initial temperature of heat sources between $700 \text{ K} < T_p < 1500 \text{ K}$ and varying the parameter of L (where $L = \Delta x/x_p$) that characterizes the distance between two particles in the range of $0.25 < L < 2$.

The dependence of polymeric material ignition delay time on the value of L at the initial temperature of heat sources $T_p = 900$ K is shown in Figure 2. It was found that in the “two hot particles—polymeric material—air” system the value of t_d rises for increasing L from 0.25 to 1.5. In case of $L > 1.5$, the ignition delay time does not change ($t_d = 0.0936$ s). It corresponds to the ignition period of PMMA at its interaction with a single hot particle (curve 1 in Figure 3). Thus, the value of $L = 1.5$ is the limit (for $T_p = 900$ K) when the particles still have a joint effect on the intensity of heat and mass transfer processes in the system (Figure 1).

It is seen from Figure 2 that the maximum change of ignition delay time in the “two hot particles—polymeric material—air” system is 6.7% at the parameters $0.25 < L < 1.5$ and $T_p = 900$ K. The joint effect of several particles at t_d decreases for increasing the heat sources initial temperature. The dependence of PMMA ignition delay time at the initial temperature of a single particle (curve 1) and two particles

FIGURE 2: PMMA ignition delay time t_d versus L at $T_p = 900$ K.FIGURE 3: PMMA ignition delay time t_d versus initial temperature of particle T_p : 1: one particle; 2: two particles at $L = 0.25$.

(curve 2) at $L = 0.25$ is shown in Figure 3. The values of ignition delay time at $T_p > 1150$ K do not differ from the cases of a single hot particle and two hot particles. It can be explained by the fact that for increasing T_p the heat content of particles rises. The influence of neighboring particles on the warming of polymeric material near-surface layer by thermal conduction and gas mixture by thermal convection decreases. In this case, the temperature of PMMA pyrolysis products increases and less time is required for warming the mixture of combustible gases and oxidizer. Ignition zones as in case of a single particle [10, 11] are formed near the lateral sides of the local heat sources and move to the “polymeric material—hot particle” border ($x = x_1$, $x = x_2$, $x = x_3$, $x = x_4$, and $y \rightarrow y_1$). Besides, it was determined that at the conditions of $700 \text{ K} < T_p < 1150 \text{ K}$ and $L > 1.5$ or $T_p > 1150 \text{ K}$ and $0.25 < L < 1.5$ the characteristics of heat and mass transfer processes at the PMMA ignition by several hot particles are identical to values of t_d [10, 11] calculated at the PMMA ignition by a single hot particle.

The isotherms in the “two hot particles—polymeric material—air” system are shown in Figure 4 at the ignition moment for three different values of L . Opposite to the “single hot particle—polymeric material—air” system [10, 11] at variation of $700 \text{ K} < T_p < 1150 \text{ K}$ and $0.25 < L < 1.5$, two ignition models are realized. It is characterized by localization

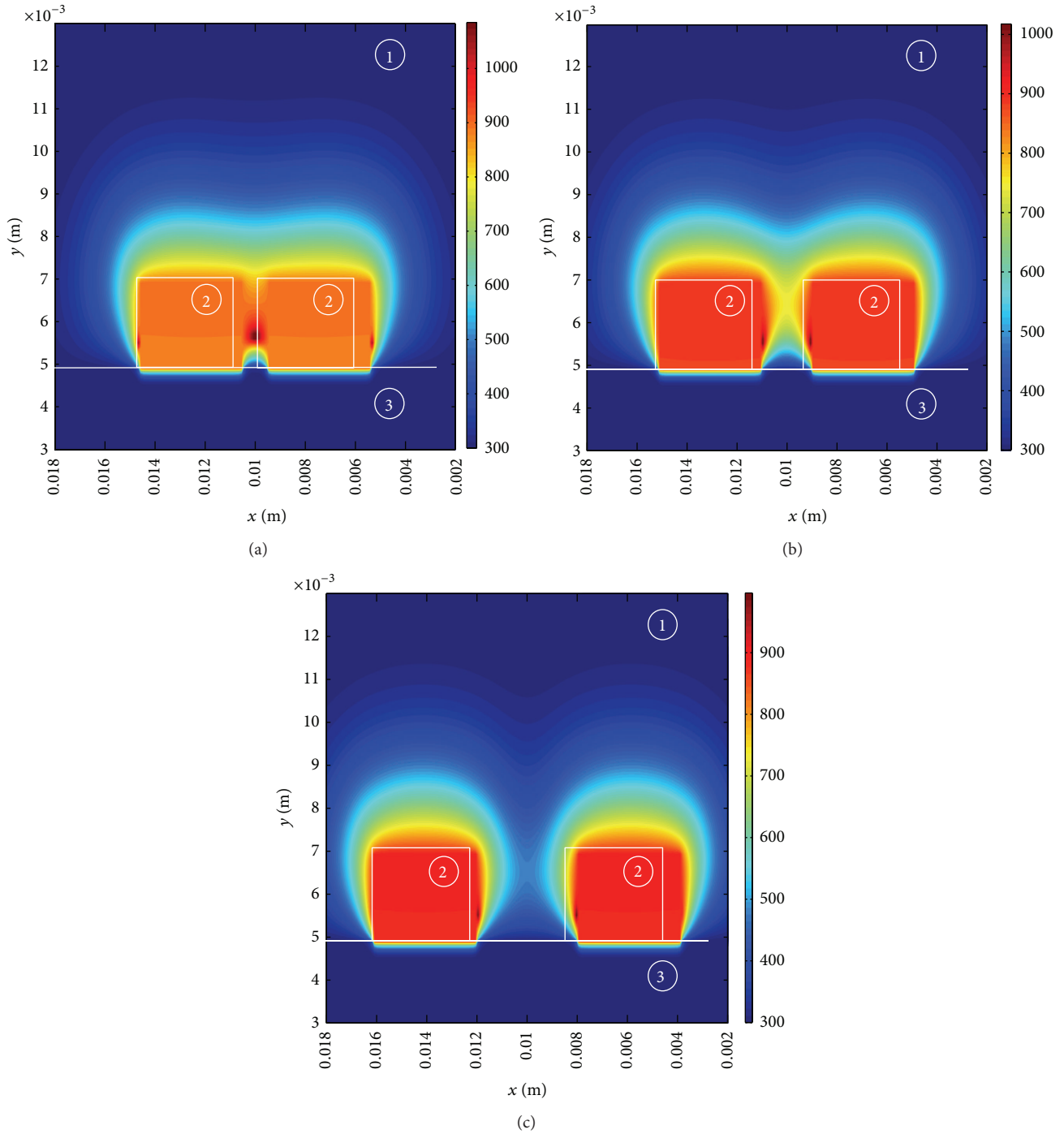


FIGURE 4: Isotherms (T , K) at ignition moment $t_d = 0.087$ s, $L = 0.25$ (a), $t_d = 0.092$ s, $L = 0.5$ (b), $t_d = 0.096$ s, and $L = 1$ (c) at $T_p = 900$ K: 1: gas mixture; 2: hot steel particle; 3: PMMA.

of an oxidation reaction in the gas area relative to the surfaces of polymeric material and local heat sources. It is seen in Figure 4(a) that one local ignition zone is formed in case of the small ($L = 0.25$) distance between particles. The ignition zone is located on the symmetry axis $x = x_L/2$ of the solution area (Figure 1). The maximum temperature gradients and the largest concentration of combustible products (PMMA gas) occurred in comparison with areas $x < x_1$ and $x > x_4$ as a result of hot particles joint effect. For increasing L and other

equal conditions, two ignition areas were formed near the internal lateral sides ($x = x_2$, $x = x_3$, and $y_1 < y < y_2$) of hot particles (Figures 4(b) and 4(c)).

It is seen from Figure 5 that two main convective whirlwinds intensifying heat and mass transfer processes formed in the gas area at various distances between hot particles.

It leads to the decrease of temperature and concentration of combustible gases near the external lateral sides ($x = x_1$, $x = x_4$, and $y_1 < y < y_2$) of hot particles. Therefore,

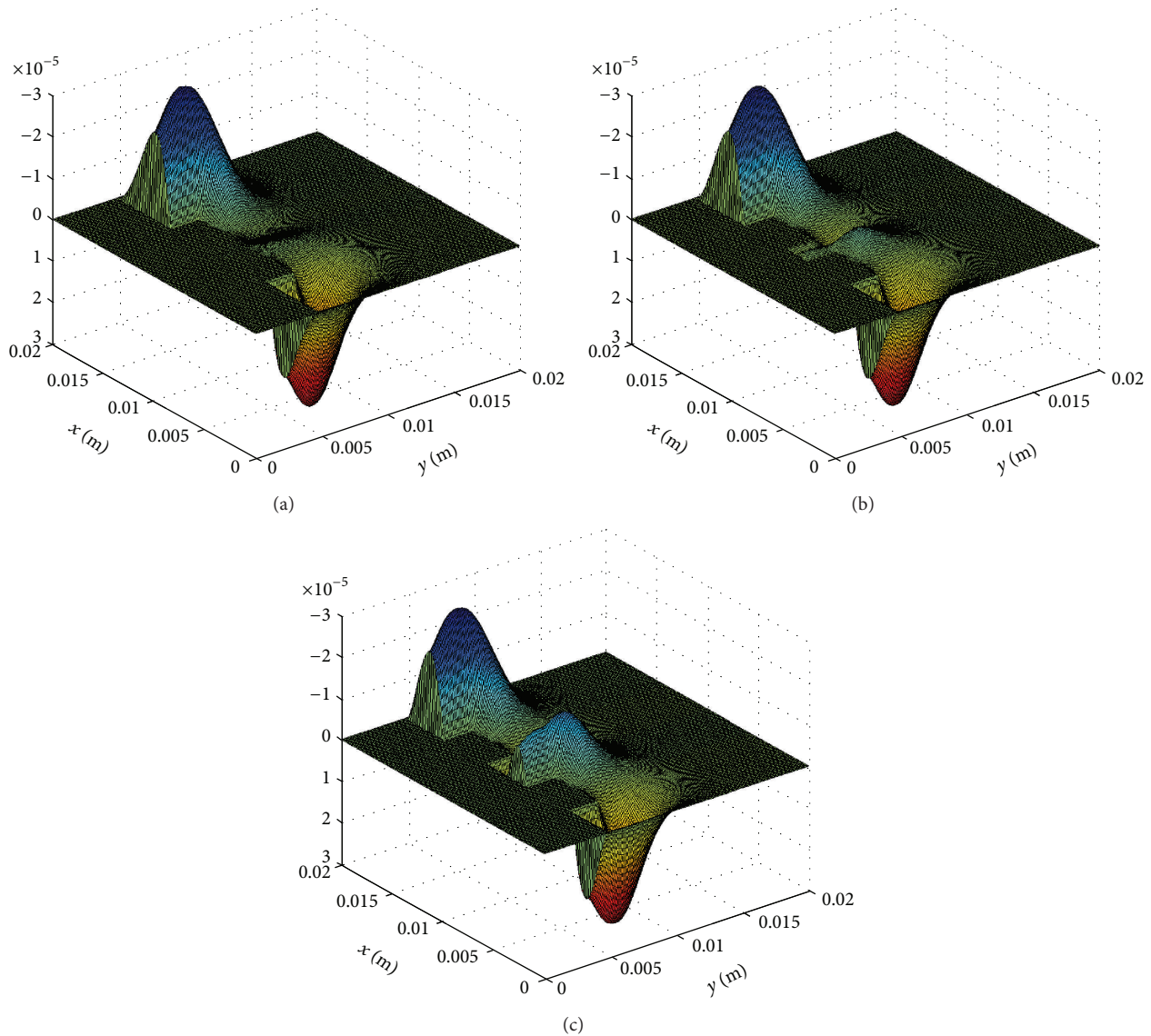


FIGURE 5: Stream function (ψ , m^2/s) at ignition moment $t_d = 0.087$ s, $L = 0.25$ (a), $t_d = 0.092$ s, $L = 0.5$ (b), $t_d = 0.096$ s, and $L = 1$ (c) at $T_p = 900$ K.

in these zones, gases-phase ignition does not occur. At the small distance between heat sources diffusion (Figure 5(a)), convection and heat sink from zones $x_2 < x < x_3$ and $y_1 < y < y_2$ is absent (Figure 1). Ignition occurs near the symmetry axis $x = x_L/2$ in the zone with maximum concentration and temperature of gas mixture (Figure 1). For increasing the distance between hot particles (Figures 5(b) and 5(c)) in zones $x_2 < x < x_3$ and $y_1 < y < y_2$, the secondary convective whirlwinds forms. It leads to the decrease of temperature and concentration of gas mixture near the symmetry axis $x = x_L/2$. In such conditions, ignition occurs near the internal lateral sides ($x = x_2$, $x = x_3$, and $y_1 < y < y_2$) of heat sources.

5. Conclusions

- (1) The predictive mathematical model of interconnected heat and mass transfer processes at the ignition of polymeric material by several small-size hot metallic particles was developed. It considers thermal conduction and thermal decomposition in a condensed substance, thermal convection, and diffusion and oxidation reaction in the gas area.
- (2) Characteristics of a local heat sources and its relative location on a polymeric material surface ($700 \text{ K} < T_p < 1150 \text{ K}$ and $L > 1.5$ or $T_p > 1150 \text{ K}$ and $0.25 < L < 1.5$) were established when the regularities of heat and mass transfer processes in the “two hot particles—polymeric material—air” system are similar to regularities of heat and mass transfer processes in the “single hot particle—polymeric material—air” system.
- (3) The developed mathematical model can be used in mechanical engineering for a definition of the most

fire danger parts of polymeric material constructional products during the process of its interaction with several local heat sources which are formed as a result of technological processes. Besides, the model can be used in chemistry for the definition of effective kinetic characteristics of polymeric material thermal decomposition and oxidation.

Nomenclatures and Units

C :	Constant specific heat, J/(kg·K)
C_f :	Dimensionless concentration of combustible gases in the gas mixture
C_o :	Dimensionless concentration of oxidant in the gas mixture
D_0 :	Coefficient of diffusion (at $T = 293$ K), m^2/s
D_1 :	Coefficient of diffusion, m^2/s
E :	Activation energy, J/mol
g :	Gravitational acceleration, m/s^2
k^0 :	Preexponential factor, s^{-1}
L :	Dimensionless parameter, characterized the distance between two neighboring particles ($L = \Delta x/x_p$)
Q_1 :	Heat effect of combustible gas mixture oxidation reaction, J/kg
Q_3 :	Heat effect of polymeric material thermal decomposition reaction, J/kg
R :	Ideal gas constant, J/(mol·K)
t :	Time, s
Δt :	Time step, s
t_d :	Ignition delay time, s
T :	Temperature, K
T_p :	Initial temperature of hot particles, K
T_s :	Temperature of the thermal decomposition beginning for polymeric material, K
T_0 :	Initial temperature of air and polymeric material, K
u, v :	Components of combustible gas velocity at the projection onto the axes x, y , m/s
W_1 :	Mass rate of combustible gas mixture oxidation reaction, $kg/(m^3 \cdot s)$
W_3 :	Mass rate of polymeric material thermal decomposition reaction, $kg/(m^3 \cdot s)$
x, y :	Cartesian coordinates, m
Δx :	Distance between two particles, m
x_L, y_L :	Solution domain sizes, m
x_p, y_p :	Hot particle sizes ($x_p = x_2 - x_1, y_p = y_2 - y_1$), m.

Greek Symbols

β :	Coefficient of thermal expansion, K^{-1}
λ :	Thermal conductivity, W/(m·K)
ρ :	Density, kg/m^3
ν :	Coefficient of kinematic viscosity, m^2/s
φ_i :	Volume fractions of PMMA gasification products

φ_o :	Volume fractions of air
ψ :	Stream function, m^2/s
ω :	Vortex velocity vector, 1/s.

Subscripts

- 1: Gas mixture (air and PMMA gas)
- 2: Hot particles
- 3: Polymeric material.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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References

- [1] K. Meissner and B. Poltersdorf, "Thermomechanical load and property changes in processing of polymeric materials," *Advances in Polymer Technology*, vol. 10, no. 4, pp. 265–276, 1990.
- [2] A. V. Telnov, N. V. Zavyalov, Y. A. Khokhlov et al., "Radiation degradation of spent butyl rubbers," *Radiation Physics and Chemistry*, vol. 63, no. 3–6, pp. 245–248, 2002.
- [3] A. Bonati, F. Merusi, G. Polacco, S. Filippi, and F. Giuliani, "Ignitability and thermal stability of asphalt binders and mastics for flexible pavements in highway tunnels," *Construction and Building Materials*, vol. 37, pp. 660–668, 2012.
- [4] Y. Wang and J. Zhang, "Influences of specimen size and heating mode on the ignitability of polymeric materials in typical small-scale fire test conditions," *Fire and Materials*, vol. 36, no. 3, pp. 231–240, 2012.
- [5] M. Summerfield et al., *Aeronautical Engineering Report*, vol. 661, Princeton University, 1963.
- [6] U. I. Goldshleger, V. V. Barzykin, and A. G. Merzhanov, "Mechanism and laws of ignition of condensed systems by a two-phase flow," *Combustion, Explosion, and Shock Waves*, vol. 7, no. 3, pp. 277–286, 1974.
- [7] R. S. Burkina and E. A. Mikova, "High-temperature ignition of a reactive material by a hot inert particle with a finite heat reserve," *Combustion, Explosion and Shock Waves*, vol. 45, no. 2, pp. 144–150, 2009.
- [8] G. V. Kuznetsov and P. A. Strizhak, "Transient heat and mass transfer at the ignition of vapor and gas mixture by a moving hot particle," *International Journal of Heat and Mass Transfer*, vol. 53, no. 5–6, pp. 923–930, 2010.
- [9] D. O. Glushkov, G. V. Kuznetsov, and P. A. Strizhak, "Research of macroscopic regularities of heat and mass transfer at the ignition condition of a liquid high-energy material by an immersed source with a limited energy capacity," *Advances in Mechanical Engineering*, vol. 2014, Article ID 764537, 9 pages, 2014.
- [10] D. O. Glushkov and P. A. Strizhak, "Heat and mass transfer at ignition of solid condensed substance with relatively low calorific power by a local energy source," *Journal of Engineering Thermophysics*, vol. 21, no. 1, pp. 69–77, 2012.

- [11] D. O. Glushkov, G. V. Kuznetsov, and P. A. Strizhak, "Theoretical assessment of ignition stability of a typical polymeric material by a local power source," *Fire and Explosion Safety*, vol. 23, no. 2, pp. 10–19, 2014 (Russian).
- [12] G. V. Kuznetsov and P. A. Strizhak, "On the scale of "simultaneous" influence of several "hot" particles on the conditions of heat and mass transfer at ignition of liquid condensed substance," *Journal of Engineering Thermophysics*, vol. 18, no. 4, pp. 263–270, 2009.
- [13] V. N. Vilyunov and V. E. Zarko, *Ignition of Solids*, Elsevier, Amsterdam, The Netherlands, 1989.
- [14] D. A. Frank-Kamenetsky, *Diffusion and Heat Transfer in Chemical Kinetics*, Plenum Press, New York, NY, USA, 1969.
- [15] G. V. Kuznetsov and M. A. Sheremet, "Conjugate natural convection in an enclosure with local heat sources," *Computational Thermal Sciences*, vol. 1, no. 3, pp. 341–360, 2009.
- [16] S. Bhattacharjee, M. D. King, and C. Paolini, "Structure of downward spreading flames: a comparison of numerical simulation, experimental results and a simplified parabolic theory," *Combustion Theory and Modelling*, vol. 8, no. 1, pp. 23–39, 2004.
- [17] K. K. Wu, W. F. Fan, C. H. Chen, T. M. Liou, and I. J. Pan, "Downward flame spread over a thick PMMA slab in an opposed flow environment: experiment and modeling," *Combustion and Flame*, vol. 132, no. 4, pp. 697–707, 2003.
- [18] M. B. Ayani, J. A. Esfahani, and A. C. M. Sousa, "The effect of surface regression on the downward flame spread over a solid fuel in a quiescent ambient," *Thermal Science*, vol. 11, no. 2, pp. 67–86, 2007.
- [19] N. B. Vargaftik, *Reference Book on Thermophysical Properties of Gases and Liquids*, Stars, Moscow, Russia, 2006 (Russian).
- [20] S. M. Dakka, "TG/MS of poly(methyl methacrylate) the effect of heating rate on the rate of production of evolved gases," *Journal of Thermal Analysis and Calorimetry*, vol. 75, no. 3, pp. 765–772, 2004.
- [21] J. D. Peterson, S. Vyazovkin, and C. A. Wight, "Kinetic study of stabilizing effect of oxygen on thermal degradation of poly(methyl methacrylate)," *The Journal of Physical Chemistry B*, vol. 103, no. 38, pp. 8087–8092, 1999.



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