Solid rocket propellant transparency effect on ignition by radiation

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The influence of solid rocket propellant optical properties on the ignition process in the case of heat supply by radiation was analyzed. Temperature and concentration in the solid phase were calculated numerically. Transparency increase causes the extension of ignition delay time and the decrease of ignition temperature. The ignition process character is under the influence of the applied heat flux as well. The investigation results are presented in the form of tables and diagrams.

Ključne reči: solid rocket propellants, combustion, ignition.

Introduction

DURING the ignition process heat is transferred to a solid propellant from an external source by conduction, convection and radiation. Heat transfer by radiation in the sequence of ignition can be very important, especially in large rocket motors. In addition, radiant heating is widely used in solid rocket propellant ignition studies [1,9,11-13]. The reason for this is a possibility of choice and a good control of experimental conditions. It is possible to ignite a solid rocket propellant sample by a selected heat flux value independently of the other parameters. Diagnostic tests with a possibility to cut off heat supply in a predetermined moment can also be done in that way. With radiation as a heat source, optical features of rocket propellants (reflection and absorption) have a significant role. One part of thermal energy is returned to the surrounding atmosphere because of reflection. The remaining part heats the solid rocket propellant and depending on the propellant transparency the heat flux penetrates the propellant up to some depth which may be less than, approximatively equal to or much greater than the chemical reaction zone depth. In the case of so-called opaque propellants the absorption coefficient $n[1/m]$ (in some papers named coefficient of transparency) is so high that the penetration zone depth of the radiative flux $x_r=1/n$ is very small (for example $80 \cdot 10^{-6}$m) and the heating process is the same as when the heat is transferred in a different way. When propellants are transparent, radiation penetrates deeper so heat transfer and temperature growth processes are considerably different when compared to non-transparent propellants. In the literature are presented approximate [2,4,7,9] and numerical [5,9] methods of this problem solution. In this paper a numerical model for solving non-stationary energy and concentration conservation equations, based on the thermal ignition theory, is developed.

Influence of propellant transparency on the radiation ignition process

It is well known that some solid rocket propellants have such optical properties that the heat flux from an exterior source penetrates deeply into the material thus heating deeper layers. In these cases the heat conduction equation for the semi-infinite plate (neglecting chemical reactions in the propellant) can be used in the form [10]

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) - \frac{\partial \dot{q}_r}{\partial x} \qquad (1)$$

where the second term on the right side includes a phenomenon of radiation penetration into the material. The radiation heat flux in the propellant at the distance x from the surface exposed to radiation is given by the expression

$$\dot{q}_r = \left(1 - f_r\right)\dot{q}_s e^{-nx} \qquad (2)$$

where f_r is the coefficient of diffusive reflection of the material with the incident radiant flux $\dot{q}_s$ and n is the coefficient of absorption which represents propellant transparency. Greater values characterize less transparent propellants with a faster decreasing parameter $\dot{q}_r$. Instead of the coefficient of absorption i.e. attenuation of radiation parameter $x_r=1/n$ can be used [2,5] with the meaning of radiation path length or absorption zone width. The values f_r and n can be determined experimentally (for example [11]) and depend not only on the material properties but on the characteristics of the radiation source as well. Using the effective value of the heat flux applied by radiation from expression (1) the following equation is obtained

$$\frac{\partial T}{\partial t} = a \frac{\partial^2 T}{\partial x^2} + \frac{\dot{q}n}{qc} \cdot e^{-nx} \qquad (3)$$

with the initial and boundary conditions

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$$T(x,0) = T_i = \text{const.} \quad \text{for} \quad 0 \le x < \infty$$

$$T(\infty,t) = T_i \quad \text{for} \quad t \ge 0 \quad \Bigg\} \quad (4)$$

$$-\lambda (\partial T/\partial x)_{x=0} = 0 \quad \text{for} \quad t \ge 0$$

By applying the Laplace transform to solving eqs.(3) and (4) in reference [10] the following equation was obtained

$$\frac{d^2\overline{T}}{dx^2} - \frac{p}{a}\cdot\overline{T} = -\frac{T_i}{a} - \frac{n\cdot\dot{q}}{\lambda p}\cdot e^{-nx} \qquad (5)$$

the solution of which determines the dependence $\overline{T}(x,p)$. When $\dot{q}$ =const (independent of time), the inverse Laplace transform gives the law for $T(x,t)$, which after rearrangement of the original equation, has the form

$$T(x,t) = \frac{T_i}{p} + \frac{2\dot{q}}{\lambda}\sqrt{at}\cdot\left[\frac{1}{\sqrt{\pi}}\cdot e^{-\frac{x^2}{4at}} - \frac{x}{2\sqrt{at}}\cdot erfc\left(\frac{x}{2\sqrt{at}}\right)\right] -$$
$$- \frac{\dot{q}}{\lambda n}\cdot e^{-nx} + \frac{\dot{q}}{2\lambda n}\cdot e^{n^2at-nx}\cdot erfc\left(n\sqrt{at} - \frac{x}{2\sqrt{at}}\right) + \quad (6)$$
$$+ \frac{\dot{q}}{2\lambda n}\cdot e^{n^2at+nx}\cdot erfc\left(n\sqrt{at} + \frac{x}{2\sqrt{at}}\right)$$

where $erfc(Z) = 1 - erf(Z) = 1 - \frac{2}{\sqrt{\pi}}\cdot\int_O^Z e^{-\eta^2}d\eta$.

It is clear that eq.(6) with only first two terms on the right side corresponds to the process of heating an absolutely opaque material with a constant heat flux by radiation (that results from (6) for $n\to\infty$). The upper relation for the temperature field in the solid rocket propellant can be obtained from reference [8] for the case of heating a semi-infinite solid body with a constant initial temperature within which, for $t>0$, exists a source producing heat quantity in the unit of time due to the dependence $\dot{q}_x = \dot{q}e^{-nx}$ and where there is no thermal flow on the surface $x=0$.

Price and coworkers in reference [7] presented the solution of eqs.(3) and (4) in the form:

$$n\frac{\lambda n\Delta T_s}{\dot{q}} = 2\sqrt{\frac{a}{\pi}}\cdot\sqrt{\frac{q}{\dot{q}}}\cdot n + e^{n^2a\frac{q}{\dot{q}}}\cdot erfc\left(n\sqrt{a\frac{q}{\dot{q}}}\right) - 1 \qquad (7)$$

where ΔT_s is the growth of propellant surface temperature. For high heating rates they omitted the conductive term in eq.(3) and established the relation

$$n^2a\frac{q}{\dot{q}} = 2n\sqrt{\frac{a}{\pi}}\cdot\sqrt{\frac{q}{\dot{q}}} + e^{n^2a\frac{q}{\dot{q}}}\cdot erfc\left(n\sqrt{\frac{q}{\dot{q}}}\right) - 1 \qquad (8)$$

from which the dependence $q = f(\dot{q})$ for different values of n can be found.

In reference [1] on the basis of experiments and physical process consideration the relation for the ignition time delay was proposed

$$t_{ig} \approx t_{ch} + \frac{1}{n}\cdot\frac{\rho c\Delta T^*}{\dot{q}} + \frac{\pi a}{4}\left(\frac{\rho c\Delta T^*}{\dot{q}}\right)^2 \qquad (9)$$

and for the ignition energy

$$E_{ig} = \dot{q}t_{ig} \approx \dot{q}\cdot t_{ch} + \frac{\rho c\Delta T^*}{n} + \frac{\pi}{4}\cdot\frac{a}{\dot{q}}\left(\rho c\Delta T^*\right)^2 \qquad (10)$$

Expressions (9) and (10) direct attention to the fact that propellant transparency affects the increase of the time delay and the heat quantity necessary for its ignition.

Thermocouple measurement of solid propellant temperature in ref. [3] pointed out that the measured values show a good agreement with the temperatures calculated by eq.(6) for lower heat flux values up to a sharp raise due to chemical reactions occuring in the ignition process.

In reference [2], utilizing the heat conduction equation including chemical reactions in the propellant

$$\frac{\partial T}{\partial t} = a\frac{\partial^2 T}{\partial x^2} + \frac{\dot{q}n}{\rho c}\cdot e^{-nx} + \frac{Q\cdot z}{\rho c}e^{-E/RT} \qquad (11)$$

and applying the approximative method, were obtained the relations

$$T_{ig} = T_p + 2\dot{q}\sqrt{\frac{t_{ig}}{\pi\lambda\rho c t_{ig}}} - \frac{\dot{q}}{n\lambda}\cdot\left[1 - e^{n^2at_{ig}}\cdot erfc\left(n\sqrt{at_{ig}}\right)\right] \quad (12)$$

and

$$\dot{q} = \left\{\frac{\pi\lambda RT_{ig}^2}{2\dot{q}nE\left[1 - e^{n^2at_{ig}}\cdot erfc\left(n\sqrt{at_{ig}}\right)\right]}\right\}^{1/2}\cdot$$
$$\cdot Qz\cdot\exp\left(-\frac{E}{RT_{ig}}\right) \qquad (13)$$

which enable the determination of temperatures and time delays for different values of $\dot{q}$ and n. The authors perceived the existence of a region (for every $\dot{q}$) where the coefficient of absorption change practically did not have influence on the ignition time delay.

The experimental investigations of double–based solid rocket propellants ignition by radiation in [12,13] pointed out a considerable difference between the incident and absorbed heat flux due to the low diffuse reflection coefficient of some propellants (~60%). By adding 0.2% of carbon (C) to the base composition, the absorption capacity increases 20 times as much until the coefficient of reflection decreases to 5%. By adding 1% of carbon, the volumetric capability of radiation absorption increases 5 times but the reflection coefficient remains at the level of 5%.

Khlevnoi and Mikheev in [11] also investigated experimentally nitrocellulose propellants by radiation and concluded that for ignition of more transparent propellants a greater amount of energy was needed and that the ignition temperature was lower in comparison with propellants with added carbon.

Considering eq.(11) in his monograph [5], Vilyunov applied the approximate adiabatic ignition theory and temperature laws for inert bodies (eq.(6) and (12)) and obtained nondimensional relations which resulted in equations for defining the intensive chemical reactions occurrence time

$$t_* = \frac{\pi}{a} \cdot \left\{ \frac{\lambda(T_* - T_p)}{2\dot{q}} - \frac{1}{2n}\left[1 - \frac{\rho Qz}{\dot{q}n\exp(E/RT_*)}\right]\right\}^2 \qquad (14)$$

the temperature at which effects of chemical reactions become significant

$$T_* = \frac{E}{R\ell n\left\{\dfrac{\rho Qz}{\dot{q}n\exp\left(n^2 at_*\right)erfc\left(n\sqrt{at_*}\right)}\right\}} \qquad (15)$$

and the time of ignition

$$t_{ig} = t_* + \left(1 + 2\frac{RT_*}{E}\right)\cdot\frac{RT_*^2}{E}\cdot\frac{c}{Qz}\cdot\exp(E/RT_*) \qquad (16)$$

Eqs.(14) and (15) can be solved iteratively and relation (16) implies that t_* is close to t_{ig}. The author payed attention to the boundary conditions of ignition as well. For weakly transparent propellants $\left(n\sqrt{at_*} \gg 1\right)$ he obtained approxi-mate relations

$$T_* = \frac{E}{2R\ln\sqrt{\dfrac{\pi}{2}\cdot\dfrac{\rho Qz\cdot\lambda(T_* - T_i)}{\dot{q}^2} + \dfrac{\pi}{4n}\cdot\dfrac{\rho Qz}{\dot{q}}\exp(-E/RT_*)}} \qquad (17)$$

and

$$t_* = \frac{1}{2}\cdot\frac{c}{Qz}\cdot\exp(E/RT_*)\cdot$$
$$\cdot\left[T_* - T_i + \frac{1}{n}\cdot\sqrt{\frac{\rho Qz\frac{\pi}{2}(T_* - T_i)}{\lambda\exp(E/RT_*)}}\right] \qquad (18)$$

In the case of very transparent materials $\left(n\sqrt{at_*} \ll 1\right)$ and extremely high heat fluxes utilizing expansion into a series of characteristic functions the following relations were produced

$$\exp(E/RT_*) =$$
$$= \frac{\rho Qz}{\dot{q}}\left[\sqrt{\frac{4\lambda(T_* - T_i)}{\pi}\cdot\frac{\exp(E/RT_*)}{\rho Qz}} + \frac{1}{n}\right] \qquad (19)$$

and

$$t_* = \frac{c(T_* - T_i)\cdot\exp(E/RT_*)}{Qz}\cdot$$
$$\cdot\left[1 - \frac{4n}{\sqrt{\pi}}\cdot\sqrt{\frac{\lambda(T_* - T_i)\exp(E/RT_*)}{\rho Qz}}\right] \qquad (20)$$

The disadvantage of these expressions is in the fact that there are many situations when the parameter $n\sqrt{at_*}$ does not satisfy the given conditions.

In refference [6] the ignition of reactive material exposed to a heat flux due to radiation was studied on the basis of the following equations:

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho c}\cdot\frac{\partial^2 T}{\partial x^2} + \frac{\dot{q}n}{\rho c}\cdot\exp(-nx) +$$
$$+\frac{Qz\rho^m Y^m}{\rho c}\cdot\exp(-E/RT) \qquad (21)$$

$$\frac{\partial Y}{\partial t} = D\frac{\partial^2 Y}{\partial x^2} - \rho^m Y^m\cdot\frac{z}{\rho}\cdot\exp(-E/RT) \qquad (22)$$

where Y is the nonreacted propellant concentration $(Y_i = 1)$ and m is the chemical reaction order. The initial and boundary conditions agree with those defined by eq.(4). Applying the Laplace transforms to (21) and (22) and using the propellant temperature solution for the inert heating case, a connection between parameters defining tempe-rature and those defining reactive material concentration on the surface was established and expressed in the following way

$$T(0,t) = T_i(0,t) + \frac{Q}{c}\left[Y_p - Y(0,t)\right] \qquad (23)$$

Here $T_{in}(0,t)$ is the solution of eq.(21) without the third term on the right side. Thus the system of partial differential eqs.(21) and (22) was reduced to one ordinary differential equation from which the surface temperature of reactive material can be determined. The asymptotic method $\left(for\,\Omega_o = E(T_* - T_i)/2RT_*^2 \gg 1\right)$ was employed in finding the solution so the following system of equations was obtained

$$\left.\begin{aligned} &b_1 = \lambda\left(T_*^{(j)} - T_i\right)/(2\dot{q}) \\ &b_2 = 1 - \rho Qz/\left\{\dot{q}n\cdot\exp\left[E/RT_*^{(j)}\right]\right\} \\ &t_*^{(j)} = \left(b_1 + \frac{b_2}{2n}\right)^2\cdot\frac{\pi}{a} \\ &T_*^{(j+1)} = \frac{E}{R\cdot\ln\left[\dfrac{\rho Qz}{\dot{q}n\cdot\exp\left(n^2 at_*^{(j)}\right)\cdot erfc\left(n\sqrt{at_*^{(j)}}\right)}\right]} \end{aligned}\right\} \qquad (24)$$

The propellant surface temperature at which chemical reactions occur and the time necessary to reach it can be found from (24) by iteration.

The governing equations for temperature and concentration field change determination, used in this paper, (when a solid rocket propellant has some degree of transparency), are

$$\frac{\partial T(x,t)}{\partial t} = a\frac{\partial^2 T}{\partial x^2} + \frac{\dot{q}n}{\rho c}\cdot\exp(-nx) +$$
$$+\frac{Qz}{c}\cdot Y(x,t)\cdot\exp\left[-E/RT(x,t)\right] \qquad (25)$$

and

$$\frac{\partial Y(x,t)}{\partial t} = -zY(x,t)\cdot\exp\left[-E/RT(x,t)\right] \qquad (26)$$

with the initial and boundary conditions for temperatures corresponding to eq.(4) and for the concentration accor-ding to

$$Y(x,0) = Y_i = 1$$

$$\frac{\partial Y(0,t)}{\partial x} = \frac{\partial Y(\infty,t)}{\partial x} = 0 \qquad (27)$$

The characteristic temperature at which significant chemical reactions occur and the time necessary to reach it, on the basis of the analysis in [6], can be obtained by solving iteratively the equations

$$C_1^j = \lambda n \frac{T_*^{(j)} - T_i}{\dot{q}} \qquad (28)$$

$$C_2^{(j)} = \frac{Qz\rho\lambda\left(T_*^{(j)} - T_i\right)}{\dot{q}^2 \exp\left[E/RT_*^{(j)}\right]} \qquad (29)$$

$$C_3^{(j)} = C_2^{(j)} / C_1^{(j)} \qquad (30)$$

$$t_*^{(j)} = \frac{\pi}{4}\left\{1 + \frac{1}{C_1^{(j)}}\left[1 - C_3^{(j)}\right]\right\}^2 \frac{\lambda\rho c\left(T_*^{(j)} - T_i\right)^2}{\dot{q}^2} \qquad (31)$$

$$C_3^{(j+1)} = \exp\left[n^2 a t_*^{(j)}\right]\cdot erfc\left(n\sqrt{a t_*^{(j)}}\right) \qquad (32)$$

$$T_*^{(j+1)} = \frac{E}{R\left[\ell n\left(\frac{Qz\rho}{\dot{q}n}\right) - \ell n C_3^{(j+1)}\right]} \qquad (33)$$

The temperature obtained in the case of a completely opaque propellant with an equal heat flux was chosen as an initial value of T_* (see [14]). Simultaneous and numerical solving of eq.(25) and (26) with corresponding initial and boundary conditions, using the method of finite differences, enabled obtaining the temperature and concentration profile in a propellant layer. In the initial estimation phase, the temperature is calculated by eq.(6) while the concentration has the starting value.

Table 1

Value	n [1/m]	$\dot{q}\left[kW/m^2\right]$			
		41.868	209.34	418.68	2093.4
t_*, s according to [5, 6]	8000	10.608	0,969	0.388	0.0583
	6000	11.221	1.105	0.457	0.0725
	4000	12.425	1.366	0.589	0.0997
	2000	15.878	2.093	0.958	0.1765
t_{ig}, s according to [6]	8000	11.546	1.04	0.413	0.0616
	6000	12.189	1.182	0.486	0.0764
	4000	13.451	1.456	0.624	0.105
	2000	17.079	2.200	1.011	0.1855
t_*, s from numerical calculation	8000	11.76	1.046	0.395	0.059
	6000	12.28	1.154	0.455	0.072
	4000	12.98	1.382	0.594	0.097
	2000	16.06	2.054	0.936	0.178
T_*, K by eq. (33)	8000	479.74	518.73	533.77	574.56
	6000	479.31	517.24	533.59	570.68
	4000	478.49	514.72	530.07	564.97
	2000	476.33	509.28	523.06	554.77

Table 1 and the figures present the calculated results for the propellant N [5,6] ($E=1.4654\cdot10^5$[J/mole], $Q=1.13\cdot10^6$ [J/kg], $z=9.08\cdot10^{13}$ [s^{-1}], $\rho=1600$ [kg/m^3], $c=1465$ [J/kgK], $\lambda=0.2345$ [W/m^{2}K]) with different values of the absorption coefficient n [m^{-1}] during heating with various amounts of the radiation energy flux.

The change of ignition delay time due to the absorption coefficient of propellant ignited with various values of externally applied heat is presented in Fig.1. Fig.2 shows much greater influence of the parameter n on the solid rocket propellant ignition temperature with a higher intensity of the heat flux by radiation.
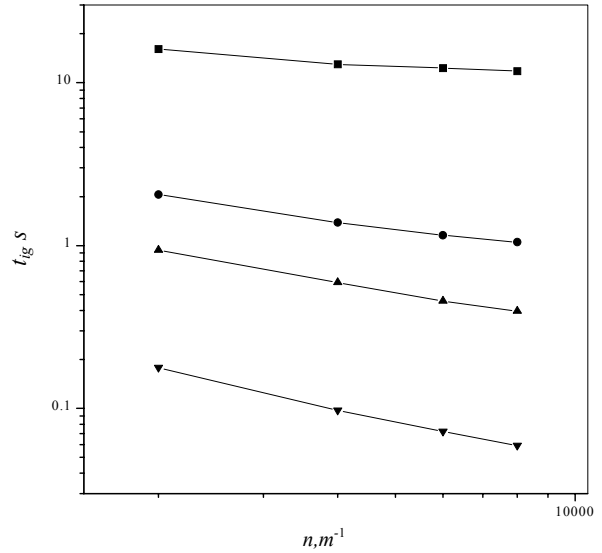
Figure 1. Ignition time delay dependence on the absorption coefficient n for different values of the heat flux $\dot{q}$: ■ $\dot{q}$ =0.041858; ● 0.20934; ▲ 0.41868 and ▼ 2.0934 MW/m^2
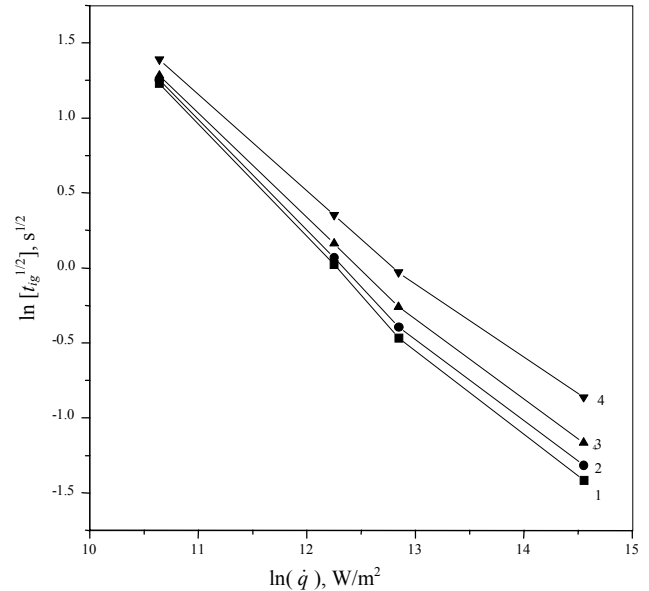
Figure 2. Ignition temperature of a double–based rocket propellant [6] as a function of the radiation heat flux for various absorption coefficients ▼ n=2000 [m^{-1}]; ▲ 4000; ● 6000; ■ 8000

The relation in the form $\ln\left[t_{ig}^{1/2}\right] = f\left(\ln\dot{q}\right)$, frequently used in papers concerning solid rocket propellant ignition process research, is shown in Fig.3. It is easy to conclude that the increase of absorptivity, with the same heat fluxes, reduces the ignition time.
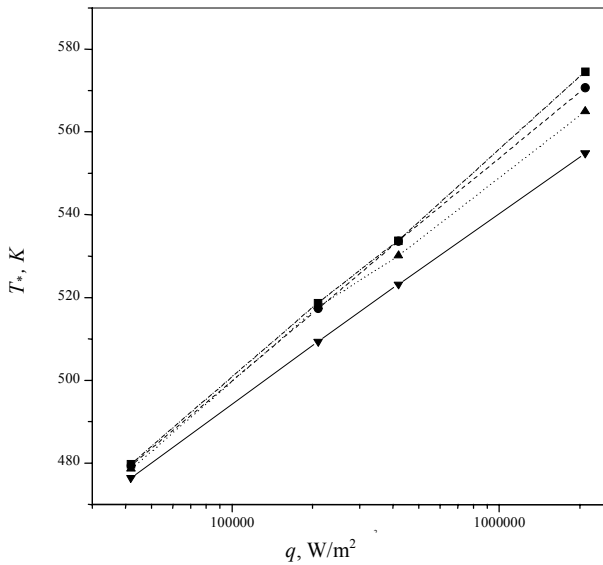
Figure 3. Ignition delay time dependence on the applied heat flux by radiation for various values of the parameter *n*: 1 ■ *n*=8000[m⁻¹]; 2 ● *n*=6000[m⁻¹]; 3 ▲ *n*=4000[m⁻¹]; 4 ▼*n*=2000[m⁻¹]
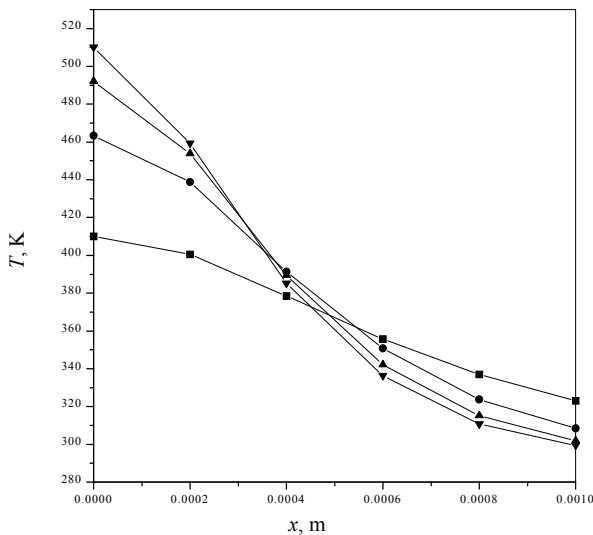

Figure 4. Temperature profiles in a heated propellant layer of 1·10⁻³ [m] in depth, with $\dot{q}$ =0.20934 MW/m², in a selected moment of time *t*=1.0 s, for the values of *n* [m⁻¹]: ■ 2000, ● 4000, ▲ 6000, ▼ 8000
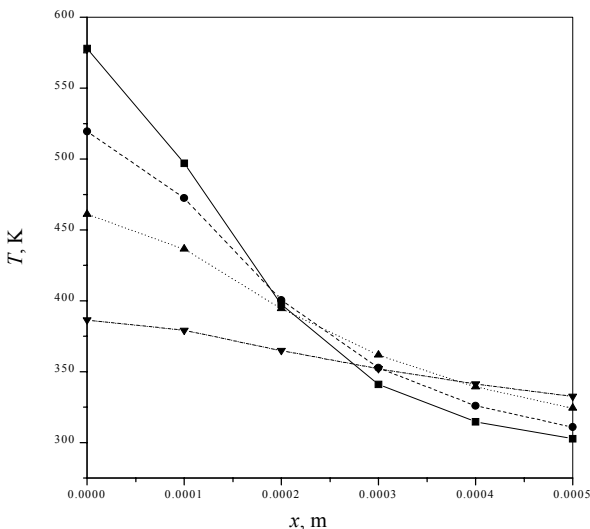

Figure 5. Temperature distribution in a propellant surface layer heated by the radation flux $\dot{q}$ =2.0934 MW/m² in a selected moment of time *t*=0.059 s, for different values of *n*[m⁻¹]: ▼ 2000, ▲ 4000, ●6000, ■ 8000

The comparison of temperature fields in a heated solid rocket propellant layer for different absorption coefficients *n* in a chosen moment of time is given in Figs.4 and 5. For the value of the given parameter of 8000 [m⁻¹], the ignition temperature is realized in both cases at selected times. With lower values of *n*, heating in deeper layers is greater thus producing higher ignition delay times in more transparent propellants. As for opaque propellants, higher heat fluxes lead to higher temperature gradients in heated layers.

The comparison of propellant surface temperature changes as a function of time, up to the moment of ignition, for various values of transparency at heating by the equal energy flux intensity is presented in Fig.6. The temperature growth in the heated propellant layer during the ignition process is illustrated in Fig.7.
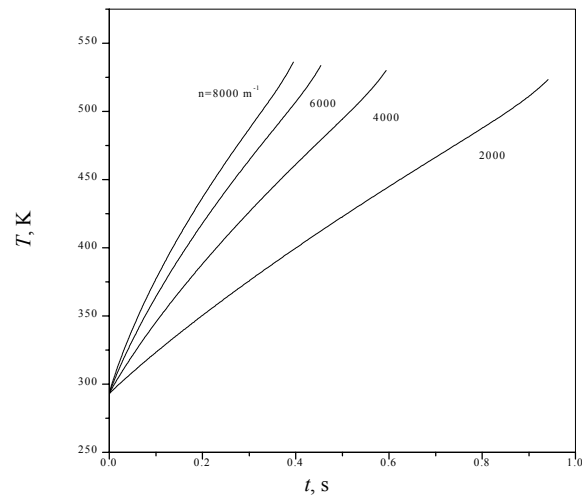

Figure 6. Temperature history diagram of the solid rocket propellant surface ignited by the heat flux $\dot{q}$ = 0.41868 MW/m² for various values of *n*
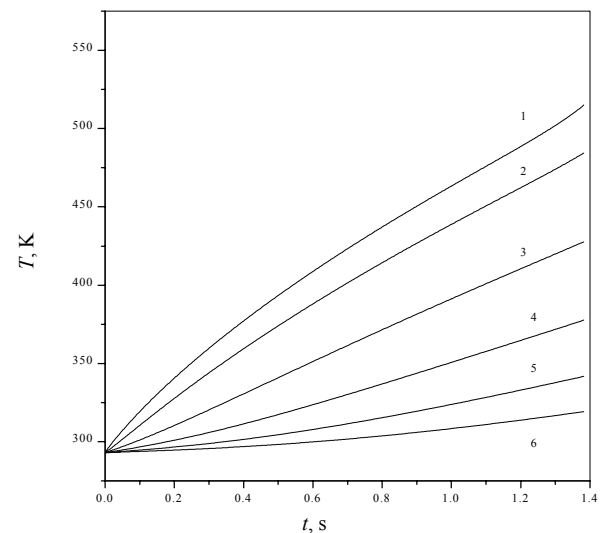

Figure 7. Calculated surface layer temperatures of the propellant with *n*=4000 [1/m] as a function of time, for a case of ignition by the heat flux of intensity $\dot{q}$ =0.20934 MW/m²: 1 – *T* on the surface; 2 – *T* at a depth of *x*=5·10⁻⁵; 3 – *x*=1·10⁻⁴ [m]; 4 – *x*=1.5·10⁻⁴ [m]; 5 – *x*=2·10⁻⁴ [m]; 6 – *x*=2.5·10⁻⁴ [m]

Time delay and ignition temperature divided by corresponding values for non-transparent propellants, calculated using the numerical model from reference [14], are presented in Figs.8 and 9.
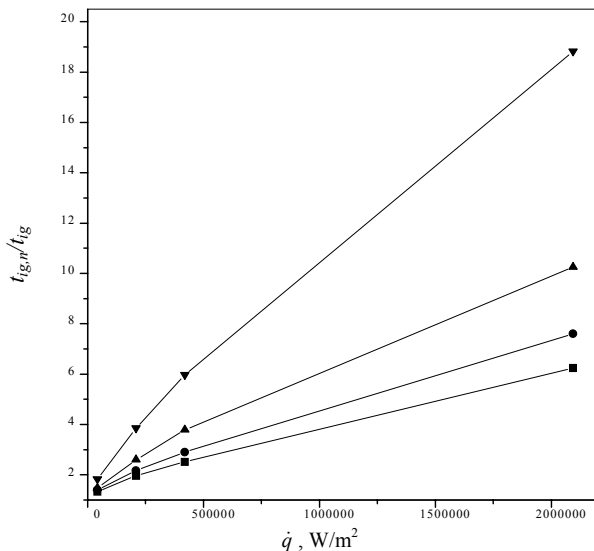
Figure 8. Comparison of the computed ignition delay times of transparent and opaque propellants as a function of the radiation heat flux for the following values of n: ■8000 [m^{-1}]; ●6000 [m^{-1}]; ▲4000[m^{-1}]; ▼2000 [m^{-1}]
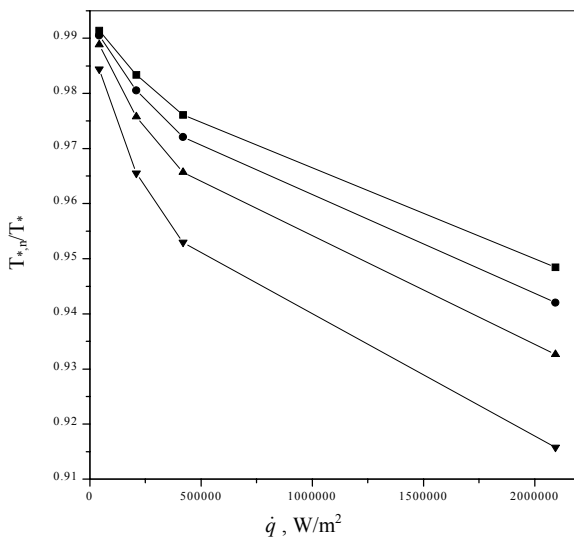
Figure 9. Dependence of the relation between the ignition temperatures of transparent and non-transparent propellants on the heat flux by radiation for various quantities of n[m^{-1}]: ■ 8000; ● 6000; ▲ 4000; ▼ 2000

Differences in time are drastic for higher heat transfer rates, and it can be concluded from Fig.9. that the ignition temperature deviation from non-transparent propellant ones is very small for lower $\dot{q}$.

Conclusion

Influence of transparency on ignition time delay in radiant heating of solid rocket propellants is important. Increasing heat flux intensifies that influence and ignition time delay increases (even for an order of magnitude) while the ignition temperature decreases. Propellant transparency growth changes temperature growth dynamics in heated

layers for the same exterior heat flux (Fig.4 and 5). A low propellant coefficient of absorption n (greater transparency) produces temperature gradient reduction, more intensive heat transfer into the propellant depth and later fulfiling of surface critical conditions characterizing ignition. From the presented diagrams it can be clearly seen that the influence of transparency change is much greater in the region of lower propellant absorption coefficients n. The developed numerical model enables the calculation of needed parameters for the solid rocket propellant radiation ignition process with various values of absorptivity and heat flux, which can be also time–dependent.

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Uticaj providnosti čvrstih raketnih goriva na proces pripaljivanja zračenjem

Analiziran je uticaj optičkih svojstava čvrstog raketnog goriva na proces pripaljivanja u slučaju dovođenja toplote zračenjem. Temperatura i koncentracija u čvrstoj fazi određivane su numeričkim putem. Parametri pripaljivanja razlikuju se u odnosu na neprovidno gorivo. Povećanje providnosti dovodi do povećanja vremena kašnjenja pripaljivanja i sniženje temperature pripaljivanja. Na karakter odvijanja procesa utiče i intenzitet primenjenog toplotnog fluksa. Rezultati su prikazani tabelarno i u obliku dijagrama.

Ključne reči: **čvrsta raketna goriva, sagorevanje, pripaljivanje.**

Influence de la transparence des propergols solides sur l'allumage par rayonnement

L'article analyse l'influence des propriétés optiques du propergol solide sur l'allumage quand la chaleur est transférée par rayonnement. La température et la concentration dans la phase solide sont déterminées par la voie numérique. Les paramètres de l'alumage sont différents par rapport du propergol opaque. L'augmentation de la transparence provoque l'augmentation du temps de retard de l'allumage et la diminution de la température de l'allumage. L'intensité du flux de chaleur influence aussi le caractère du processus. Les résultats sont présentés par tables et diagrammes.

Mots-clés: **propergols solides, combustion, allumage.**