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# A study of delayed spontaneous insulation fires

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### Abstract

The phenomenon of gaseous thermal explosion within inert insulation material filled with a combustible evaporating fuel is considered. A novel approach to estimate the activation energy is suggested using the available experimental data and the relevant theoretical predictions concerning the delay ignition time. © 2003 Elsevier Science B.V. All rights reserved.

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# 1. Introduction

The present Letter is concerned with the phenomenon of self-ignition within insulation materials (also known as spontaneous insulation fires). A fluid leaks from a hot pipe into porous insulation material dispersing over an extremely large internal surface. Due to highly insulated environment heat losses are remarkably low, and self-ignition might occur as a result of exothermic oxidation reaction. Experimental data testifies that even under heavy loading of the initially dry solid matrix, the most part of internal space (up to 80–90%) remains empty (e.g., filled by an air and vapour of the liquid fuel). This gaseous mixture serves as an oxidizer supplier. Flammable fluid evaporation provides a combustible component into the gas mixture that accelerates the oxidation. The initial concentration of the flammable vapor in the gas phase is relatively low due to the low initial temperature of the system. The system behavior is supposed to be driven by the two processes: heat losses due to heating and evaporating of the flammable liquid film, and heat release associated with the exothermic oxidation. Competition between these processes may lead to situations when the system seems to be safe for a long time before the final ignition event. This is justified by the laboratory experimental studies of spontaneous ignition within various types

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of porous materials [1–3]. The present Letter proposes a novel approach of determining the activation energy, on the basis of delay time estimations. For this purpose the available experimental data are compared with the relevant theoretical predictions. The mathematical model used in this Letter was developed in our previous paper [4]. The main results of the Ref. [4] are given in Section 2. A brief survey of the available experimental results is given in Section 3. The proposed approach is explained in Section 4, and some results are presented in Section 5.

#### 2. Theoretical predictions of the delay time

In the previous work [5] devoted to modelling of the spontaneous insulation fires, the authors suggested a simplified one-temperature model which did not take into account a heat capacity of the liquid and its heating during the self-ignition process. The main goal was to gain a conceptual understanding of the self-ignition processes in the insulation materials. To verify applicability of the model, the theoretical delay time was calculated for some experimental data taken from the work of Britton [1]. Kaylo-10 insulation filled with methyldiethanolamine (MDEA) was considered. The thermophysical properties of the liquid and the liquid vapor were calculated as functions of the temperature in accordance with the expressions presented in the DIPPR Data Compilation of Pure Compound Properties Database. The deficient data (such as an average radius of a pore, pre-exponential factor, activation energy, etc.) were interpolated on the basis of these data for the similar substances. The comparison between the theoretical predictions and the experimental data demonstrated sufficient qualitative agreement. Moreover, the analytical delay time estimations were quite close to the experimental ones. The conclusion stated that the obtained results lend credence to the used approach, which should be improved for more precise description of the phenomenon. Some progress was made in Refs. [4,6] where the more realistic model was developed and analyzed in detail. The results of this study is used in the present Letter. The model is briefly described below including the main results.

The model is based on the conventional cell approach to the analysis of dynamical processes in multiphase media [7]. The porous medium is modeled as a set of equal parallel capillaries of the same inner radius. It is assumed that the same processes take place within all the capillaries. The internal porous structure of the medium is assumed to be ideal to simplify the considered problem and to allow use of analytical methods. The combustible gas mixture is assumed to be in the center of a capillary, in the shape of cylinder with radius  $R_G(t)$ . The combustible liquid is assumed to be spread on the inner surface of a capillary, as a uniform thin layer with depth  $R_{ci} - R_G(t)$  (see Fig. 1). Hydrodynamic effects (for example, gas filtration through the porous media, or combustible liquid flow) are ignored. The influence of pressure disturbances on the thermal explosion dynamics is also ignored. The gas temperature is controlled by the two main processes: heat release associated with an oxidation reaction and heat sink due to heat transfer to the liquid on the capillary wall. Heat flux from the gas phase to the liquid film  $q_{GL}$  is considered to be proportional to the temperature difference between the gas and liquid phases. The model uses



Fig. 1. A porous medium modeled as a set of equal capillaries (left) and schematic cross-section of a single cell (right).

the adiabatic approach, as well as the spatially uniform approach to energy (both gas and liquid) and concentration equations. The chemical reaction is assumed as gaseous only and it is modeled as a first order highly exothermic reaction. The governing equations read as:

$$\pi R_{G0}^2 c_{pG} \rho_G \frac{dT_G}{dt} = \pi R_{G0}^2 Q_F \mu_F C_F A \exp\left(-\frac{E}{BT_G}\right) - \alpha_{GL} (T_G - T_L) 2\pi R_{G0} H(R_{ci} - R_G), \qquad (2.1)$$

$$\pi \left( R_{\rm ci}^2 - R_{\rm G0}^2 \right) c_{\rm L} \rho_{\rm L} \frac{dT_{\rm L}}{dt} = \alpha_{\rm GL} (T_{\rm G} - T_{\rm L}) 2\pi R_{\rm G0} \zeta(T_{\rm L}) H (T_{\rm LS} - T_{\rm L}) H (R_{\rm ci} - R_{\rm G}), \tag{2.2}$$

$$\pi R_{\rm G0}^2 \frac{dC_{\rm F}}{dt} = -\pi R_{\rm G0}^2 C_{\rm F} A \exp\left(-\frac{E}{BT_{\rm G}}\right) + \frac{1}{L\mu_{\rm F}} \alpha_{\rm GL} (T_{\rm G} - T_{\rm L}) 2\pi R_{\rm G0} (1 - \zeta(T_{\rm L})) H(R_{\rm ci} - R_{\rm G}),$$
(2.3)

$$\frac{d}{dt} \Big[ \pi \Big( R_{\rm ci}^2 - R_{\rm G}^2(t) \Big) \rho_{\rm L} \Big] = \frac{1}{L} \alpha_{\rm GL} (T_{\rm G} - T_{\rm L}) 2\pi R_{\rm G} \Big( 1 - \zeta(T_{\rm L}) \Big) H(R_{\rm ci} - R_{\rm G}).$$
(2.4)

Subject to the initial conditions:

$$T_{\rm G}(t=0) = T_{\rm G0}, \qquad T_{\rm L}(t=0) = T_{\rm L0}, \qquad C_{\rm F}(t=0) = C_{\rm F0}, \qquad R_{\rm G}(t=0) = R_{\rm G0}.$$
 (2.5)

Here A pre-exponential factor (s<sup>-1</sup>); B universal gas constant; C concentration of combustible component in gaseous mixture (kmol m<sup>-3</sup>); c thermal capacity (Jkg<sup>-1</sup> K<sup>-1</sup>); E activation energy (Jkmol<sup>-1</sup>); L latent heat of evaporation (Jkg<sup>-1</sup>); Q heat combustion (Jkg<sup>-1</sup>); q heat flux (Jm<sup>-2</sup> s<sup>-1</sup>);  $R_{ci}$  internal radius of a capillary (m);  $R_{ce}$  external radius of a capillary (m);  $R_{G}$  radius of the gas phase inside a capillary (m); T temperature (K);  $\alpha_{GL}$  is a convection heat transfer coefficient on the gas–liquid boundary (W m<sup>-2</sup> K<sup>-1</sup>);  $\rho$  density (kg m<sup>-3</sup>). The following subscripts are used: F combustible component of gaseous mixture; G gas phase; L liquid fuel film; S saturation conditions; 0 undisturbed state of the system. The Heaviside unit step function of the liquid film thickness  $H(R_{ci} - R_G)$  means that the heat sink due to evaporation exists while there is a liquid film, the Heaviside unit step function  $H(T_{LS} - T_L)$  means that the liquid temperature increases till the saturation value. The function  $\zeta(T_L)$  describes the part of the total heat flux from the burning gas to the fuel film, which is spent to the heating of the liquid fuel only. Correspondingly,  $(1 - \zeta(T_L))$  describes a component of the heat flux transferred to the fuel evaporation. We assume that for the temperatures which are far below the boiling point, almost all heat is transferred to the liquid heating, while close to the saturation line it is spent mostly to liquid evaporation. Under this assumption, the function  $\zeta(T_L)$  looks as:

$$\zeta(T_{\rm L}) = \frac{T_{\rm LS} - T_{\rm L}}{T_{\rm LS} - T_{\rm L0}}.$$
(2.6)

The analysis of the system (2.1)–(2.6) was conducted for the data taken from experiments [1,3] on cubes of calcium silicate impregnated (150% weight loading was mainly used) with fuel named MDEA (*N*-methyl-diethanol-amine). It is assumed that the initial temperatures of the gas and liquid phases are equal:

 $T_{\rm G0} = T_{\rm L0}.$ 

The following parameter values were used:

$$\begin{split} \rho_{\rm L} &= 1.03 \times 10^3 \; ({\rm kg}\,{\rm m}^{-3}), \qquad L = 5.29 \times 10^5 \; ({\rm J}\,{\rm kg}^{-1}), \qquad Q_{\rm F} = 2.567 \times 10^7 \; ({\rm J}\,{\rm kg}^{-1}), \\ c_{\rm L} &= 2.334 \times 10^3 \; ({\rm J}\,{\rm kg}^{-1}\,{\rm K}^{-1}), \qquad c_{\rm pG} = 1.25592 \times 10^3 \; ({\rm J}\,{\rm kg}^{-1}\,{\rm K}^{-1}), \qquad C_{\rm F0} = 6 \times 10^{-4} \; ({\rm kmol}\,{\rm m}^{-3}), \\ A &= 8.062 \times 10^{12} \; ({\rm s}^{-1}), \qquad E = 1.26697 \times 10^8 \; ({\rm J}\,{\rm kmol}^{-1}), \qquad \mu_{\rm F} = 1.1916 \times 10^2 \; ({\rm kg}\,{\rm kmol}^{-1}), \\ R_{\rm G0} &= 1.12 \times 10^{-6} \; ({\rm m}), \qquad R_{\rm ci} = 1.2 \times 10^{-6} \; ({\rm m}), \qquad R_{\rm ce} = 1.25 \times 10^{-6} \; ({\rm m}), \\ \alpha_{\rm GL} &= 50 \; ({\rm W}\,{\rm m}^{-2}\,{\rm K}^{-1}), \qquad T_{\rm S} = 518 \; ({\rm K}), \qquad 370 \; ({\rm K}) \leqslant T_{\rm G0} = T_{\rm L0} \leqslant 426 \; ({\rm K}). \end{split}$$

The conventional Semenov approach is used for non-dimensionalization, based on the initial characteristic values [8]:

$$\theta_{\rm G} = \frac{T_{\rm G} - T_{\rm G0}}{T_{\rm G0}} \frac{E}{BT_{\rm G0}}, \qquad \theta_{\rm L} = \frac{T_{\rm L} - T_{\rm G0}}{T_{\rm G0}} \frac{E}{BT_{\rm G0}}, \qquad \eta = \frac{C_{\rm F}}{C_{\rm F0}}, \tau = \frac{t}{t_{\rm react}}, \qquad t_{\rm react} = A^{-1} \exp\left(\frac{E}{BT_{\rm G0}}\right),$$
(2.8)

where the reaction time  $t_{\text{react}}$  is the time required for the reactant concentration to fall by a factor *e* from its initial value under the isothermal conditions. The dimensionless liquid film thickness is taken as:

$$\delta = \frac{R_{\rm ci} - R_{\rm G}}{R_{\rm ci} - R_{\rm G0}}.\tag{2.9}$$

The dimensionless model was treated as a multi-scale system with a small parameter, due to a great difference in characteristic times of the processes involved (highly exothermic chemical reaction, evaporation). The system was analyzed by the method of integral manifolds (MIM, [9]). It was shown that in the used parameter region, the system demonstrates explosive behavior with long-time delays before the final ignition. It was also shown that the final thermal explosion normally occurs within the temperature interval below the boiling point of the liquid fuel. That means that accepted safety regulations (chemical industry, heavy processing plants, etc.) might be a subject of additional thorough verification versus the obtained results. The main result of the theoretical study was the delay time estimations. Physically, the delay time is related to the temporary balance between the chemical heat release and the *internal* heat losses to the liquid phase. Due to the used non-dimensionalization (2.8), the dimension delay time is given by:

$$t_{\rm delay} = \tau_{\rm delay} A^{-1} \exp\left(\frac{E}{BT_{\rm G0}}\right),\tag{2.10}$$

where the dimensionless delay time was derived in the form [4]:

$$\tau_{\text{delay}} = \int_{0}^{\text{Ln}(\varepsilon_1)} \frac{dv}{(1 - v/\theta_{\text{S}}) \left(\frac{\varepsilon_3}{\varepsilon_1} - \psi_{\text{F}}v + \theta_{\text{LS}}(1 - \psi_{\text{F}})\ln(1 - v/\theta_{\text{LS}})\right) \exp(v)},\tag{2.11}$$

with the dimensionless parameters given by:

$$\psi_{\rm F} = \frac{Q_{\rm F}}{L}, \qquad \varepsilon_1 = \frac{2\alpha_{\rm GL}T_{\rm G0}\beta\exp(\beta^{-1})}{AC_{\rm F0}\mu_{\rm F}Q_{\rm F}R_{\rm G0}}, \qquad \varepsilon_3 = \frac{2\alpha_{\rm GL}\exp(\beta^{-1})}{Ac_{\rm L}\rho_{\rm L}}\frac{R_{\rm G0}}{R_{\rm ci}^2 - R_{\rm G0}^2}, \qquad \beta = \frac{BT_{\rm G0}}{E}.$$

To recap, we should note that the adiabatic assumption of our analysis imposes definite limitations on the model applicability. For example, under the used approximations the self-ignition will finally occur in any case, independently of other conditions. It is evident that this is not obeyed in real experimental conditions. The presence of a heat sink to ambient, which exists in any realistic system might prevent the explosion. In this case the parametric region where the delayed explosion occurs will shrink, and a qualitatively different type of the dynamical system behaviour, namely the slow non-explosive behaviour (safe regime) will appear.

# 3. Experimental observations

The phenomenon of spontaneous insulation fires has been investigated for a long time. A number of experimental methods were developed to estimate a potential danger of the phenomenon. Norton [10] reported on experimental studies of spontaneous ignition in lagging materials impregnated with different oils. Bowes and

Langford [11] suggested and investigated two methods for assessing the hazard of spontaneous ignition in oilsoaked lagging in hot pipes. They concluded that the method based on electrically heated plate yields more direct result but it is less suitable for use in a large number of tests. Gugan [12] reported that the lowest spontaneous ignition temperature (SIT) is observed when the wetting liquid occupies 6–12% by volume of the void spaces, corresponding to the weight loading 150–300% for a typical insulation soaked with mineral oil. Bowes [13] tested liquid soaked insulation regarding their ability to reduce hazards of spontaneous ignition within porous sample. This test method is similar to that developed for addressing spontaneous heating of solids, and it is used in particular by Bowes and Langford [11] and Gugan [12]. The method was improved later by Beever and Thorne [14]. At present the algorithm is called as a standardized spontaneous ignition temperature (SIT) test method, and it is used by the most experimental groups.

A number of experimental groups have conducted experimental researches on the phenomenon of spontaneous insulation fires using a wide range of fuels and insulations. We will comment here very briefly the most relevant works.

In the series of experiments conducted by John Griffiths and his colleagues [2,15] the self-ignition phenomenon of alcohols placed within the porous medium was investigated. The minimum ignition temperature of the fluid in the insulation material was established by mounting a series of experiments in which a block, freshly impregnated with one of the alcohols in the  $C_6-C_{11}$  range, was located in a re-circulating air oven thermostatted at successfully increased temperatures for each experiment. Prior to each experiment the insulation block was impregnated uniformly with the same amount of one or other of the alcohols (10 cm<sup>3</sup>) by dissolving it in dietyl ether (50 cm<sup>3</sup>) and allowing the solution to penetrate the block. The dietyl ether was then evaporated off in a low temperature drying over some hours. An oven temperature was reached eventually at which "ignition" could be distinguished from "slow combustion". The temperature difference between the center of the cube and the oven temperature (constant) was recorded as a function of time. The distinction between stable exothermic reaction and fully developed explosion (unstable oxidation reaction) could be clearly discerned from this temperature-time records. The obtained experimental data were processed and the minimum spontaneous ignition temperature was determined. The authors mention that the initial stage of the ignition process (from the beginning till the final explosion) lasted about 2 hours and slightly varied under the conditions adopted in this series of experiments.

Britton [1] adopted the standardized spontaneous ignition temperature test method in his research. The used procedure can be shortly described as follows. A two-inch cube of dried insulation (mostly mineral wool was used, a limited number of tests were performed with calcium silicate) is weighted then sectioned either into a number of half-inch cubes. The test liquid is applied in equal aliquots to each section to give the required total loading, then the sections are compressed together into  $2 \times 2 \times 2$  inch light steel mesh basket. The basket is equipped with wire loops to suspend it in an air convection oven controlling to within 1-2 °C of the set temperature. During placement of the sample cube a fine thermocouple is pushed into the center of the test cube and a second pushed between the insulation and the mesh side. The "edge" thermocouple should read within a couple of degrees of the oven set temperature of the oven set temperature, although at temperatures much above the minimum SIT, significant selfheating can occur at the edge. Samples are heated at constant temperature and their internal temperatures monitored for exotherm. After several tests, two temperatures can be identified which separate "ignition" from "no ignition" by a few degrees Celsius. The mean of these is cited as the SIT for the particular size of cube and liquid loading. The author came to the conclusion that spontaneous insulation fires are predictable, nevertheless, to minimize the risk he recommended to use non-porous insulation, such as cellular glass. (The non-porous, non-combustible insulation suitable for a wide rage of system temperatures. The disadvantage is that the price is extremely high.)

One of the latest experimental researches in this direction was conducted by Pegg and Pan [3]. They performed a number of series of experimental runs on insulation fires using the standardized spontaneous ignition temperature test method. Experiments were conducted on cubes on calcium silicate insulation (Thermo-12 Gold) impregnated with *N*-methyl-diethanol-amine (MDEA). Nominal cube sizes of 25 mm, 51 mm and 102 mm were used. The center square of each cube was carefully scored to accurately position the thermocouples. Temperature was measured at the center, two locations equispaced from the center, the edge of the cube and in the oven. The



Fig. 2. Typical time history of the experiments conducted by Pegg and Pan [3].

squares of insulations were soaked in the solvent for at least 24 hours before a test. Nominal solvent loadings of 150% (weight) were used for all tests. The authors mentioned that the measured delay time varied widely in the experimental runs (from tens of minutes to more then ten hours). The initial temperature of the cube of insulation was mentioned as one of the important factors affecting the system dynamics. The typical temperature–time record of the performed experiments is presented in the Fig. 2.

# 4. Proposed approach to estimate the activation energy

The goal of the present Letter is to predict the important thermo-chemical properties of the fuel, namely activation energy and pre-exponential factor. Before explaining the novelty of the proposed method, let us briefly summarize the essence of the well-known relevant methods, namely the Frank–Kamenetskii method and the Crossing Point Method.

The Crossing Point Method was developed by Dong Chen and his colleagues [16–18] for determination of the activation energy of the wood sawdust of coals and is widespread at present [3,19]. The apparatus required for the Crossing Point Method consists of the temperature-controlled oven with a wire-mesh basket made into a cube for holding the samples and an open top. The sample having five pre-calibrated thermocouples inside it is suspended in the oven. All the thermocouples are aligned in a straight line. The first point is the center of the sample, the second at some distance from the center, the third at a larger distance and so on. The time history of the temperatures and their derivatives are registered. Special efforts are made to determine the moment when the temperature distribution within the slab became to be homogeneous (temperature-time histories for various thermocouples are crossing each other—this gave the name to the method). The method of data processing is based on the analysis of the energy equation for a reactive porous slab

$$c_{\rm p}\rho \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} + Q\rho A \exp\left(-\frac{E}{RT}\right),\tag{4.1}$$

where k is the thermal conductivity of the solid (W m<sup>-1</sup> K<sup>-1</sup>), x is a distance (m). When the temperature profile becomes flat, the conduction term in (4.1) vanishes. Eq. (4.1) reduces:

$$c_{\rm p}\rho \frac{\partial T}{\partial t} = Q\rho A \exp\left(-\frac{E}{RT}\right). \tag{4.2}$$

The temperature measured at the center line (which is greater than the ambient temperature) is noted as  $T_p$ . Eq. (4.2) indicates that the plot of  $\ln(dT/dt)$  versus  $1/T_p$  is linear with the slope (-E/R) and intercept  $\ln(QA/c_p)$ . This approach is used as a basis in determining kinetic parameters.

The Frank–Kamenetskii approach to determine kinetic parameters is based on the steady-state analysis of Eq. (4.1). The analysis produces a solution depending on the single dimensionless parameter often referred to as the Frank–Kamenetskii number

$$\delta = \frac{x_0^2 Q \rho A \exp\left(-\frac{E}{RT_a}\right)}{k \frac{RT_a^2}{E}},\tag{4.3}$$

where  $x_0$  is a half of the characteristic dimension of the sample and  $T_a$  is the ambient temperature. A series of tests (for various values of the parameter  $x_0$ ) is carrying out to obtain the critical ambient temperature at which ignition occurs. The activation energy *E* is determined using the slope of the log-temperature plot versus  $1/T_a$ , obtained from Eq. (4.3):

$$\ln\left(\frac{\delta T_{a}^{2}}{x_{0}^{2}\rho}\right) = \ln\left(\frac{EAQ}{Rk}\right) - \frac{E}{RT_{a}}.$$
(4.4)

The Frank–Kamenetskii method and the Crossing Point Method are known to work well in coals and other combustible solids [16–18]. The present Letter, however, deals with *evaporating* fluids, where the aforementioned methods cannot be applied. We propose a new method to predict thermo-chemical properties of the fuel which is designed especially for systems involving ignition delays. Such ignition delays are typical for flammable evaporating fluids in insulation material, due to competition between heat production (exothermical chemical reaction) and heat losses (evaporation of the liquid fuel). Similar to the Frank–Kamenetskii method and the Crossing Point Method, the proposed method uses the ideas of comparing slopes and intercepts of the relevant plots. The new point is that we use the plots of the delay time (which is quite easy to measure) versus the reciprocal of the initial temperature. The basis of the suggested method is described below.

The approach is based on the delay time measurements under controlled initial conditions (see [3]). The used model does not take into account the external shape and size of the specific sample of insulation material. The model accounts for the parameters of the conditional capillary, which serves as a basic element for all further calculations. Therefore we display all experimental points obtained by Pegg and Pan in a single figure (see Fig. 3). The performed measurements are presented as a logarithmic dependence of the delay time Ln( $t_{delay}$ ) (min) on the reciprocal of the initial temperature  $10^3/T_{G0}$  (K<sup>-1</sup>). The experimental points can be approximated by the linear least squares fit:

$$\operatorname{Ln}(t_{\text{delay}}) \approx a \left(\frac{1000}{T_{\text{G0}}}\right) + b \tag{4.5}$$

(solid line, Fig. 3). The similar logarithmic dependence of the delay time on the reciprocal of the initial temperature can be easily obtained analytically from Eqs. (2.10), (2.11):

$$\operatorname{Ln}(t_{\text{delay}}) = \left(\frac{E}{BT_{\text{G0}}} - \operatorname{Ln}(A)\right) + \operatorname{Ln}(\tau_{\text{delay}}),\tag{4.6}$$

where the dimensionless delay time  $\tau_{delay}$  is given by Eq. (2.11). Comparing the experimental results (4.5) and the theoretical results (4.6), we can estimate the two important chemical parameters, namely the activation energy (*E*)



Fig. 3. Letters denote: a the linear least squares fit (5.1) corresponding to the depicted experimental points [3]; b the function  $F_1$  (5.3); c the function  $F_2$  (5.4). The coordinates: ordinate  $Ln(t_{delav})$  (min), abscissa  $(10^3/T_{GO})$  (K).

and the pre-exponential factor (*A*). More specifically, if the term  $Ln(\tau_{delay})$  in the formula (4.6) depends linearly on the reciprocal of the initial gas temperature  $(1/T_{G0})$ , the parameters (*E*) and (*A*) can be obtained by comparing the corrected slope and intercept of the straight lines (4.5) and (4.6).

It is evident that the final conclusion cannot be made on the basis of a limited number of available experimental runs. Nevertheless, the proposed approach can be certainly applied to determination of the thermo-chemical characteristics of the fuel under consideration.

# 5. Results

To demonstrate a typical calculation we compare the experimental results (4.5) and the theoretical results (4.6), for the available experimental data. Concerning the experimental data (points, Fig. 3), the linear least squares fit (the straight line a, Fig. 3) reads as:

$$Ln(t_{delay}) \approx 15.2463 \left(\frac{10^3}{T_{G0}}\right) - 33.0625.$$
(5.1)

The theoretical formula (4.6) can be rewritten as:

$$\operatorname{Ln}(t_{\operatorname{delay}}) = F_1 + F_2, \tag{5.2}$$

where

$$F_1 = \left(\frac{E}{BT_{G0}} - \operatorname{Ln}(A)\right),\tag{5.3}$$

$$F_2 = \operatorname{Ln}(\tau_{\text{delay}}). \tag{5.4}$$

The function  $F_1$  given by (5.3) depends linearly on the reciprocal of the initial gas temperature. The detailed numerical simulations for fixed values of the parameters (*E*) and (*A*), show that the dependence of  $F_2$  on the ratio  $1/T_{G0}$  is also close to linear with rather small slope. Thus for the appropriate values of the parameters (*E*) and (*A*), the sum of the two straight lines b and c (given by (5.3) and (5.4), respectively) will fit the experimental least squares fit a (5.1) (see Fig. 3). Fig. 4 demonstrates how the theoretical expression (5.2) (solid line, Fig. 4) approximates the used experimental points. One can easily note that the solid line in Fig. 4 looks very similar to the least square fit of the experimental points (line a, Fig. 3). This testifies that the suggested approach allows to describe the independent measurements quite accurate. The visual impression is justified by numerical estimation of the relative error, shown in Fig. 5. The accuracy of the approximation is rather good—it varies within a vicinity of a few percent.



Fig. 4. Comparison between the experimental points and the theoretical plot defined by (5.2).



Fig. 5. The relative error between the experimental data and the theoretical line given in Fig. 4.

The two determined values ( $E = 1.26697 \times 10^8$ ,  $A = 8.06155 \times 10^{12}$ ) represent the desired thermo-chemical characteristics of the used fuel. It should be noted here that a limited number of experimental data available to authors might be a possible reason of potential error of the gained result. It would be worthwhile to underline here, that in our previous paper on insulation fires [5] the inverse problem was considered. Namely, in accordance with the suggested one-temperature model the delay time was predicted analytically, and the results were compared with the experimental data provided by Britton [1]. For the used activation energy ( $126 \text{ MJ kmol}^{-1}$ , which is almost the same as the value obtained in the present Letter) the comparison between the theoretical and experimental results was quite good.

# 6. Conclusions

The phenomenon of the gaseous thermal explosion in lagging material filled with a combustible evaporating fuel was studied in the present Letter. A novel approach to determination of the key thermochemical parameters (namely, the activation energy and the pre-exponential factor) was suggested. The proposed method is based on the special type of processing of the delay time measurements. More specifically, the available experimental data were compared with the relevant theoretical predictions concerning the delay time before the final ignition. The model suggested in the previous work of the authors was applied to process the available experimental data. Comparison between the experimental and theoretical results allowed us to determine the desired thermochemical characteristics of the fuel.

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