NONSTEADY-STATE INTERACTION OF A COMBUSTION WAVE WITH A DUST CLOUD

I. G. Dik, E. I. Gubin,
and A. Yu. Krainov

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A mathematical model of inhibition of gas flames by inert powders is studied.

The wide use of powders as fire preventive and extinguishing media is related to their high capabilities for these purposes and the convenience with which they may be stored and used [1, 2]. The mechanism involved in suppressing gas flames has been explained in [2-4] as a retardation of combustion by the heat absorbing dispersed material, as chemical inhibition, or a combination of these factors. In [5-7], which studied the effectiveness of heavy silicon-containing particles on a gas flame, it was found that an increase in mass concentration of the dispersed material with fixed particle size decreases the combustion rate, while increase in particle size for constant mass concentration decreases the effect of the solid phase upon the combustion rate.

From the viewpoint of the thermodiffusion model of flame propagation, these results can be explained by the inert nature of heat exchange between the particles and gas. In particular, quantitative estimates of the decrease in steady-state flame rate in a dusty gas can be carried out within the framework of methods developed within the combustion theory of [8].

In practice a combustion wave in a gas interacts with a solid particle suspension partially in nonsteady-state regimes. The two corresponding model problems are presented below. Results of these problems are interpreted using conclusions from steady-state theory.

1. Nonsteady-State Interaction of a Flame Front with a Dust Cloud. We assume that a high-temperature hearth initiates a combustion reaction within the gas, such that after a set-up period a flame propagates through the gas at constant velocity. To phlegmatize the combustion along the path of the flame there is created a cloud of uniformly distributed inert particles of radius r and numerical concentration N_0. Because of heat exchange between the particles and gas, which (we will assume) obeys Newton's law with a heat liberation coefficient $\alpha = \lambda_g Nu/r$, cooling of the gas occurs, as a result of which the reaction rate, and hence, the combustion rate, decrease.

We describe the evolution of such a system by the thermal conductivity equation for the gas (for simplicity we model a one-dimensional situation):

$$c_g\rho_g \frac{dT_g}{\partial t} = \lambda_r \frac{\partial^2 T_g}{\partial x^2} + kbQ\exp(-E/RT_g) - \alpha s_p N_0 (T_g - T_p)\,\eta(x - x_0), \quad (1)$$

the heat-exchange equation for the particle

$$w_p c_p \rho_p \frac{dT_p}{dt} = \alpha s_p (T_g - T_p) \quad (2)$$

and the diffusion equation for the original reagent

$$\frac{\partial b}{\partial t} = D\frac{\partial^2 b}{\partial x^2} - bk\exp(-E/RT_g). \quad (3)$$

In Eq. (1) $\eta(x-x_0)$ is a Heaviside function, equal to zero for $x < x_0$ and unity for $x \geqslant x_0$.

The initial conditions for Eqs. (1)-(3) must reflect the character of initiation.

Since we have not considered the initial period of flame development the reagent concentration will be specified in the form $b(x, 0) = 1$, while the temperature field, as in a steady-state combustion wave, will be given by

$$T_g(x, 0) = (T_+ - T_-)\exp(-xc_g\rho_g/\lambda_g u_+) + T_-$$

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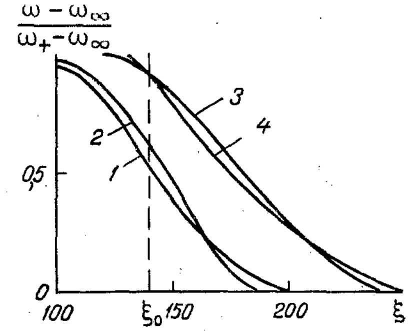

Fig. 1. Relative change in flame velocity with coordinate for various dust cloud parameters: 1) $B = 0.2$, $\varkappa = 10$; 2) $B = 0.1$, $\varkappa = 10$; 3) $B = 0.2$, $\varkappa = 10^3$; 4) $B = 0.1$, $\varkappa = 10^3$, $\gamma = 0.1$.

(a Michelson profile [8]), where T_- is the original gas temperature; T_+ is the adiabatic combustion temperature, $T_+ = T_- + Q/C_g\rho_g$; u_+ is the adiabatic combustion rate:

$$u_+^2 = \frac{2\lambda_g}{\rho_g c_g (T_+ - T_-)^2}\left(\frac{RT_+^2}{E}\right)^2 k\exp(-E/RT_+). \tag{4}$$

The boundary conditions, aside from the obvious $\partial T_g(\infty,\ t)/\partial x = \partial b(\infty,\ t)/\partial x = \partial b(0,\ t)/\partial x = 0$, reflect the continuous action of the heat source, $T_g(0,\ t) = T_+$.

The characteristic scale factors of the problem are the adiabatic reaction period at a combustion temperature $t_+ = RT_+^2\, c_g\rho_g \exp(E/RT_+)/EQk$, the corresponding length $x_+ = \sqrt{\lambda_g t_+/c_g\rho_g}$ and the temperature change RT_+^2/E, use of which transforms Eqs. (1)-(3) to a problem with five parameters: $Le = Dc_g\rho_g/\lambda_g$, $\beta = RT_+/E$, $\gamma = RT_+^2 c_g\rho_g/EQ$, $B = N_0 \bar{w}_p c_p\rho_p/c_g\rho_g$, $\varkappa = c_p\rho_p w_p/s_p\alpha t_+$. We assume, as is usual for gas flames, that $Le = 1$. The parameter β corresponds to nonlinear terms of the expansion of T_g^{-1} in a series of $T_g - T_+$ with Arrhenius exponent and may not be varied in calculations for high E.

Consequently, the solution of the problem, in particular the velocity of flame motion (which we understand as the rate of displacement of the coordinate at which one half of the gas has been reacted) $\omega = t_+ dx/x_+ dt$, is defined by three significant parameters, two of which, B and $\varkappa$, are related to the presence of the dispersed material.

Computer calculations of the dynamics of combustion wave velocity (with a grid becoming more dense in the intense chemical liberation zone) are shown in Fig. 1. Meeting the cloud of inert particles (with initial coordinate ξ_0), the flame decreases its velocity to the level ω_∞, determined by the characteristics of the dispersed material. With increase in particle size (parameter $\varkappa$) the distance at which change in flame propagation velocity changes increases. With increase in B (for constant $\varkappa$) there is a similar pattern, but less well expressed. The smaller the size of the particles, the greater the distance from the cloud boundary ξ_0 do they have an effect upon the flame front. The order of magnitude of thickness of the particle cloud sufficient for phlegmatization of a gas suspension of given composition is $\lambda_g/c_g\rho_g u$. An upper limit for this value will be obtained by using the steady state flame velocity in the dusty medium for u, which agrees well with calculated data. Therefore we will turn to calculation of the steady state flame velocity.

The drop in combustion rate in the dusty medium is related to a decrease in temperature in the zone of active chemical reaction due to expenditure of a part of the heat liberated on particle heating.

Neglecting the power dependence of combustion rate on temperature, but considering the fundamental exponential in Eq. (4), we obtain the relationship

$$\frac{u^2}{u_+^2} \approx \exp\left[-\frac{E}{R}\left(\frac{1}{T_{g0}} - \frac{1}{T_+}\right)\right] \approx \exp\left[-\frac{E}{RT_+^2}(T_+ - T_{g0})\right], \tag{5}$$

where T_{g0} is the temperature in the combustion zone in the presence of particles. The value of T_{g0} (and consequently the flame rate u) can be estimated analytically, if after transformation to a coordinate system fixed to the flame, in accordance with the narrow zone method [8] we assume that the chemical reaction occurs only on the surface $x = 0$, where complete conversion of the material occurs ($b(x = 0) = 0$), so that the difference between thermal fluxes to the right and left of the surface will be

$$\lambda_g \frac{\partial T_g}{\partial x}\bigg|_{x=+0} = -\lambda_f \frac{\partial T_g}{\partial x}\bigg|_{x=-0} = Q\rho_g D \frac{\partial b}{\partial x}\bigg|_{x=-0}. \tag{6}$$

For x ≠ 0 in the case of steady state flame propagation the equations

$$u\frac{dT_g}{dx} = \frac{\lambda_g}{c_g\rho_g}\frac{d^2T_g}{dx^2} - \frac{N_0 s_p \alpha}{c_g\rho_g}(T_g - T_p), \tag{7}$$

$$u\frac{db}{dx} = D\frac{d^2b}{dx^2}, \tag{8}$$

$$u\frac{dT_p}{dx} = \frac{\alpha s_p}{c_p\rho_p w_p}(T_g - T_p) \tag{9}$$

are valid. For $x = -\infty$ $T_p = T_g = T_-$, $b = 1$. The values $T_g(x = 0) = T_{g0}$, $T_p(x = 0) = T_{p0}$, $T_g(x = \infty) = T_\infty$ are unknown.

Writing the limited general solutions of Eqs. (7)-(9) for x > 0 and x < 0 and merging them at x = 0 with the aid of Eq. (6), we obtain

$$T_\infty = T_- + \frac{T_+ - T_-}{1+B}, \tag{10}$$

$$\sqrt{1 + 4B\tau_1(T_{g0} - T_{p0})/(T_{g0} - T_-)} = 2\tau_1(T_{g0} - T_{p0})/(T_{p0} - T_-) - 1, \tag{11}$$

$$\sqrt{1 + 4B\tau_1(T_{g0} - T_{p0})/(T_{g0} - T_\infty)} = 1 - 2\tau_1(T_{g0} - T_{p0})/(T_{p0} - T_\infty). \tag{12}$$

Equation (10) is in fact the thermodynamic equation for the mixture temperature behind the combustion front where heat exchange between particles and gas has already ended. The difference between T_∞ and T_{g0} is determined by the rate of heat exchange between the phases. The parameter corresponding to this process in Eqs. (11), (12) is $\tau_1 = (\alpha s_p/w_p c_p\rho_p)(\lambda_g/c_g\rho_g\cdot u^2)$, which is the ratio of the flame characteristic thermal time and the particle thermal reaction time. If $\tau_1 \to \infty$, then the temperatures of particles and gas do not differ, and $T_{g0} \to T_\infty$. For the case $\tau_1 \to 0$ during their traversal of the flame front the particles do not absorb heat, remaining cold, while within the reaction zone the gas reaches the adiabatic temperature $T_{g0} = T_+$.

Introducing the quantities $X = (T_{g0}-T_\infty)/(T_\infty-T_-)$, $Z = (T_\infty-T_{p0})/(T_{g0}-T_\infty)$ and $V = (1+X^{-1})\cdot(1+Z)^{-1}$ we obtain from Eq. (12) an equation for Z:

$$Z^{-2} + Z^{-1}(1 + \tau_1^{-1}) = B/\tau_1, \tag{13}$$

and from Eq. (11) an equation for V:

$$\sqrt{1 + 4B\tau_1/V} = 2\tau_1/(V-1) - 1, \tag{14}$$

after finding which we obtain X:

$$X = [V(1+Z) - 1]^{-1}$$

and thus find the temperature T_{g0}.

The solutions of Eqs. (13), (14) are cumbersome. We will limit ourselves to the limiting cases in τ_1 (the parameter B is usually much less than unity).

As $\tau_1 \to 0$ we obtain $ZB \to 1 + \tau_1$, $V \to 1 + \tau_1$ and $X \to B[1 + \tau_1(2 + B)]^{-1}$. For $\tau_1 \to \infty$ $ZB \to \tau_1$, $V \to \tau_1(1 + B)^{-1}$ and $X \to B(1 + B)/\tau_1^2 \to 0$. As an interpolation expression for the monotonically varying function $X(B, \tau_1)$ with correct limiting cases we may use

$$X = \frac{B}{1 + \tau_1(2+B) + \dfrac{\tau_1^2}{1+B}} \approx \frac{B}{(1+\tau_1)^2}. \tag{15}$$

It follows from Eq. (15) that for the variation of τ_1 from zero to ∞, T_{g0} changes from T_+ to T_∞. Then, as analysis of the change in Z shows, the particle temperature in the reaction zone T_{p0} takes on values from T_- to T_∞.

Now performing a replacement in Eq. (5) with consideration of Eq. (10)

$$T_+ - T_{g0} = (T_+ - T_\infty)\left(1 + \frac{T_\infty - T_{g0}}{T_+ - T_\infty}\right) = \frac{T_+ - T_-}{1+B}B\left[1 - \frac{T_{g0} - T_\infty}{T_+ - T_-}\frac{1+B}{B}\right],$$

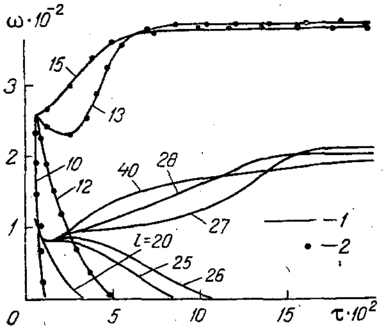

Fig. 2

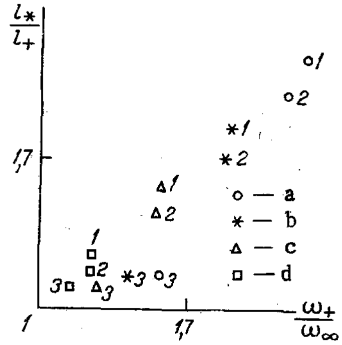

Fig. 3

Fig. 2. Dynamics of changes in flame velocity with time for various hearth sizes $l = L/x_{+}^{-1}$ and dust cloud parameters: 1) B = 0.2, $\varkappa$ = 10; x) B = 0.2, $\varkappa = 10^4$, γ = 0.1.

Fig. 3. Critical hearth size vs steady state velocity in dusty region: a) B = 0.2; b) 0.15; c) 0.10; d) 0.05; 1, $\varkappa$ = 10; 2, $\varkappa = 10^2$; 3, $\varkappa = 10^3$, γ = 0.1.

we obtain

$$\left(\frac{u}{u_+}\right)^2 = \exp\left\{-\frac{B}{\gamma(1+B)}\left[1-\frac{X}{B}\right]\right\} \approx \exp\left\{-\frac{B}{\gamma(1+B)}\left[1-\frac{1}{1+\tau_1(2+B)+\tau_1^2(1+B)^{-1}}\right]\right\}.$$

The undefined u appears in the expression for τ_1. Introducing the parameter $\tau_+ = \alpha s_p \lambda_g / w_p c_p \cdot \rho_p c_g \rho_g u_+^2 = (2\gamma^3\varkappa)^{-1}$, we find $\tau_1 = (u_+/u)^2/2\gamma^3\varkappa$.

Denoting $v = u_+^2/u^2$, we arrive at the transcendental equation

$$\frac{1}{v} = \exp\left\{-\frac{B}{\gamma(1+B)}\right\}\exp\left\{\frac{B}{\gamma(1+B)\left[1+\frac{2+B}{2\gamma^3\varkappa}v+\frac{v^2}{4\gamma^6\varkappa^2(1+B)}\right]}\right\}. \quad (16)$$

A computer analysis showed that for $B/\gamma \lesssim 3.3+4B$ Eq. (16) has a unique root for all $\varkappa$.

The calculation region in the present study was limited to the upper value $B/\gamma \gtrsim 2$, so that it is wholly contained with the region of uniqueness of the root.

In principle it is possible for three roots to exist over some range of $\varkappa_1(B/\gamma) < \varkappa < \varkappa_2(B/\gamma)$. For $B/\gamma \gtrsim 3.3+4B$ the flame velocity value may be nonunique depending on the initial initiation conditions. In this sense the situation is analogous to that of combustion of a bar packed within an inert shell [9].

It is possible that nonuniqueness of the combustion rate can be found at high particle mass concentrations (B ≈ 0.5 to 1.0), if initiation is modeled by a hearth of different temperature, which lies outside the formulation described above.

Experiment has shown that Eq. (16) can be solved by the iteration method, at least in the calculation region, beginning with v = 1. The first iteration gives the relationship

$$\left(\frac{u}{u_+}\right)^2 = \exp\left\{-\frac{B}{\gamma(1+B)}\right\}\exp\left\{\frac{B}{\gamma(1+B)\left[1+\frac{2+B}{2\gamma^3\varkappa}+\frac{1}{4\gamma^6\varkappa^2(1+B)}\right]}\right\}, \quad (17)$$

which has proper limiting cases for change in $\varkappa$. As $\varkappa \to 0$ $u \to u_+ \exp\{-B/2\gamma(1+B)\}$, corresponding to $T_{g0} \to T_\infty$, while for $\varkappa \to \infty$ $u \to u_+$, in accordance with the above.

Equation (17) corresponds with an error of no more than 7% with results obtained in a numerical computer calculation. The dependence found describes the experimental results of [5-7] qualitatively correctly. In particular, if we assume B << 1, $\varkappa$ >> 1, $w_p/s_p = r/3$, $\alpha = \gamma_g/r$ then Eq. (17) takes on the form

$$\frac{u}{u_+} \approx 1-\frac{B}{2\gamma^4\varkappa} = 1-\left(\frac{3\lambda_g t_+}{2c_g\rho_g\gamma^4}\right)\frac{N_0 r^3}{r^2},$$

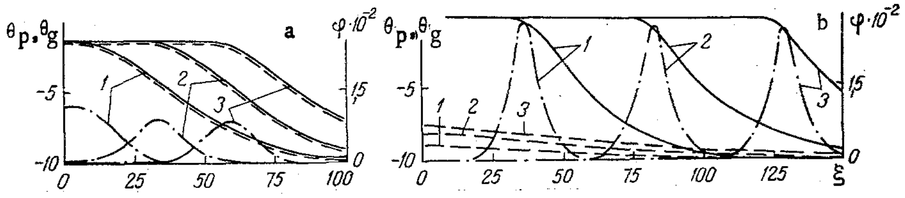

Fig. 4. Temperature distribution of particles $\theta_p = (T_p - T_+)E/RT_+^2$ (dashed line) and gas $\theta_g = (T_g - T_+)E/RT_+^2$ (solid line) and heat liberation function φ (dash–dot line) at times: 1, $\tau = 1225$; 2, 2450; 3, 3675; a) $l = 28$, $B = 0.2$, $\varkappa = 10$; b) $l = 13$, $B = 0.2$, $\varkappa = 10^4$.

similar to the approximation functions of [5-7]. In contrast to [5, 6] the cofactor of the ratio of the volume particle concentration to the square of the particle radius is not completely determined by the thermal diffusivity of the gas and the normal flame rate – it explicitly contains the parameter γ, i.e., the activation energy and thermal effect of the reaction.

Knowing the dependence of u on the gas suspension properties, we can estimate the phlegmatizing capability of the cloud. Thus, the layer thickness capable of reducing the flame rate $\sim u^{-1}$ increases with increase in concentration and with decrease in particle size.

2. Combustion Propagation from a Hot Hearth Filled by a Suspension. We will consider the following scheme of phlegmatization of gas combustion by an inert powder.

Let a layer of thickness 2L be filled by the hot combustion products. A cloud of inert particles is sprayed into this hearth and the surrounding space. Depending on the parameters of the fuel gas and the powder, either development of combustion through the dusty medium or extinguishing of the flame is possible.

To clarify the development of the process and find the critical conditions for Eqs. (1)-(3) we formulate the following initial and boundary conditions:

$$T_g(x, 0) = \begin{cases} T_+, & x \leqslant L, \\ T_-, & x > L, \end{cases} \qquad b(x, 0) = \begin{cases} 0, & x \leqslant L, \\ 1, & x > L, \end{cases}$$

$$T_p(x, 0) = T_-, \qquad \left.\frac{\partial T_g}{\partial x}\right|_{x=0,\,\infty} = \left.\frac{\partial b}{\partial x}\right|_{x=0,\,\infty} = 0.$$

The dynamics of the change in flame propagation velocity for a fixed value of dust concentration B at two values of the particle size $\varkappa$ with variation of the hearth size l are shown in Fig. 2. The critical conditions for combustion propagation are quite evident. For a given γ (dependent only on the fuel gas properties) the critical size l_* is larger, the greater the difference between flame propagation rates in the fuel gas and dusty medium.

It can be proposed that the critical size should be of the order of the thickness of the flame propagation [8]. Consequently, the product $(l_*\omega)$ should be constant for the case of a pure gas and a gas suspension. Figure 3 shows that this relationship is satisfied quite well for various B, but moderate $\varkappa$ (up to $\varkappa \approx 10^2$). At $\varkappa \approx 10^3$ and above the value of $(l_*\omega)$ decreases, so that it is not possible to recommend a single analytical expression for l_* over the entire range of $\varkappa$. The situation is similar for other values of γ.

The insensitivity of l_* to the presence of coarse particles (large $\varkappa$) is related to the inertial nature of heat exchange between the particles and gas.

Figure 4a shows phase temperature and heat liberation profiles at various times for fine particles ($l \geqslant l_*$). The gas and particle temperatures are similar, and the major heat liberation occurs in the section where $\theta_p \approx \theta_g \approx \theta_\infty$ (maximum flame temperature in the gas suspension). Figure 4b depicts another situation: coarse particles cannot heat through and the combustion front separates from the particle heating zone. In this case the critical dimension l_* in the dust–gas mixture falls to the critical hearth dimensions for the pure gas mixture: $l_+ = l_*$ (B = 0).

It was noted in [6] that a finely dispersed dust was capable of extinguishing a propane–air flame while a coarse dispersion, even when supplied in much higher concentration, did not produce extinction. In interpreting the experimental results, aside from the effects referred to above, one must keep in mind the possibility of extinction due to convective heat losses

[8] in a small radius burner, which may prove significant because of retardation of the flame in the gas suspension as compared to the case of a pure gas mixture. Radiant heat loss from radiating particles may also play some role.

Consideration of these effects requires further development of the model of powder—flame interaction. The theory presented here indicates that all the basic experimental facts presented above are adequately described by a model including only the thermal interaction mechanism.

NOTATION

T_g, c_g, ρ_g, λ_g, gas temperature, specific heat, density, and thermal conductivity; T_p, c_p, ρ_p, w_p, s_p, particle temperature, specific heat, density, volume, and area; E, k, R, Q, activation energy, preexponential term, ideal gas constant, thermal effect of combustion of initial reagent b; θ_p, θ_g, dimensionless gas and particle temperatures; $\tau = t/t_+$ and $\xi = x/x_+$, dimensionless time and coordinate; ω, B, $\varkappa$, $l = L/x_+$, τ_1, parameters; L, half width of ignition hearth; l_*, critical hearth size.

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METHODS OF RESEARCHING THERMOPHYSICAL PARAMETERS AND PHENOMENA BY MEANS OF NONSTATIONARY-FREQUENCY MEASUREMENTS. PART 2. STEP AND INSTANTANEOUS HEATING METHODS

A. G. Shashkov, V. I. Krylovich,
and A. S. Konovalov

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Various types of instantaneous and stepped heat source are considered, which act in unbounded bodies. A method has been devised for using the solutions to define the thermophysical parameters by means of nonstationary-frequency measurement methods.

Pulse, stepped, and periodic heating methods are [1] the most promising and correspond to current requirements as regards speed, accuracy, and informativeness. Phase and frequency measurements may be made instead of amplitude ones to considerable advantage as regards resolution and speed [1], but in that study, the restricted volume meant that it dealt with only one form of step methods, namely a semiinfinite body with boundary conditions of the first kind. That however demonstrated the main advantages of the formulation and solutions. Therefore, here and subsequently we avoid giving excess details.

Applied Physics Institute, Academy of Sciences of the Belorussian SSR, Minsk.

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