

3. B. N. Srivastava, Ch. J. Nait, and O. Tsappa, "Suppression of acoustic disturbances in a pulsed laser system," *Raket. Tekh. Kosmn.*, 18, No. 6 (1980).
4. T. A. Saltanov, *Nonequilibrium and Non-Steady-State Processes in Gas Dynamics* [in Russian], Nauka, Moscow (1979).
5. V. A. Levin and Yu. V. Tunik, "The flow of a relaxing mixture of gases in two-dimensional flat nozzles," *Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza*, No. 1 (1976).
6. G. N. Sayapin, "Nonequilibrium flows of oxygen and nitrogen in nozzles taking into account the excitation of vibrational degrees of freedom," *Scientific notes from the N. Ye Zhukovskii Central Institute of Aerohydrodynamics (TsAGI)*, 8, No. 6 (1977).
7. V. N. Komarov and O. Yu. Polyanskii, "Calculating the temperatures of frozen vibrational degrees of freedom for gas flows in nozzles," *Scientific notes from N. Ye. Zhukovskii Central Institute of Aerohydrodynamics (TsAGI)*, 9, No. 5 (1978).
8. R. Finni, "Dimensionless solutions for flows with vibrational relaxation," *Raket. Tekh. Kosmn.*, 2, No. 2 (1964).
9. S. K. Godunov, A. V. Zabrodin, M. Ya. Invanov, et al., *Numerical Solutions for Multi-dimensional Problems in Gas Dynamics* [in Russian], Nauka, Moscow (1976).
10. V. V. Mikhailov and L. Ya. Khaskin, "The discharge of gas from a container placed in a vacuum," *Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza*, No. 1 (1978).
11. V. V. Mikhailov, "The discharge of gas from a restricted volume through a Laval nozzle," *Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza*, No. 2 (1978).
12. V. L. Grigorenko, "Numerical study of shock ignition for supersonic nozzles and a comparison with experimental data," *Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza*, No. 1 (1980).
13. N. V. Stankus, "Numerical study of supersonic nozzles and undersized streams with vibrational relaxation," Preprint 101-83, Institute of Thermal Physics (ITF), Sib. Otd., Akad. Nauk SSSR (1983).
14. L. A. Safronov and V. A. Lebsak, "Non-steady-state processes in electric-arc heaters," *Sib. Otd. Akad. Nauk SSSR*, No. 3, Issue 1 (1967).
15. L. A. Safronov, "Equations for the transfer processes in electric-arc heaters," *Transactions from the N. Ye. Zhukovskii Central Institute of Aerohydrodynamics (TsAGI)*, No. 1179 (1970).

THE SLOW BURNING CONDITION IN A DUST-GAS MIXTURE

B. M. Smirnov

UDC 536.46

1. Combustion-wave propagation in a gas phase is determined not only by the reaction rate at the maximum temperature of the gas mixture but also by heat transfer through the gas. A rigorous mathematical theory exists [1-5], which relates the wave propagation speed to the parameters of the chemical and thermal processes. In particular, the Arrhenius temperature dependence for the rate constant k , $k \sim \exp(-E_a/T)$, implies that the wave speed u is related to the gas temperature T_m after combustion as follows, where E_a is the activation energy [1, 2]:

$$u \sim \exp(-E_a/2T_m). \quad (1.1)$$

In the burning of a dust-gas mixture, there is an additional process that influences the speed: the emission from the dust particles. If the transverse dimension of the combustion zone is small by comparison with the photon mean free path, the contribution from dust emission to the heat balance is related to the wave speed. The less the speed, the longer the time spent at the maximum temperature and the greater the dust radiation heat loss. In (1.1), the speed is very much dependent on the maximum temperature, so the propagation conditions markedly affect the contribution from emission to the heat balance. This leads to two modes of burning in a dust-gas mixture [6]. In the fast mode, the emission makes a comparatively

small contribution, so the maximum temperature is determined by the initial amount of chemical energy in the gas, which is used in heating it. The gas temperature in the combustion zone is high in that state, and the combustion wave propagates quite rapidly, so the state is analogous to that of burning in a gas mixture.

The slow mode is specific for a dust-gas mixture. In that case, some fraction of the chemical energy is consumed in the dust emission, so the maximum temperature in the combustion wave is somewhat less than that in the fast mode. Because of the sharp temperature dependence of (1.1), the wave speed in the slow mode is much less than in the fast one. Here we consider calculating wave parameters for the slow mode, and the use of the formulas for the combustion of coal dust in air.

2. Consider the propagation of a combustion wave in a dust-gas medium. For simplicity we assume that a dust particle is spherical and of radius r_0 , while there are n particles in unit volume. It is realistic to assume that a particle is in equilibrium with the surrounding gas, i.e.,

$$\tau \gg r_0^2/\chi, \quad (2.1)$$

where τ is the combustion time and χ is the thermal diffusivity of the gas; the right side is the characteristic time for heat to propagate by a distance of the order of the particle size. In particular, for air at atmospheric pressure and at about 1000°K with $r_0 \approx 10 \mu\text{m}$, the right side of (2.1) is about 10^{-6} sec. Condition (2.1) is obeyed with a considerable margin in the detailed cases to be considered below of dust-gas mixtures at atmospheric pressure.

The relation between the particle temperature T and the temperature of the surrounding gas T_g can be found from the balance equation for a particle. If we neglect the radiation incident on the particle, this equation is

$$\frac{\kappa}{r_0} (T - T_g) + a\sigma T^4 = \frac{r_0}{3} q(T), \quad (2.2)$$

where κ is the thermal conductivity of the gas and $q(T)$ is the heat production rate in combustion per unit particle volume*; a , particle grayness; and σ , Stefan's constant. The first term on the left in (2.2) is the heat flux between the particle and the surrounding gas due to thermal conduction in the gas, while the second is the radiation flux from the particle. On the right, we have the heat flux produced by particle combustion.

One naturally represents the temperature dependence of the heat production rate during combustion as an Arrhenius law:

$$q(T) = q_0 \exp(-E_a/T), \quad (2.3)$$

where E_a is the activation energy. The temperature T_{cr} at which the energy production by combustion becomes equal to the radiation loss is of fundamental significance:

$$\frac{r_0}{3} q(T_{cr}) = a\sigma T_{cr}^4. \quad (2.4)$$

At this particle temperature, the value is the same as that of the surrounding gas.

We now examine the heat-balance equation for a dust particle in the range $T - T_{cr} \ll T$; we have

$$\frac{\kappa}{r_0} (T - T_g) = a\sigma T_{cr}^4 (e^{\alpha\Delta T} - 1), \quad (2.5)$$

where $\alpha = E_a/T_{cr}^2$; $\Delta T = T - T_{cr}$; it follows from (2.5) that emission from the particles consumes a fraction $e^{-\alpha\Delta T}$ of the energy produced by particle combustion, so a fraction $1 - e^{-\alpha\Delta T}$ goes to heat the gas. The gas is heated not only in the region around the particle but also in adjacent regions because of thermal conduction.

*This characteristic is convenient since the results can be used subsequently for the burning of porous coals, where the combustion occurs throughout the volume. If the process occurs only at the surface of the particles, it is convenient to introduce another characteristic: $r_0 q/3$.

On this basis, we use a simple model in which the main heat production in the wave occurs at the maximum temperature. Let ΔH be the enthalpy change in unit mass of gas on heating, while Q is the chemical energy per unit mass of gas, which is released by combustion. Then the above gives us that

$$\Delta H = Q [1 - e^{-\alpha(T_m - T_{cr})}]$$

where T_m is the maximum temperature in the wave. The enthalpy change in unit mass of gas on heating is

$$\Delta H = \int_{T_0}^{T_m} c_p dT$$

where c_p is the specific heat, ρ is the mass density of the mixture, and T_0 is the temperature ahead of the wave front. For simplicity we assume that c_p and ρ are independent of temperature, so $\Delta H = c_p(T_m - T_0)$. Then we get a relation between the chemical energy Q consumed and the maximum temperature T_m in the wave:

$$Q = \frac{c_p(T_m - T_0)}{1 - \exp[-\alpha(T_m - T_{cr})]} \quad (2.6)$$

Figure 1 shows the dependence of (2.6) for Q/c_p on T_m , which shows that for $Q > Q_{min}$, when there is a combustion wave, one can get two different modes of combustion with the same stored energy. In the case $Q \gg Q_{min}$, these modes differ in physical nature. The slow mode (region 1) occurs near T_{cr} , and most of the energy loss is by particle radiation. In the other mode (region 2), the radiation losses are relatively small, when most of the energy goes to heat the gas.*

3. In deriving (2.6) we have assumed that the radiation from the particles leaves the system freely, which is so if the width of the combustion zone Δx (the region in which the particles burn) is small by comparison with the photon mean free path:

$$\lambda \gg \Delta x. \quad (3.1)$$

In other words, the combustion region is optically transparent. This is a general property of slowly propagating combustion waves in dust-gas mixtures. A proof of this is given below.

The ratio of the combustion-region width to the photon free path is

$$\Delta x/\lambda = u\tau/\lambda, \quad (3.2)$$

where u is combustion wave speed and τ is the characteristic combustion time. Close to T_{cr} , the power available from an individual dust particle is $4\pi r_0^2 a \sigma T_{cr}^4$ by radiation; these radiative losses per unit volume of mixture are less than the stored energy $Q\rho$ per unit volume, so

$$Q\rho > 4\pi r_0^2 a \sigma T_{cr}^4 n \tau,$$

where n is the number of particles in unit gas volume. We use the expression for the photon mean free path in the mixture

$$\lambda = (a\pi r_0^2 n)^{-1}$$

and the above to get from (3.2) that

$$\Delta x/\lambda < uQ\rho/(4\sigma T_{cr}^4) = u/u_{max}. \quad (3.3)$$

It follows from (3.3) that the combustion zone is optically transparent for a flow wave. Figure 2 gives values of

$$u_{max} = 4\sigma T_{cr}^4 / (Q\rho),$$

*In fact, the combustion reaction becomes different as the temperature rises. Firstly, when the combustion is rapid, the rate is limited by the rate of arrival of reacting molecules at the particles, so the combustion occurs in diffusion mode. Secondly, when there is vigorous combustion, only part of the particle volume is used. These factors and others restrict the rate of increase in $q(T)$ with temperature, so it may be that the radiation losses are important. However, this occurs at higher temperatures and therefore does not influence our conclusions.

corresponding to the combustion of a coal-air mixture at atmospheric pressure. Using the energy content $Q = 2.2$ kJ per gram of air, which corresponds to the combustion with an excess coal content and the formation of 50% CO and 50% CO₂, we get from Fig. 2 that $u_{\max} \sim 10^2-10^3$ cm/sec for a combustion temperature in the region of 1000-1500°K. The slow mode corresponds to wave speeds of the order of cm/sec, i.e., the combustion zone is certainly transparent.

We note that the condition for free radiation escape from the combustion zone together with (3.1) requires that

$$\lambda \gg \Delta y, \quad (3.4)$$

where Δy is the transverse dimension of the combustion zone.* If (3.4) is not obeyed, the radiation emitted by the particles is returned, which leads to violation of (2.6) and a deviation from the conclusions about the slow mode derived from (2.6). We further consider the one-dimensional case of a combustion wave, which corresponds to

$$\Delta y \gg \Delta x, \quad (3.5)$$

i.e., the transverse dimension of the combustion zone is large in comparison to the width of the combustion front.

4. Formula (2.6) has been obtained with model assumptions, which do not incorporate various factors: the temperature distribution in the combustion zone, the effects of radiation on adjacent regions, incomplete combustion, and so on. To elucidate the combustion-wave characteristics, it is desirable to eliminate the model assumptions and to examine the thermal processes in the wave and the related temperature profile. We used the two-temperature approximation, in which the mixture at any point is described by the dust temperature T and the gas temperature T_g , which are related by (2.2). This applies if the heat has time to propagate in the gas in the gaps between adjacent particles within the characteristic heat-production time, and it requires obedience to a condition more stringent than (2.1): $\tau \gg n^{-2/3}\chi^{-1}$. Estimates show that this condition is obeyed for the calculations made below. Then the energy-balance equation for the combustion wave is

$$\kappa \frac{d^2 T_g}{dx^2} - u \rho_g \left(c_p^g \frac{dT_g}{dx} + m c_p^d \frac{dT}{dx} \right) + F = 0, \quad (4.1)$$

where c_p^d and c_p^g are the specific heats of dust and gas; ρ_d and ρ_g , mass densities of dust and gas correspondingly; m , of dust per unit mass of gas; and F , heat production rate going to heat unit volume of the mixture. Equation (4.1) reflects the fact that the heat in the combustion wave propagates through the mixture by thermal conduction in the gas, while the radiation escapes freely from the region.

We write out the expression for the heat production rate in unit volume F used in heating the gas. This quantity is the difference between the heat production due to the combustion and the losses due to radiation, and in accordance with (2.2)

$$F = \frac{4}{3} \pi r_0^3 q(T) n - a \sigma (T^4 - T_0^4) 4 \pi r_0^2 n = \frac{4}{\lambda} \left[\frac{r_0 q(T)}{3a} - \sigma (T^4 - T_0^4) \right].$$

Here T_0 is the temperature of the surrounding gas at a distance of the order of the photon mean free path or the temperature of the walls of the system containing the mixture. We assume that this temperature is the same as the gas temperature ahead of the combustion wave.

We write an expression for the specific heat production rate in a more convenient form by introducing $\tau(T)$ as the time in which the stored energy is used. We consider the case where the combustion occurs with an excess of fuel (coal), i.e., the energy release is determined by the amount of oxidizing agent (atmospheric oxygen). We assume that the heat production rate is proportional to the unused part of the oxidant, which gives

$$F = \frac{Q \rho_g c}{\tau} - \frac{4 \sigma (T^4 - T_0^4)}{\lambda}, \quad (4.2)$$

where Q is the stored chemical energy per unit mass of gas and c is the unused fraction of the oxidant. Then according to the definition of (2.4) we have

*In accordance with whether this condition is obeyed or not, experiment gives different values for the wave speed and the minimal dust concentration allowing the fast mode of combustion [7].

$$\tau(T_{cr}) = \frac{Q_{0g}\lambda}{4\sigma(T_{cr}^4 - T_0^4)}.$$

System (2.2) and (4.1) describe the temperature distributions for the gas and dust in the combustion zone and apply if thermal equilibrium is rapidly established near a particle, which corresponds to obedience to (2.1).

In the case of the slow mode, we consider the case where the temperatures of gas and particle are similar and the amount of dust in the gas is relatively small, so the dust makes only a small contribution to the specific heat. The scope for using the one-temperature approximation is determined by the smallness of the parameter

$$\xi = \frac{E_a}{T^2} (T - T_g) = \frac{r_0}{\kappa} E_a a \sigma T_{cr}^2 (e^{\alpha \Delta T} - 1),$$

where $\Delta T = T_m - T_{cr}$, while as the temperature we take the maximum temperature in the wave, at which the temperature difference is maximal. Then $\xi = 1$ corresponds to thermal explosion in the dust particles leading to acceleration in the particle combustion and conversion of the combustion to the fast mode. The slow mode occurs only for $\xi < 1$, which justifies us in using the one-temperature approximation, which provides analytic expressions for the wave parameters.

System (2.2) and (4.1) can be used in the one-temperature approximation as a single equation for energy transport in the wave, which is derived from (4.1) with $T = T_g$:

$$\kappa \frac{d^2 T}{dx^2} - u \rho_g \frac{dH}{dx} + F(T) = 0,$$

where $H(T) = \int (c_p^g + m c_p^d) dT$ is the enthalpy per unit mass of gas.

To find the wave speed, we use a standard method developed in [1-3].

We introduce a new function $Z = dT/dx$ and reduce the order of the equation:

$$\begin{aligned} \kappa Z dZ/dT - u Z \rho_g dH/dT + F(T) &= 0, \\ Z(T_0) = Z(T_m) &= 0. \end{aligned} \quad (4.3)$$

We substitute (4.2) into this equation for the specific production rate going to heat the gas. If the combustion rate is proportional to c , this quantity satisfies $dc/dt = -c/\tau$; as $dt = dx/u = dT/Zu$, then

$$c = \exp \left[- \int_{T_0}^T \frac{dT}{Z u \tau} \right]. \quad (4.4)$$

Also, $cdT = -Z u \tau dc$. We use this in (4.3) on the basis of (4.2) to reduce (4.3) to the form

$$dZ = \frac{u \rho_g}{\kappa} dH + \frac{4\sigma(T^4 - T_0^4)}{\lambda \kappa Z} dT - \frac{Q \rho_g u}{\kappa} dc. \quad (4.5)$$

Then (4.5) is an equation for the temperature profile in a one-dimensional combustion wave in the one-temperature approximation, i.e., when the dust temperature is close to the gas one. From (4.5) we can get the relation between the combustion-wave parameters in a dust-gas mixture; it must be solved with the boundary conditions

$$Z(T_0) = Z(T_m) = 0. \quad (4.6)$$

Also, with this assumption, we get (3.3) for $T_m - T_{cr} \ll T_{cr}$ that

$$c(T_m) = \exp [-\alpha(T_m - T_{cr})]. \quad (4.7)$$

5. The energy transport equation of (4.5) can be used with the boundary conditions of (4.6) and (4.7) to determine the wave speed and maximum temperature. We use the traditional approach [1-3] based on dividing the regions where the reaction mainly occurs, i.e., the heat production, and where the energy loss occurs. Correspondingly, we assume that the heat

TABLE 1

$\alpha(T_m - T_{cr})$	b	$\alpha(T_m - T_{cr})$	b	$\alpha(T_m - T_{cr})$	b	$\alpha(T_m - T_{cr})$	b
1,0	0,209	2,0	0,484	3,5	0,795	6,0	1,150
1,2	0,268	2,5	0,600	4,0	0,879	8,0	1,355
1,6	0,381	3,0	0,703	5,0	1,025	10,0	1,521

TABLE 2

No.	Coal	$q_0, 10^{10} W/g$	kcal/mole	Source
1	Semianthracite coke	20	40	[8]
2	Fired coal	8	32	[9]
3	Activated birch charcoal			
4	»	2	35	[10]
		4	34	[11]

Note: The parameters in (2.4) for a specific heat production rate are given.

production by combustion occurs only in a region with temperatures close to T_m . Outside that region, the last term in (4.5) can be neglected.

This model assumption enables one to solve (4.5) and to link up the solutions at the boundaries between the regions, namely to determine the wave speed u and the proportion of the stored energy going to heat the gas:

$$u = \frac{1,4T_m \sqrt{\kappa}}{[1 - e^{-\alpha(T_m - T_{cr})}] \sqrt{E_a Q_0 \rho_g \tau(T_m) b^{1/4}}}; \quad (5.1)$$

$$\frac{\Delta H_i}{Q} = [1 - e^{-\alpha(T_m - T_{cr})}]^2 - \frac{0,42\sigma T_m^3 E_a}{q(T_m) \rho_g r_0 \sqrt{b}}. \quad (5.2)$$

Here Q_0 is the total chemical energy per unit mass of gas and q is the heat production rate per unit mass of dust. The numerical parameter $b \sim 1$ arises on comparing (4.4) and (4.7) and is determined by

$$\sqrt{b\pi e^b} = \alpha(T_m - T_{cr}). \quad (5.3)$$

Table 1 gives numerical values for this parameter, while in the range $2 < \alpha(T_m - T_{cr}) < 10$ the solution to (5.3) can be approximated as $b = 0.12 + 0.58 \ln [\alpha(T_m - T_{cr})]$ with an accuracy better than 10%.

According to (5.1),

$$u \sim \tau^{-1/2}(T_m) \sim \exp(-E_a/2T_m),$$

which agrees with (1.1) and is a general result from gas combustion theory. Also, (5.2) incorporates radiative losses in the combustion zone to the heated region ahead of the wave, where the reaction is slow (second term in (5.2)), as well as incomplete oxidant use. The criterion for using this formula is related to obedience to the condition $\alpha(T_m - T_{cr}) \gg 1$.

6. We use the formulas to examine wave propagation in coal-air mixtures at atmospheric pressure, which reveals the regularities in the slow combustion of an actual mixture. We consider porous coals, in which the reaction occurs throughout the volume. Table 2 gives the corresponding heat production rates. These results are not very accurate, and sometimes they have been used outside the temperature range for which they were obtained. Nevertheless, the statistical data indicate that the conclusions drawn from the set of measurements are correct.

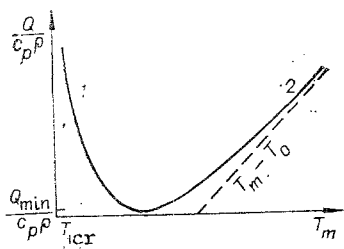


Fig. 1

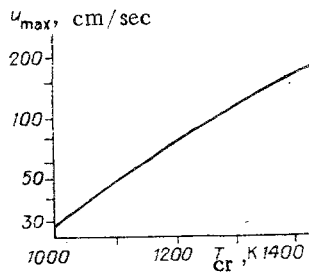


Fig. 2

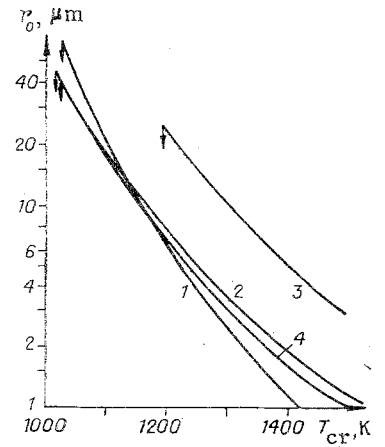


Fig. 3

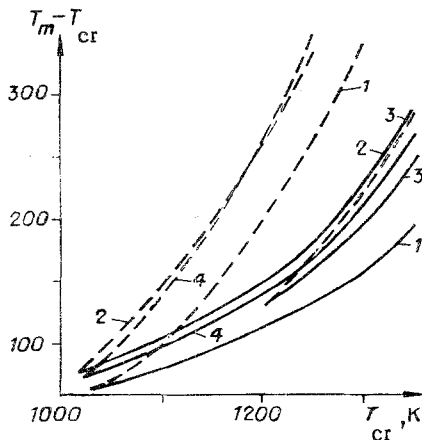


Fig. 4

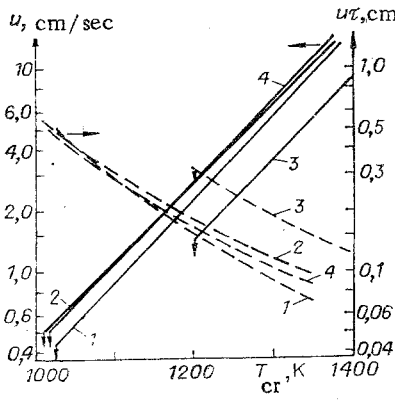


Fig. 5

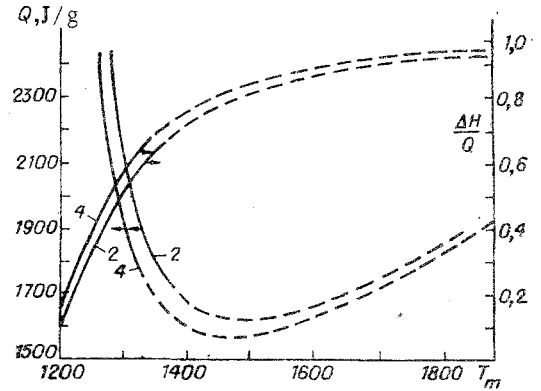


Fig. 6

Figures 3-6 show the calculations on a coal-air mixture based on the above formulas and the production-rate data of Table 2. Curves 1-4 correspond to the cases in Table 2. Figure 3 gives the relation between the particle radius and critical temperature for given specific heat-production rates. It is evident from Fig. 4 that the slow mode is not realized for large particles, and instead, thermal explosion (dashed lines) goes over to rapid combustion. Figure 5 shows the propagation rate calculated from (5.1). This is relatively small for the slow mode, being of the order of cm/sec for particles with $r_0 \approx 10 \mu\text{m}$. The combustion zone is also narrow, namely a fraction of a centimeter.

The specific stored energy in the fuel is dependent on the degree of combustion of the carbon. Table 3 gives heat-production parameters for limiting modes of combustion in the presence of excess coal (Figs. 3-6) and also for stoichiometric coal contents in air. All the calculations were based on the parameters corresponding to case 3 in Table 3, i.e., the intermediate type of coal combustion.

Figure 6 shows the dependence of the specific energy in the mixture on the maximum temperature in the combustion zone and the fraction of the stored energy going to heat the gas for two detailed cases. The dependence of the specific energy on the maximum combustion temperature is as in Fig. 1. However, above a certain T , thermal explosion in the dust can occur, which converts the system to the fast mode.

The calculations show that coal dust burning in air can give rise to the slow mode with a maximum temperature in the combustion zone somewhat exceeding 1000°K . This corresponds to a wave speed of the order of cm/sec and a width for the combustion zone of a fraction of a centimeter. For large particles, this does not occur because of thermal explosion, which raises the particle temperature sharply and transfers the system to the fast mode. Increase in the temperature ahead of the wave also produces thermal explosion in smaller particles.

The stability of the slow mode under perturbations is also important. The fast mode is more stable. In fact, in the slow mode, any local energy input raises the temperature

TABLE 3

No.	Combustion products	Energy production		Minimum amount of coal per gram of air in complete use of oxygen, g,
		per oxygen molecule eV	per gram of air, kJ	
1	CO	2,26	1,6	0,16
2	CO ₂	4,02	2,8	0,08
3	50% CO, 50% CO ₂	3,14	2,2	0,12

and accelerates the combustion, which in turn leads to less radiation losses and additional heating. Therefore, the slow mode is metastable. Analysis of the stability by traditional methods [12] shows that there are two possible instabilities involving transition to the fast mode. One of them is thermal explosion in the particles, which occurs for large sizes (Figs. 3-6), while the other is due to local inhomogeneities, which lead to breakaway from the slow mode in individual regions and propagation of the instability to the whole of the space. This mechanism has a bearing on real systems. Nevertheless, there is a wide parameter range where the slow mode in a dust-gas mixture can occur.

LITERATURE CITED

1. Ya. B. Zel'dovich and D. A. Frank-Kamenetskii, "Theory of thermal flame propagation," *Zh. Fiz. Khim.*, 12, No.1 (1938).
2. Ya. B. Zel'dovich and N. N. Semenov, "Reaction kinetics in flames," *Zh. Eksp. Teor. Fiz.*, 10, No. 9-10 (1940).
3. Ya. Z. Zel'dovich, *Gas Combustion Theory* [in Russian], Izd. Akad. Nauk SSSR, Moscow (1944).
4. Yu. V. Frolov (ed.), *The Theory of Combustion and Explosion* [in Russian], Nauka, Moscow (1981).
5. Ya. B. Zel'dovich, G. I. Barenblatt, V. B. Librovich, and G. M. Makhviladze, *The Mathematical Theory of Combustion and Explosion* [in Russian], Nauka, Moscow (1980).
6. B. M. Smirnov, *The Theory of Combustion-Wave Propagation in a Dust-Gas Mixture* [in Russian], Preprint ITF Sib. Otd. Akad. Nauk SSSR, No. 102 (1983).
7. S. E. Slezak et al., "Coal dust flame propagation in a laboratory flammability tube," *Combust. Flame*, 54 (1983).
8. I. M. Smith and R. J. Tyler, "Internal burning of pulverized semianthracite," *Fuel*, 51 (1972).
9. I. M. Smith and R. J. Tyler, "The reactivity of porous brown coal char to oxygen between 630 and 1817°K," *Combust. Sci. Technol.*, 9 (1974).
10. G. Yu. Grigor'ev, S. B. Dorofeev, and B. M. Smirnov, "Heat-production parameters in the combustion of activated charcoal," *Khim. Fiz.*, 3, No. 4 (1984).
11. G. Yu. Grigor'ev, S. B. Dorofeev, et al., "Combustion rates for wood charcoal," *Fiz. Goreniya Vzryva*, No. 5 (1984).
12. H. Haken, *Synergetics* [Russian translation], Mir, Moscow (1980).