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1961

SovietRxiv

Abstract

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PHYSICAL CHEMISTRY

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THE ROLE OF CONVECTIVE MIXING IN THE COMBUSTION OF CONDENSED MIXTURES

(Presented by Academician V. N. Kondrat’ ev, 2 XII 1960)

In the combustion of condensed mixtures—at least in the important special case in which gasification of the components precedes the mixing of the principal part of the components—when the particle sizes are sufficiently large (several hundred microns and above), a sharp weakening is observed (1) in the dependence of the normal burning velocity u_n on the particle size d*. This phenomenon can be explained if one assumes that, at sufficiently large d, in addition to molecular diffusion, convective mixing begins to play an essential role, as a result of which the coefficients of mass and heat transfer increase with increasing d.

A special feature of the problem under consideration is that here one may expect the occurrence of two different kinds of turbulence. The first of them is connected with the fact that the initial condensed mixture itself, with a disordered arrangement and shape of the particles, represents a kind of “frozen” turbulence, which “comes to life” during gasification of the components. Thus we are dealing with artificially created turbulence, similar to that which arises during the operation of various mixers, etc. This type of turbulence has no direct connection with the parameters (and, in particular, with the value of Re) of the established flow of the gasification and combustion products. The level of artificially created turbulence is highest near the surface of the condensed phase (k-phase), i.e., precisely in the zone that usually has the greatest influence on the burning velocity. Farther downstream, the artificially created turbulence dies out. The principal scale of turbulence in this case should be proportional to d.

In addition, in the flow of the gasification and combustion products, at sufficiently large Re, ordinary turbulence will arise, whose principal scale is proportional to G, where G is the diameter of the burning channel or, in end-face combustion, the diameter of the cylindrical charge. If we restrict ourselves to the case of end-face combustion, then this type of turbulence apparently will not substantially affect the burning velocity, since the level of such turbulence can become significant only at a sufficiently large distance from the surface of the k-phase.

Fig. 1

Figure 1: Fig. 1

Let us now consider the physical picture of mixing in the presence of artificially created turbulence. Let us examine the causes that may lead to mutual penetration of volumes filled with products of gasification of the components. Among such causes one should first of all include the nonparallelism of the flows of the gasification products of the components, as well as the inequality of the absolute magnitudes of the flow velocities.

Experience shows that, at least for not too small d, the surface of the condensed phase facing the flame is not planar, and wedge-shaped recesses are formed along the contact boundaries of the components (Fig. 1), which grow with increasing d. In the immediate vicinity of the surface of the c-phase, the gasification products move perpendicular to it, owing to the absence of any tangential forces on the surface. Therefore the direction of the gas velocity at the surface $\mathbf{v}$ changes from point to point, and near the surface collisions of gas flows occur, leading to their mixing.

Fig. 1

For the absolute values of the velocities of the gasification products, from the condition of conservation of mass flux for each of the components one may write

$$v_1 = \frac{\rho_1 u_1}{(\rho_1)_r}; \qquad v_2 = \frac{\rho_2 u_2}{(\rho_2)_r}, \tag{1}$$

where ρ, ρ_r are the densities of the condensed component and of the products of its gasification; u is the gasification rate (the rate of disappearance of the c-phase).

The time-averaged values $\bar{u}_1$ and $\bar{u}_2$ are proportional to one another and proportional to u_n, but the instantaneous values u_1 and u_2 at any moment of time may be in an arbitrary ratio. Since ρ_1 and ρ_2; $(\rho_1)_r$ and $(\rho_2)_r$ are also in an arbitrary ratio, generally speaking, $v_1 \neq v_2$.

The inequality of the absolute values of the velocities of the gasification products promotes their mixing in the tangential direction (perpendicular to $\mathbf{u}_n$) and makes convective mixing possible in the axial direction (parallel to $\mathbf{u}_n$). Indeed, consider the moment of time when, at a given point of the surface, component

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* We shall consider the frequently occurring case in which one of the components of the mixture is plastic (or has a particle size much smaller than that of the second component) and forms a medium in which solid particles of the second component are distributed. If the latter have approximately the same size d, then the interlayers of the plastic component are also proportional to d.

2 is replaced by component 1. Since, generally speaking, $v_{1a} \neq v_{2a}$, either an elementary shock wave must travel along the flow (for $v_{1a} > v_{2a}$), or an elementary rarefaction wave (for $v_{1a} < v_{2a}$); these, being reflected from density inhomogeneities existing in the flow and from the surface of the c-phase, generate gradually decaying secondary, tertiary, etc. waves. As a result, for example, when $v_{1a} > v_{2a}$, the flow of gas 1 will penetrate into the volume of gas 2, and the boundary between them will be blurred by pulsations of pressure and gas velocity arising during the passage of the elementary waves.

It is essential, however, to emphasize that gas mixing in the axial direction plays an insignificant role compared with mixing in the tangential direction, since upon gasification of a cube of a solid component we obtain a rectangular volume of gas whose base dimensions have not changed, whereas its height (and with it the mixing path in the axial direction) has increased by a factor of ρ/ρ_r (i.e., under ordinary conditions, by one to three orders of magnitude).

For the artificially created turbulence under consideration we have one parameter with the dimension of length (d) and one parameter with the dimension of velocity ($v_1 - v_2$), from which one can form a combination having the dimension of the coefficient of turbulent exchange (cm^2/s):

$$D_{\text{turb}} \sim d(v_1 - v_2); \tag{2}$$

here, for mixing in the tangential direction one should take $(v_{1t} - v_{2t})$, and for mixing in the axial direction $(v_{1a} - v_{2a})$.

Substituting (1) into (2) and taking into account that $\bar{u}_1 \sim \bar{u}_2 \sim u_n$, we obtain

$$D_{\text{turb}} \sim du_n \frac{\rho}{\rho_r} \sim \frac{du_n}{p}. \tag{3}$$

Taking into account now that the coefficient of molecular diffusion is

$$D_{\text{molec}} \sim \frac{1}{p} \tag{4}$$

and does not depend on d, and also that usually $u_n \sim p^{0.5 \div 0.7}$. It follows from this that the role of convective mixing increases as d and p increase. It should also increase as the surface of the k-phase becomes more curved, since this increases the angle at which the jets collide and since the path of mixing in the tangential direction is much shorter than in the axial direction.

Formula (3), of course, does not yet make it possible to estimate, for a given system, the value of d starting from which convective mixing becomes comparable with molecular mixing, since there are no considerations concerning the magnitude of the numerical proportionality coefficient on the right-hand side of (3). For the purpose of a qualitative verification of the considerations set forth regarding the role of convective mixing, experiments were carried out by us jointly with Yu. V. Frolov, in which, using a motion-picture camera with a set of light filters, the height h of the core of the flame of cylindrical charges ($G = 1$ cm) of a mixture of $KClO_4$ + bitumen was determined for $KClO_4$ particle sizes $d \simeq 10$, $\simeq 180$, and $\simeq 1700$ μ. The combustion of the flame took place inside a large vessel filled with nitrogen at 1 ata and 20°. It was found that the height of the flame core not only did not increase, but, on the contrary, decreased somewhat in going from $d \simeq 10$ μ to $d \simeq 1700$ μ, which speaks in favor of an increase in the mass-transfer coefficient with increasing d.

The dependence $h(d)$ was also determined for the case of combustion of an individual "particle." For this purpose, powdered $KClO_4$ was pressed into thick cylindrical plexiglass shells with different internal diameters (from 0.4 to 1.4 cm). We note that in this case one should take $G = d$. From dimensional considerations it follows that

$$h \sim \frac{vd^2}{D} \sim \frac{ud^2}{\rho_r D}, \tag{5}$$

where for the system under consideration u is almost independent of d (2). Therefore, for molecular mixing, $h \sim d^2$ must hold. Conversely, if the mixing is turbulent ($D_{\text{turb}} \sim d$), then $h \sim d$. In the experiments carried out it was found that $h \sim d$, which also indicates a significant role of convective mixing.

I express my gratitude to A. S. Sokolik, O. I. Leipunsky, and B. V. Novozhilov for discussion of the work and valuable comments.

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Received
3 XI 1960

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