

RAPID FILTRATION COMBUSTION WAVES DRIVEN BY CONVECTION

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Abstract

We consider combustion in porous media, in which the reaction occurs between the fuel part of the solid and the oxidizer part of a gas which flows through the pores to the reaction site. This type of combustion is referred to as filtration combustion (FC).

We describe a new type of FC wave, driven by convection rather than conduction of heat [1]. Such a wave arises due to the imbalance between the temperatures of the solid and gas phases. These waves can propagate much more rapidly than FC waves driven by diffusion of heat, and may be observed even in mixtures with very low thermal conductivity. Thus, it poses a greater danger from the point of view of fire safety.

Filtration of gas is an important aspect of the FC process. It plays the dual role of transporting oxidizer and heat to the reaction site. For the practically important case of coflow (forward) FC, where the gas flows in the same direction as the FC wave, filtration may result in the superadiabatic effect, in which the combustion temperature is significantly higher than the adiabatic combustion temperature, due to recovery of the energy stored in the combustion products. Analysis of a one temperature model shows that though filtration may significantly affect the FC wave characteristics such as the combustion temperature and wave velocity, it does not change the mechanism of wave propagation. The rapid equilibration of solid and gas temperatures implied by the one-temperature model requires that the mechanism is due to heating of the fresh mixture by diffusion, just as in conventional gaseous or gasless solid fuel combustion waves, where the wave velocity is controlled by the kinetic mode of wave propagation. In this case the expression for the velocity in FC has the same form as in gasless solid combustion without filtration.

The propagation of coflow FC waves may be significantly enhanced by increasing the infiltrating gas flux through the hot porous product region. For relatively small flux, enhancement occurs by the superadiabatic effect, i.e., by increasing the maximum temperature (T_b), and thus, the reaction rate $W(T_b)$ in the combustion front. Though convection of heat from the product region increases T_b , the mechanism of FC wave propagation is controlled by diffusion of the heat released in the reaction.

An alternative mechanism of enhancement, which occurs for relatively large gas fluxes, and corresponds to pronounced temperature nonequilibrium between the gas and solid phases, leads to an increase of the FC wave velocity without increasing the combustion temperature. The propagation of such waves is controlled by the convection of heat stored in the products, rather than by diffusion of the heat released in the reaction. Such

waves may propagate if diffusion is minimal or even absent altogether, due, e.g., to poor contact between the particles comprising the porous matrix.

Analysis of FC waves which account for thermal nonequilibrium between the gas and solid phase leads to important conclusions. The first concerns the mechanism of overheating the reaction zone. The two-temperature approach shows that the gas passing through the hot product brings heat not only to the reaction site, but also ahead of the reaction zone. Indeed, most of the heat is passed to the unreacted fuel mixture ahead of the reaction zone. The combustion temperature is therefore raised as a consequence of increasing the effective initial temperature of the fuel, by preheating it. The same mechanism of superheating also occurs in the one-temperature model but it occurs so quickly, due to the rapid equilibration of the gaseous and solid temperatures, that the heat transfer cannot be observed.

The second conclusion which this paper addresses is the existence of the convective mechanism of FC wave propagation, which differs from the conventional diffusion mechanism. The convective mechanism involves preheating the fuel by heat exchange between the hot gas which passed through the product and the solid particles comprising the porous matrix. The diffusion of heat through the matrix itself is a secondary effect which may be neglected. Specifically, the convective mechanism allows the wave to propagate through porous media with very poor contact between the particles, i.e., with very low conductivity. In comparison with diffusion driven FC waves, the convective mechanism of propagation ensures a higher wave velocity, though it has a lower combustion temperature.

In FC there is a high temperature domain (HTD) in which the temperature is constant at the burning temperature T_b . Ahead of and behind the HTD the temperature is also constant, at the low temperature T_0 . Separating the HTD from the low temperature domains are layers which are thin on the scale of the sample. These are the combustion layer, consisting of the preheat and reaction zones, and the heat transfer layer, in which temperature changes are due to heat transfer between the solid and the gas. Since different physical processes dominate in the two layers, their speeds will, in general, differ. Two structures are therefore possible, depending on which speed is greater and therefore, which layer precedes the other. In the first, referred to as the reaction leading structure, the velocity of the combustion layer is the greater of the two velocities, so that the combustion layer precedes the heat transfer layer. In the second, referred to as the reaction trailing structure, the velocity of the combustion layer is the smaller of the two velocities, so that the heat transfer layer precedes the combustion layer. We note that the convective mode of FC wave propagation may be realized only for the reaction leading wave structure, which allows oxidizer to leak through the reaction zone and initiate reaction ahead of the reaction zone, thus preheating the unreacted solid. This mechanism can not occur in the reaction trailing structure since all the oxidizer is completely consumed in the reaction zone, so that preheating the fresh solid does not lead to reaction ahead of the reaction zone.

Unlike conventional (driven by diffusion of heat) combustion waves, the combustion velocity of convection driven FC waves is not controlled by the maximum temperature T_b , but rather by an intermediate temperature T_i which launches the reaction. Here, T_i , the temperature at which the rate of heat release in the reaction equals the rate of heat exchange between the gas and solid phases, is the temperature at which the reaction begins to self-accelerate. The lower T_i the higher the velocity of the wave. Rapid propagation of the FC wave occurs due to the hot gas penetrating deeply into the

medium, which initiates reaction in a thick layer ahead of the reaction front.

The structure of the convective FC wave is quite different than the structure of standard combustion waves. For the latter, the reaction typically occurs in a narrow temperature region in the vicinity of the maximum temperature. In other words, for a standard combustion wave the reaction occurs at essentially isothermal ($T \sim T_b$) conditions because all the energy released in the reaction diffuses into the fresh mixture. In contrast, for the convective mode of FC wave propagation the reaction is initiated at a certain "self-ignition" temperature T_i . The reaction occurs under essentially adiabatic conditions because the rate of heat release in the reaction significantly exceeds the rate of heat exchange between the solid and the gas. This results in a temperature jump in the reaction zone from T_i to T_b . In contrast to conventional combustion waves the processes in the reaction zone are not of such great importance for convective wave propagation. In a sense, convective FC waves are similar to detonation waves where the role of the reaction is merely to support the propagating shock wave by supplying it with energy.

References

- [1] A.P. Aldushin, B.J. Matkowsky, *Rapid Filtration Combustion Waves Driven by Convection*, to appear, Comb. Sci. & Tech.