FILTRATION COMBUSTION
IN SMOLDERING AND SHS [1]

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INTRODUCTION Smolder waves and SHS (self-propagating high-temperature synthesis) waves are both examples of filtration combustion waves propagating in porous media. Smoldering combustion is important for the study of fire safety. Smoldering itself can cause damage, its products are toxic and it can also lead to the more dangerous gas phase combustion which corresponds to faster propagation at higher temperatures. In SHS, a porous solid sample, consisting of a finely ground powder mixture of reactants, is ignited at one end. A high temperature thermal wave, having a frontal structure, then propagates through the sample converting reactants to products. The SHS technology appears to enjoy a number of advantages over the conventional technology, in which the sample is placed in a furnace and "baked" until it is "well done". The advantages include shorter synthesis times, greater economy, in that the internal energy of the reactions is employed rather than the costly external energy of the furnace, purer products, simpler equipment and no intrinsic limitation on the size of the sample to be synthesized, as exists in the conventional technology.

When delivery of reactants through the pores to the reaction site is an important aspect of the combustion process, it is referred to as filtration combustion. The two types of filtration combustion have a similar mathematical formulation, describing the ignition, propagation and extinction of combustion waves in porous media. The goal in each case, however, is different. In smoldering the desired goal is to prevent propagation, whereas in SHS the goal is to insure propagation of the combustion wave, leading to the synthesis of desired products. In addition, the scales in the two areas of application differ. Smoldering generally occurs at lower temperatures and propagation velocities than in SHS. Nevertheless, the two applications have much in common, so that what is learned in one application can be used to advantage in the other.

In porous media melting often occurs ahead of the propagating combustion wave. In certain cases there is so much melting that the porous solid structure is destroyed, e.g., by melting, and a suspension arises, consisting of a liquid bath containing solid particles and/or gas bubbles. The resulting combustion wave is referred to as a liquid flame.

We have considered a number of problems involving filtration combustion. Here, we describe four such studies: (A) **rapid buoyant filtration combustion waves**, (B) **diffusion driven combustion waves**, (C) **rapidly propagating liquid flames in gravitational fields**, (D) **gas-phase influence on liquid flames in gravitational fields.**

RAPID BUOYANT FILTRATION COMBUSTION WAVES In this investigation we describe a new type of FC wave, which 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. From the point of view of SHS such waves may be desirable since products may be synthesized more rapidly.

We consider heterogeneous (solid/gas) combustion in a porous sample open to gas flow only at the top and the bottom. The reaction is initiated at the bottom of the sample and the combustion wave travels in the direction of gas filtration. There is a localized region of high temperature either ahead of or behind (depending on certain parameters) the combustion layer. Hot gas contained within this region rises due to gravity induced buoyant forces, thus drawing cool fresh gas containing oxidizer in through the bottom of the sample. A two-temperature model is employed to analyze upward buoyant filtration combustion (BFC) waves, with distinct temperatures for the solid and gas phases.

We focus on the reaction leading structure, in which the reaction occurs at the leading edge of the heated portion of the sample. The gas infiltrating through the hot product region significantly enhances the propagation of the combustion wave. For a relatively small gas flux, the infiltrating gas delivers heat from the hot product region to the reaction zone, thus increasing the maximum burning temperature, and hence, the combustion rate. This is referred to as the superadiabatic effect. The propagation of such waves is controlled by the diffusion of heat released in the reaction to the preheat zone. Diffusively driven BFC waves have been studied extensively using one-temperature models. One-temperature models assume a very large rate of interphase heat exchange between the solid and the gas, so that thermal equilibrium is attained almost immediately. However, if the gas flux is sufficiently large, the solid and the gas do not have sufficient time to equilibrate, and hence, the underlying assumption of one-temperature models is no longer valid. That is, one-temperature models are only appropriate for describing slowly propagating BFC waves in which the time of contact between the solid and the gas is sufficiently large for rapid thermal equilibrium to occur. However, not all BFC waves are slowly propagating. There can also be rapidly propagating BFC waves, in which case a two-temperature model, with the solid and the gas attaining distinct temperatures, is more appropriate.

For a relatively large gas flux, an alternative mechanism of enhancement occurs, in that the maximum combustion temperature is increased as a result of increasing the effective initial temperature of the solid. The propagation of such waves is controlled by the convection of heat stored in the product to the preheat zone. Convectively driven BFC waves depend on a pronounced temperature difference between the solid and the gas, and therefore, cannot be described with a one-temperature model. We employ a two-temperature model to study upward propagating BFC waves. In the appropriate limits, we consider both diffusively and convectively driven BFC waves, with the main interest lying in the latter, which requires that a two-temperature model be used. We analyze both modes of propagation and compare and contrast the results.

The filtration of gas may be driven by various mechanisms. A process which is simpler than, yet similar to, upward BFC is forced forward FC, in which the incoming gas flux is fixed by an external source. In BFC, gas flux is induced by the combustion process and must be determined, whereas in forced forward FC, the hydrodynamic description is reduced to prescribing the gas flux at the inlet of the sample. By comparing and contrasting convective upward BFC waves and convective forced forward FC waves, we determine the effects of a buoyancy driven gas flux, as opposed to a fixed gas flux, on convective FC waves.

DIFFUSION DRIVEN COMBUSTION WAVES Filtration of gas containing oxidizer, to the reaction zone in a porous medium, due, e.g., to a buoyancy force or to an external pressure gradient, leads to the propagation of filtration combustion (FC) waves. The exothermic reaction occurs between the fuel component of the solid matrix and the oxidizer. In this investigation, we analyze the ability of a reaction wave to propagate in a porous medium without the aid of filtration, as might occur in microgravity. One possible mechanism of propagation is that the wave is driven by diffusion of oxidizer from the environment. The solution of the combustion problem describing diffusion driven waves is similar to the solution of the Stefan problem describing the propagation

of phase transition waves. The difference is that in the combustion problem the temperature is not prescribed, but rather, is determined as part of the solution. The length of samples in which such self-sustained combustion waves can occur, must exceed a critical value which strongly depends on the combustion temperature T_b. Smaller values of T_b require longer sample lengths for diffusion driven combustion waves to exist. Because of their relatively small velocity, diffusion driven waves are considered to be relevant for the case of low heat losses, which occur for large diameter samples or in microgravity conditions.

Another possible mechanism of porous medium combustion describes waves which propagate by consuming the oxidizer initially stored in the pores of the sample. This occurs for abnormally high pressure and gas density. In this case, uniformly propagating planar waves, which are kinetically controlled, can propagate. Diffusion of oxidizer decreases the wave velocity. In addition to the reaction and diffusion layers, the uniformly propagating wave structure includes a layer with a pressure gradient, where the gas motion is induced by the production or consumption of the gas in the reaction as well as by thermal expansion of the gas. The width of this zone determines the scale of the combustion wave in the porous medium.

RAPIDLY PROPAGATING LIQUID FLAMES IN GRAVITATIONAL FIELDS We
consider the combustion, in a gravitational field, of a porous solid, in which the high temperature ahead of the reaction zone destroys the solid, due, e.g. to melting of some of the solid components. Thus, a suspension is formed, consisting of a liquid bath containing solid or liquid particles. The resulting combustion wave is referred to as a liquid flame. Processes such as heat and mass transfer as well as chemical reactions in the suspension determine the structure of the liquid flame and its propagation velocity. Under the influence of gravitational forces there is the possibility of relative motion of the liquid and solid. Previous theoretical analyses considered the rate of heat transfer between the solid and liquid phases to be sufficiently large that their two distinct temperatures rapidly equilibrated to a single temperature. In addition to this case, we also consider the case when the rate of heat transfer is not so large and the model involves the separate temperatures of the solid and liquid phases. We find that multiplicity of traveling wave structures is possible. In particular, in addition to a low velocity structure, which is essentially the same as that obtained from the one temperature description, we find a high velocity structure, which does not exist in the one temperature description, but rather depends on the fact that the solid and fluid temperatures differ from each other. Both structures can exist for the same parameter values in a given range. We describe the dependence of the combustion characteristics of the two structures on gravitational forces and other factors. In particular, we compare the characteristics in gravity and microgravity environments.

GAS PHASE INFLUENCE ON LIQUID FLAMES IN GRAVITATIONAL FIELDS
A porous solid is ignited at one end. A high temperature combustion wave then propagates through the sample. In this process, melting of some or all the components is often observed. Therefore, we study combustion waves propagating through a medium whose combustion temperature exceeds the melting temperatures of many components. The solid matrix is thus destroyed by the propagating combustion wave due to melting ahead of the reaction zone, and a liquid bath is formed which contains gaseous bubbles. The waves propagate in the presence of a gravitational field. Due to the effect of gravity, there is relative motion between the rising bubbles and the descending bath, which affects the composition of the medium, its thermophysical properties, the "liquid flame" structure, and the propagation velocity. To enhance our understanding of phenomena associated with the interaction of the relative motion with the propagating combustion wave we formulate and analyze a relatively simple mathematical model of liquid flames in a gravitational field. We describe the wave structure and combustion characteristics including the combustion velocity. We compare our results to existing experimental observations and suggest new experiments to be performed. We consider the effects of gravity and, in particular, examine both microgravity and large gravity conditions.

References

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