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Burning Rate Response of Solid Fuels in Laminar Boundary Layer

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***Abstract*—**Solid fuel transient burning behavior under oxidizer gas flow is numerically investigated. It is done using analysis of the regression rate responses to the imposed sudden and oscillatory variation at inflow properties. The conjugate problem is considered by simultaneous solution of flow and solid phase governing equations to compute the fuel regression rate. The advection upstream splitting method is used as flow computational scheme in finite volume method. The ignition phase is completely simulated to obtain the exact initial condition for response analysis. The results show that the transient burning effects which lead to the combustion instabilities and intermittent extinctions could be observed in solid fuels as the solid propellants.

***Keywords*—**Extinction, Oscillation, Regression rate, Response, Transient burning.

I. Introduction

SOLID polymeric materials are used in various industrial and military applications. They can be used as ablative surfaces to protect some sensitive parts of instruments exposed to high heat fluxes where the safety is important. On the other hand, they can be used as energetic materials in air-breathing engines where they called solid fuels. Fuel is any material that is burnt or chemically altered in order to release thermal energy and cannot burn alone; it requires an oxidizer to complete the chemical process. Unlike it, solid propellant is the mixture of fuel and oxidizer used in rockets with no needs for air.

The burning rate (regression rate) of solid propellants and solid fuels has strong dependence to the surrounding conditions. The instantaneous regression rate under a rapidly changing condition departs greatly from steady state regression rate measured in quasi-steady condition. This dynamic behavior is caused by the finite relaxation times required for the solid phase to adjust the temperature profile, called transient burning. Such behavior may lead to explosion or extinction in non-steady conditions or combustion instabilities in combustors.

Solid propellant transient burning has been considered extensively in past decades numerically and experimentally. They can be divided into these different categories: ignition transient [1-5], acoustic instability [6-9], dynamic extinguishment [10-13], and L* instability [14-16]. Such studies are less in the field of solid fuels.

One of the practical usages of solid fuels is to burn in the solid fuel ramjets (SFRJ). These types of air-breathing engines are newer than the solid rocket motors. Almost all studies which have been conducted on SFRJ, pertains to the analysis and prediction of the steady-state operation [17-21] and there is just one report on ignition process in such engines [22].

The solid fuels have been considered in simpler flow conditions to study the ignition transient and flame spreading [23-29] which can be related to ablative-materials and fire-safety areas. Transient burning behavior in such materials has been observed in some experimental data [30, 31]. This behavior may lead to extinction in abrupt change in surroundings condition such as gravity or pressure [32, 33].
Solid fuel transient burning analysis especially under oscillatory and abrupt change in flowfield condition will be much valuable in related applications. It will help the analysis of the required extinguishment in fire prevention problems, burning rate control in solid fuel ramjets or in combustion instability researches. Based on current information, such studies have not been performed comprehensively before. There is a published effort on an investigation of oscillatory field over a transpiring surface which has considered the cold flow semi-similar problem [34]. In the present study, the effects of imposed variations in flow field over a burning solid fuel have been studied numerically to analyze the regression rate response.

II. Governing Equations and Numerical Procedure

The unsteady equations of mass, momentum, energy and chemical species to study the compressible reactive flow over a solid fuel in a two dimensional geometry are used in a gas phase. Four species exist there: Oxygen, diluents, fuel, and products. The Schmidt number is assumed to be unity and a one step second order reaction is considered. Heat transfer into the non-charring solid phase is simulated using an unsteady two dimensional energy equation with coordinates fixed at the burning surface coupled with gas phase equations; conjugate heat transfer is considered. A schematic representation of problem is shown in Fig. 1. The regression rate is calculated from the energy balance in gas-solid interface [32].

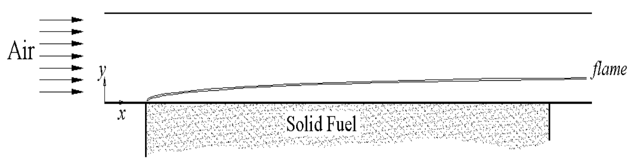

Fig. 1 Schematic configuration of problem

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Here, a cell centered finite volume method is used to discrete the gas phase equations. The time integration is accomplished by a fully explicit time stepping scheme [36]. The inviscid terms are treated using an AUSM$^+$ method (Advection Upstream Splitting Method) to express the numerical flux at cell faces [37]. The finite difference method is used to discrete the solid phase heat equation.

The developed numerical program has been validated formerly using different benchmark problems and experimental data, and used satisfactorily to study the solid fuel regression, auto-ignition and piloted ignition [22, 38-39]. It should be noticed that the grid independency studies have been done in all numerical simulations presented here. For the studies under consideration here, there are not any experimental data to compare, but due to the validations in similar problems, one can expect confidently that the final results are reliable.

III. Results and Discussion

To study the solid fuel regression rate response to the flow field variations, at first, the ignition process of the Poly-methyl-methacrylate (PMMA) within a 2D channel under the hot oxidizer gas flow has been considered. The incoming air flow properties are T=1500 *K*, p=4 *bar*, and U=150 *m/s*. the channel length and height are 40 cm and 3 cm respectively where contains the 30 *cm* length and 2 *mm* thickness solid fuel at the bottom (Fig. 1). The PMMA properties are: density=1190 kg/m^3, thermal diffusivity=8e-8 m^2/s, latent heat=1.6e6 *J/kg* and pyrolysis temperature=600 *K* and fuel initial temperature is 300 *K*.

The numerical simulation results show that although the ignition time of the fuel head-end in this surrounding is about 0.06 *s*, the total ignition time of the whole fuel surface is about 1.45 *s*; the flame spreading time is about 1.4 *s*. The solid fuel surface temperature distribution in different instances is shown in Fig. 2. The surface temperature time history in the fuel midpoint is illustrated in Fig.3. It shows the heating process, where the abrupt changes in curve slope at earlier stages is due to the gas phase ignition of the head-end that increases the heat flux to the gas-solid interface. The flame edge location is shown in Fig. 4 where indicates the flame spreading speed of about 0.21 *m/s* in this flow field.

After 1.5 seconds, the regression rate distribution along the fuel, temperature profile in the solid phase midpoint, and temperature and velocity profiles in the gas phase on the fuel midpoint is illustrated respectively in Figures 5-7. The regression rate behavior is similar to the heat flux distribution on the flat plate, as expected. It is higher for about one order of magnitude in the head-end than the aft-end.

Solid phase thermal penetration depth is of order of 1 *mm*. That is after such remarkable time just a millimeter of fuel is disturbed in this hot flow field. It shows the important time scale in heterogeneous combustible flows where arisen from the solid phase heating delay time and is the origin of transient burning phenomena. The chemical reactions occur within the boundary layer on the transpiring solid fuel in diffusion flame manner. The streamlines near the fuel head-end are illustrated in Fig. 8 where the flame is also shown. The injection and heat release cause the deflection in streamlines at upstream.

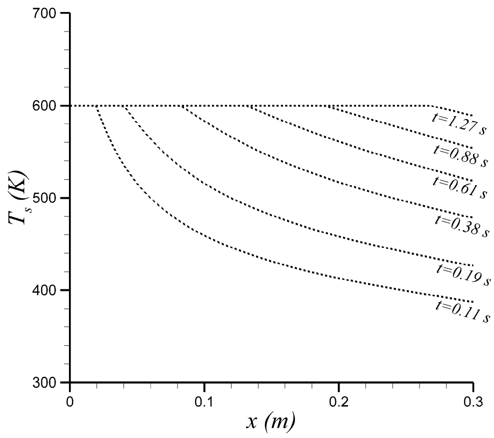

Fig. 2 Solid fuel surface temperature at ignition phase

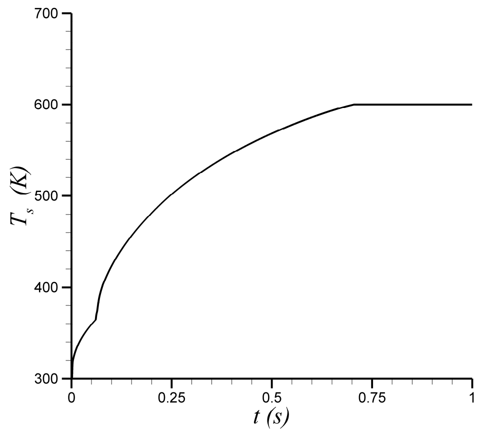

Fig. 3 Solid fuel midpoint surface temperature time history

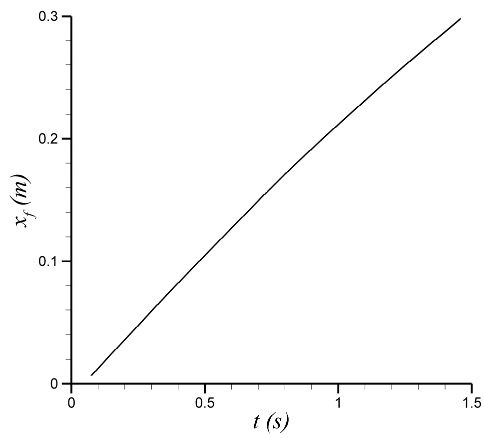

Fig. 4 Flame edge location versus time

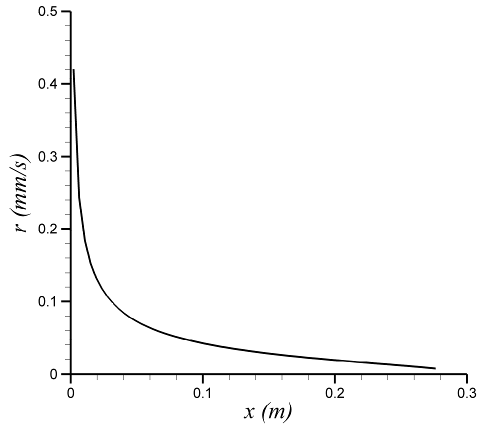

Fig. 5 Regression rate distribution after 1.5 *s*

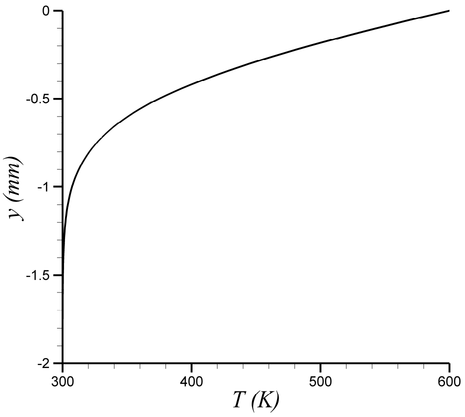

Fig. 6 Temperature profile within fuel in the midpoint after 1.5 *s*

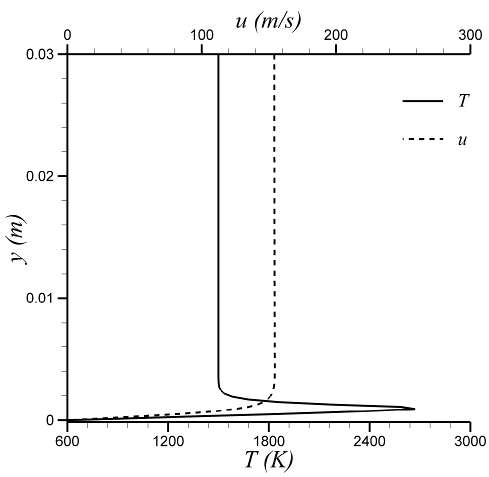

Fig. 7 Temperature and velocity profiles within gas phase in the midpoint after 1.5 *s*

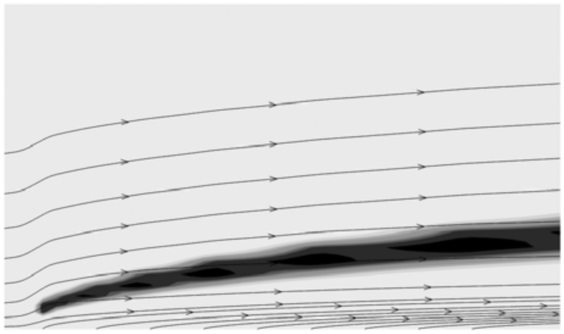

Fig. 8 Streamlines near the fuel head-end

Now, these results could be used to study the regression rate response to the abrupt change in surrounding conditions. So the reactive flow field has been considered since the final stage of previous simulation. Indeed, sudden change at inlet flow condition has been imposed. There are three different studies: temperature reduction to 300 *K*, oxygen mass fraction reduction to 0.1, and simultaneous reduction in both temperature and oxygen mass fraction to 300 *K* and 0.1.

The results show that in the first and second cases, despite the large change in flow field into unfavorable conditions, the portion of the fuel at the aft-end is turned off and then turned on again. That is, these abrupt changes don’t lead the extinguishment. The flame temperature decreases in these cases but there are still favorable conditions for chemical reactions to continue; the new situations are in flammability limit. The regression rates in different locations are shown in Fig. 9 for the first case. The fuel is off for about 0.21 *s* and ignites again at the aft-end. The regression-rate rate of change is about 80 mm/s^2 near the head-end.

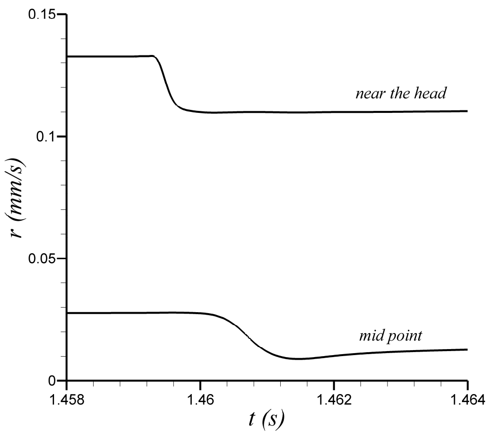

Fig. 9 Regression rate at the midpoint and near the fuel head-end

In a third case, the fuel is turned off completely where the extinguishment starts from the head-end. The regression-rate rate of change is about 330 mm/s^2 near the head-end. Burning rate time variation is illustrated in Fig. 10 and the extinguishment location is shown in Fig. 11. The extinguishment spreading speed is about 122 *m/s*. It is about the flow field velocity, against the flame spreading speed in the ignition simulation. A little increase in this curve slop is due to the upstream cooling in this situation. This study shows that to extinguish the burning polymer in such flow field, both temperature and oxygen mass fraction must be controlled and no one works alone.

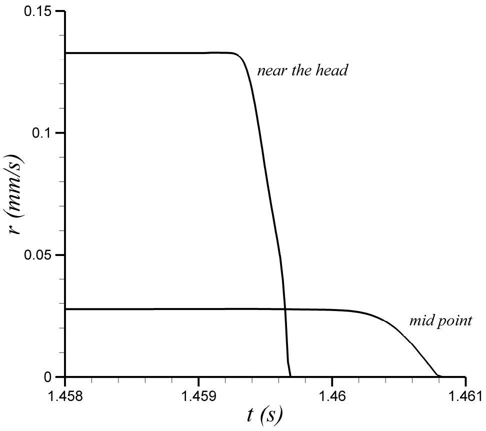

Fig. 10 Regression rate variation in abrupt extinction

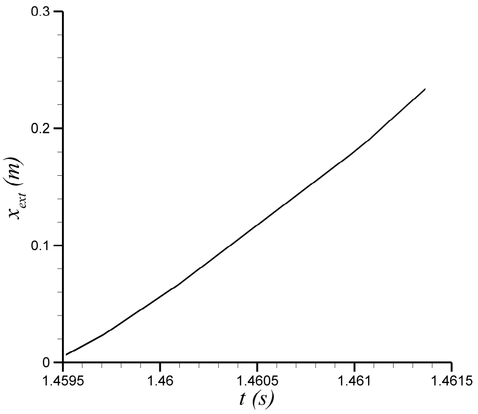

Fig. 11 Extinguishment location versus time

In a final step, the regression rate response to the imposed oscillatory excitations could be predicted. Here, two categories of simulation have been conducted; first the fluctuation in temperature and oxygen mass fraction have been considered when the inlet conditions is as the ignition case (hot air inlet), then the fluctuation in temperature, velocity and pressure have been considered when the inlet air was cooled after ignition (from the end of the first case of abrupt change studies). From practical viewpoints, these studies could be related to the ignition phase and steady state operation of solid fuel ramjets or each system containing the solid fuel combustion as in fire safety problems. In SFRJ, the combustion chamber flow field is coupled to the flight condition. If the speed varies, then the intake shock angle and the inlet conditions vary. So the fuel burning changes and vice versa. Such coupling may lead to unexpected events and should be predicted.

The analysis of simulation results are summarized briefly here. The burning rate responses in the first category are similar for temperature and oxygen mass fraction. Increasing the amplitude of the fluctuations in flow field increases the amplitude of the burning rate fluctuation, as expected (Fig. 12). Increasing the period of imposed fluctuations may sometimes increase the amplitude of burning rate response. It is not always true as will shown later. The portion of fuel with lower regression rate is more sensitive to the excitation than the portion with higher regression rate. Such behavior has been reported in erosive burning of solid propellants. A little decrease in average regression rate is observed in all cases of fluctuations.

In cold flow simulations (second category), the regression rate response to the inlet flow changes is interesting; it is more sensitive to the pressure fluctuations and less sensitive to the temperature. Such coupling between regression rate and pressure fluctuations is as the combustion instabilities in solid propellant rocket motors. The reduction in average burning rate is obvious here. There can find a fluctuation where under it, the amplitude of response is highest. This critical excitation may lead to extinguishment. It is done here by amplitude of 25% and period of 2 ms where the intermittent extinctions observed. It is like low frequency instabilities in solid rocket motors called chuffing.

These observed phenomena like oscillatory extinction or dependency of response amplitude to the excitation period in the considered situations are the transient burning behavior which arises from the significant difference in gas phase and solid phase time scales. The time scale in the solid phase is about two orders of magnitude larger than the gas phase time scale. So it takes time for temperature profile in solid phase to be adjusted with gas phase variations. This delay leads difference between instantaneous regression rate and steady state rate which finally cause extinction or instabilities.

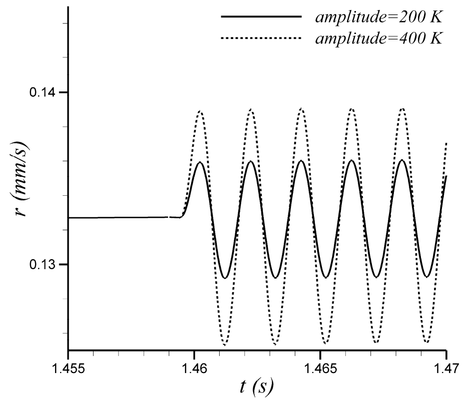

Fig. 12 Burning rate response to the temperature fluctuations near the head-end (hot air inlet, period of 2 *ms*)

IV. Conclusion

In this study, the transient reactive flow on transpiring solid polymeric material is numerically studied. The gas phase and solid phase thermal interactions at interface are considered by conjugate heat transfer simulation. The solid fuel burning process is completely simulated at ignition phase and continued in flammable limit after inflow cooling. The regression rate responses to the abrupt and oscillatory changes at surrounding conditions are analyzed in both ignition phase and operational phase. The results show that the complete extinction will be done by abrupt changes at inflow condition but intermittent extinction could be observed yet in oscillatory excitations. Solid fuel transient burning behavior cause the dependency of response amplitude to the period and amplitude of imposed perturbations. Using such studies help finding the critical condition in solid fuel ramjets operation and also to find the best way to control the burning surfaces in fire prevention problems.

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