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Proceedings of the Combustion Institute 30 (2005) 2097–2104

Proceedings of the Combustion Institute

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Combustion of sandwich propellant at low pressures

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Abstract

This article presents the results of both experimental and computational studies that were carried out at pressures close to atmospheric pressure (in numerical studies, the pressure range was from 0.078 to 1.4 MPa) to obtain an insight into the behavior of pure ammonium perchlorate (AP)–hydroxyl terminated poly butadiene (HTPB) sandwich propellant at these conditions. Numerical studies were carried out for a periodic sandwich propellant configuration with a two-dimensional unsteady model in both the gas and condensed phases accounting for the non-planar nature of the regressing surface. Appropriate boundary conditions across the gas–solid interface which lead to correct coupling of the gas phase with the condensed phase have been utilized. The three-step gas phase chemical kinetics model along with a surface decomposition model for AP and a surface pyrolysis model for fuel were utilized. The binder thickness used in these studies varied from 10 to 400 μm. The numerical study has successfully captured the splitting of the base of the flame observed at large binder thicknesses. The quenching of sandwiches has been experimentally observed and has been successfully predicted as well. The predicted pressure index of combustion of sandwiches indicated two different indices in different pressure regimes consistent with experimental observations. The predicted pressure index was 0.4 for pressures up to 0.7 MPa and for pressures greater than 0.7 MPa it was 0.74.
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Keywords: Sandwich propellant combustion; Composite propellant combustion

1. Introduction

Recent years have seen a renewed interest in the field of sandwich propellant combustion. Pure AP binder sandwich, which is a two-dimensional analogue of composite propellant, consists of binder laminae sandwiched between two AP pellets. In this study, experiments were conducted to determine the burn behavior of sandwich propellant at near atmospheric pressures with the objective of obtaining some insight into the processes that occur at such low pressures. These results do serve as a good benchmark for the computational study of sandwich propellant combustion. This paper also reports the computational study of sandwiches below 2.0 MPa.

Price et al. [1,2] have conducted extensive experiments on the burning of pure AP binder sandwiches. Valuable information on the burn rate, burn profiles, and quench limits for sandwiches can be found in these works. These and other relevant literature on sandwich propellant have been reviewed by Price [3].

The non-intrusive techniques of studying the flame structure as applied to sandwich propellant were first reported by Parr and Hanson-Parr [4].

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doi:10.1016/j.proci.2004.08.174

They used planar laser-induced fluorescence to measure the flame height and flame stand-off distance. Brewster and co-workers [5,6] have attempted to locate the flame structure relative to the regressing sandwich surface during combustion utilizing ultraviolet emission imaging technique with backlit surface profiles. They report of having observed that both the leading edge flames and the secondary flames show a tendency to merge into one flame at lower pressures and lower binder thicknesses, and tend to separate out at higher pressures and higher binder thicknesses. Their burn rate measurements of sandwiches for binder thicknesses ranging from 50 to 450 μm indicate that the regression rate is relatively independent of binder thickness above a binder thickness of 100 μm and that it is primarily a function of pressure. The pressure index of burn rate obtained by them is 0.31 from 2 to 15 atm and 0.66 from 15 to 32 atm. A 120 W/cm^2 laser flux utilized by them could lead to a lowering of the burn rate pressure index. Besides, HTPB binders have a tendency to form a melt layer that flows onto adjoining AP, which could lead to lowering of pressure index as explained by Price [7]. Further discussions on this issue will follow later. The laser assisted deflagration seems to have prevented them from observing the quenching of sandwich propellant at pressures below 2.0 MPa as reported by Price et al. [1,2].

Korobeinichev et al. [8,9] have studied sandwiches with multiple binder layers. The thermocouple and mass spectrometry data reported by them are obtained along the extended centerline of an AP slab, which is far removed from the AP–binder interface region. These results need to be carefully examined in the light of the new results obtained by Brewster and co-workers [10] that the boundary condition at the edge of the AP slab has little impact on the flame structure near the AP–binder interface region. Besides, the detailed chemistry calculations (for which data reported in [8,9] would be useful) cannot be considered at present as the sandwich propellant combustion problem even with simple chemistry is computationally intensive.

Recent literature on the modeling of pure AP sandwiches has been reviewed by Ramakrishna et al. [11]. The model presented by Hegab et al. [12], apart from the features described in [11], does not make extensive comparisons with experimental results, thus limiting their work. Knott and Brewster [13] have compared their model predictions with experimental results. They have relaxed the assumption of surface being planar during regression (made in their earlier work [14]) by imposing an additional condition that for a steadily burning sandwich propellant the vertical burn rate must be equal at all points along the regressing surface of the sandwich. But the model is still steady and does not allow for the unsteady evolution of the regressing surface with time. The lateral velocity resultant from such a non-planar regression has not been accounted for in their model. The model proposed by Price and co-workers [15] utilizes the non-planar burning surface and the regression rate as input from experiments, and solves the resultant two-dimensional non-coupled gas and condensed phase steady state equations that could have more value as insight than as predictive ability.

Therefore, the objectives of this paper were twofold. First, to carry out experiments at two different pressures (0.092 and 0.078 MPa) close to the atmospheric pressure with the objective of:

(a) determining the quench limit of sandwiches,
(b) determining the variation of sandwich burn rate with binder thickness, and
(c) studying the flame structure of sandwiches.

Second, to carry out a computational study of sandwich propellant at pressures below 2.0 MPa and juxtapose them with the experimental results:

(a) to understand the physics,
(b) to determine the influence of binder thickness, and
(c) to determine the influence of pressure.

2. Sandwich propellant experiments

2.1. AP pellet preparation

As-obtained AP was ground into fine powder (around 100 μm) and dried in the oven at 383 K for a day. The dried AP powder was then compressed to pellets of 25 × 25 × 1.5 mm dimension each, using a hydraulic press and mild steel die. A pressure of 207 MPa was applied for a period of 6–8 min. A density of 1875 kg/m^3 (96% of single crystal density) was achieved. The compression pressures and compression times utilized here are less than those reported by Price et al. [2] (210 MPa and 20 min, respectively), consequently the density is lower than the single crystal density of 1957 kg/m^3. The pellets were then dried by storing them in an oven maintained at 333 K for 8 h.

2.2. Binder and sandwich preparation

Thin binders were obtained by mixing HTPB and toluene diisocyanate (TDI)[1] in the ratio

[1] Although melt flow was observed at large binder thicknesses (150 μm and above) in the current studies, no large-scale uneven burning, leading to a loss of two dimensionality of the regression process (explained by Price [7] to be due to the curatives with the isocyanate group in them), was noticed.

90:10 in a Petri dish until a uniform consistency was obtained. The mixture of HTPB and TDI thus obtained was poured onto a flat plate with builtup side walls made of resin to retain the mixture. The mixture was then kept in an oven maintained at 333 K for a minimum of 48 h to enhance the curing rate. The glass plate was taken out of the oven and immersed in water for about an hour to help remove the thin sheet of HTPB. A cut with a slightly blunt knife was made near the edge of the glass plate, and the thin sheet of HTPB binder was peeled off from the glass plate. The binder sheet thus obtained was still sticky on the surface and was stored under water. Strips of size 25 mm × 25 mm and thickness ranging from 100 to 550 μm were cut and dried to remove water. They were then placed between two AP pellets and stored in a hot air oven at 333 K under a weight of around 10 kg to ensure good contact between the pellets and the binder. The binder size was later measured under a travelling microscope, and specimens measuring beyond the ± 10 μm were rejected. The final size of the specimen used was around 25 × 25 × 3 mm.

2.3. Experimental set-up

An ejector based system was designed to conduct experiments near atmospheric pressures. The core flow for the ejector was taken from a compressed air tank having a capacity to store air at 0.4 MPa. The flow rate in the core of the ejector was 17 g/s. The lowest pressure that could be obtained with this ejector system in the combustion chamber was 0.05 MPa (about half-an-atmosphere). The flue gas ejection rate obtained was 1.7 g/s.

The schematic diagram of the entire set-up is shown in Fig. 1. As seen in Fig. 1, the stand houses the propellant holder, electrical connections for ignition, a connection for nitrogen gas supply, an outlet for exhausting the combustion gases, and a vacuum pressure gauge connection. They were enclosed inside a bell glass jar with a view window.

The combustion gases were exhausted with the help of an ejector, described earlier. The ejector had a provision for regulating the flow of compressed air to achieve quenching by rapid depressurization. A small quantity of nitrogen was metered out from a nitrogen cylinder through a pressure regulator. A thin stainless steel strip was mounted on the provision provided for ignition such that it just rested on the sandwich propellant, and the leads from it were connected to a dimmerstat. On application of 30 V and 15 A, the stainless steel strip turned red hot and initiated ignition of the sandwich propellant. A video camera in conjunction with a 500 W halogen lamp (placed behind the video camera as shown in Fig. 1) was used to record the experiments.

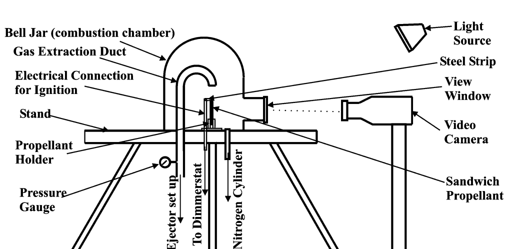

Fig. 1. Schematic diagram of the experimental set-up.

2.4. Experimental procedure

The edges (3 mm faces) of the sandwich propellant prepared, as explained in Section 2.2, were coated with a thin layer of inhibitor (aluminum oxide mixed with diluted glue) to prevent the flames from spilling over at the edges. Lines 10 mm apart were drawn on these edges with the help of a silk thread dipped in black paint. The sandwich was then placed in the propellant holder on the stand, with the edge having the markings facing the video camera. A stainless steel strip 1 mm thick was placed on top of the sandwich to initiate ignition, as explained in the earlier section. The set-up was then enclosed in the glass bell jar, that constitutes the combustion chamber. Silicone grease was smeared onto the surface of the glass bell jar in contact with the stand to make the enclosure leakproof capable of withstanding vacuum conditions. Compressed air was allowed to flow through the convergent-divergent portion of the ejector, and the flow rate was adjusted so as to obtain the desired pressure in the combustion chamber. A small flow of nitrogen was allowed to pass into the combustion chamber to flush out the flue gases. The 500 W halogen lamp was turned on. The video camera was positioned as explained earlier and focused to record the burning of sandwiches. Ignition of the sandwich was initiated by supplying electric current of 15 A and 30 V through a dimmerstat. The entire combustion process was recorded on a video cassette. The burn rate of the sandwich was calculated based on the time taken by the regression front to traverse the distance between the two markings described earlier. Two sets of readings were taken at each point at which the values of burn rate were reported to ascertain repeatability of the process. The reported burn rate was the average of the two readings.

To study the burn surface of the propellant, the propellant was quenched by rapid depressurization, and the surface was photographed. Rapid depressurization was achieved by fully opening the valve regulating the compressed air flow in the ejector almost instantaneously. This ensured that the pressure inside the combustion chamber dropped suddenly causing the sandwich propellant to quench. Typical depressurization rates required for quenching the propellant were of the order of 0.02 MPa/s. This was much lower than those required to quench a composite propellant; however, since the heat storage capacity associated with a sandwich propellant is very small, it was found to be adequate.

3. Results and discussion

The results of variation of sandwich burn rate with binder thickness, both experimental and computational, are shown in Fig. 2. The predicted results will be explained later in this paper. It is observed that with the reduction in the operating pressure (0.092–0.078 MPa), the binder thickness below which the sandwich ceases to burn (i.e., 120–180 μm) increases. Quenching at 0.092 MPa pressure is seen to occur at 120 μm, and this agrees well with the value of 130 μm at 0.1 MPa reported earlier by Price et al. [2]. The burn rate recorded at both pressures lie between 0.5 and 0.4 mm/s. At 0.092 MPa, the burn rate increases with an increase in binder thickness from the quench limit up to a certain binder thickness, beyond which it decreases and reaches a value that changes little with binder thickness. The binder thicknesses for maximum burn rate and the quench limit are the same at a pressure of 0.078 MPa.

The burn rates obtained by Chorpening and Brewster [6] for sandwiches with HTPB binder at low pressures are given by $r = 0.94P^{0.31}$ for a pressure range of 2–31 atm. Extrapolating, using this law a burn rate of 0.9 mm/s is obtained at 0.092 MPa, whereas in Fig. 2 it is 0.4–0.5 mm/s. The higher value of burn rate reported in [6] could be due to the use of laser beam of 120 W/cm^2 average flux. Their sensitivity test with laser flux does indicate that with the halving of the laser flux the burn rate decreases by 15%. Additionally, the results of Knott and Brewster [13] show that the laser flux of 120 W/cm^2 is around one-third of the gas phase flux computed by them at a pressure of 5 atm. The effect of this laser flux on their result [6] is twofold, an increased regression rate and reduction in the pressure index of regression. Hence, the pressure index of 0.3 for sandwich combustion reported by them at low pressures is lower than the 0.53 obtained in the present study.

Stills from the sandwich combustion video recording are presented in Fig. 3 for binder thicknesses of 130 and 290 μm. They are arranged from left to right with progressing time as indicated. Figure 3A shows that a flame occupying a small cross-sectional area is present over the binder. Figure 3B shows that for a thick binder the flame cross-sectional area is comparable to that of the sandwich width. The region of activity is restricted to the area in the vicinity of the binder for both cases. The edges of the sandwich hardly regress, and they protrude out to such an extent that they become structurally weak and fall off (see Fig. 3A stills (iii) and (iv)). The quenched profile seen in still (v) shows that the profiles are shallow for a thick binder as compared to those of a thin binder. This is due to the larger flame cross-section associated with the thick binder. In Fig. 3B, the base of the flame has dark regions adjacent to the binder (enclosed by a ring). These could be the mixing zones for fuel and AP vapors, and hence regions where no reaction occurs. But, these regions could also be dark due to a flow of binder melt onto adjacent AP as the still (v) of Fig. 3B also has these dark regions. Hence, given the current evidence, it is impossible to pinpoint the reason for these dark regions. Such dark regions are absent at low binder thickness (see Fig. 3A). Brewster and co-workers [5,6] have reported the phenomenon of splitting of the flame base with increase in binder thickness. Further comments on this will be presented in later.

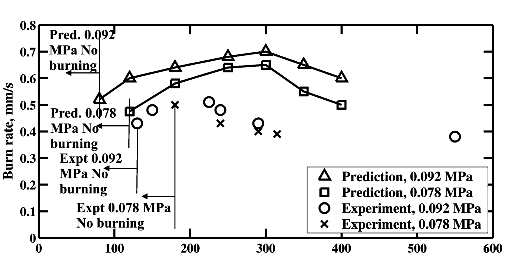

Fig. 2. Predicted variation of sandwich burn rate with binder thickness at two different near atmospheric pressures along with experimentally observed variation of the same.

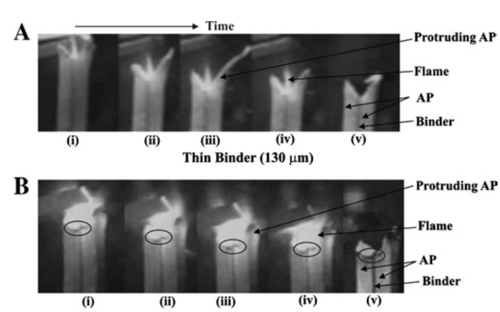

Fig. 3. Experimentally obtained pictures of sandwich burning at 0.092 MPa for binder thicknesses of 130 μm (A) and 290 μm (B). The region inside the ring shows the dark regions adjacent to the binder at the base of the flame.

4. Computational studies

The model for the periodic sandwich propellant utilized here has been described by Ramakrishna et al. [11] in detail. The two-dimensional unsteady conservation equations in the gas phase are solved using Patankar's algorithm [16]. In the condensed phase, the unsteady two-dimensional heat conduction equation is solved after obtaining the temperature of the regressing surface. Unsteady non-planar regression of the pyrolysing surface is allowed for, and the strategy adopted is similar to the one described in [11]. Lewis and Prandtl numbers are assumed to be unity, and diffusivities of all species are assumed to be identical.

The surface decomposition processes for binder and AP along with a three-step gas phase chemical kinetics model are taken as outlined in [11]. The initial conditions and boundary conditions utilized here are similar to those utilized in [11].

Computations were carried out with the same set of parameters as described in [11], except for the activation energies of the two diffusion flames. The activation parameters described in [11] were chosen for the high pressure case, wherein diffusion was the limiting process. At pressures encountered in the present study (low pressures), chemical kinetics is the limiting process. Hence, the activation energy parameters had to be reassessed. The activation energy of primary diffusion flame (reaction (R4) in [11]) was increased from 120 kJ/g mol to 153 kJ/g mol and that of final diffusion flame (reaction (R5) in [11]) was reduced from 60 kJ/g mol to 51.5 kJ/g mol. With these changes, the burn rate at a pressure of 0.092 MPa and a binder thickness of 250 μm reduced to around 0.66 mm/s from 1.4 mm/s before the change. For the new set of reaction rate parameters, the burn rates of sandwich at a pressure of 2.1, 3.5, and 6.9 MPa for a binder thickness of 25 μm were 4.1, 6, and 9 mm/s, respectively. Thus, it is evident that the new parameters helped reduce the burn rate at the low pressure end *while the results remained nearly unchanged at pressures above 2.1 MPa*. A discussion on the possible explanation for the above is presented later in this paper.

Computations with sandwich propellant configuration were carried out for binder thickness ranging from 10 to 400 μm and at pressures of 0.078, 0.092, 0.2, 0.4, 0.71, and 1.01 MPa. The cells were geometrically stretched in both the gas and condensed phase from 2 μm at the burning surface to 66 and 125 μm at the gas and condensed phase exit boundaries, respectively, in the streamwise direction (x-direction) at pressures close to 0.1 MPa. Similarly at 1.01 MPa, the grids were stretched from 0.4 μm at the burning surface to 13 and 60 μm at the gas and condensed phase exit boundaries, respectively, in the streamwise direction. The cells were geometrically stretched from 2 μm at the AP binder interface towards the edges of both binder (6 μm) and AP (50 μm) in the cross-stream-wise direction (y-direction) at pressures close to 0.1 MPa. The minimum grid size at 1.01 MPa at the AP binder interface is 0.4 μm. At the start of the calculations, the number of cells in the gas and condensed phase, (y-direction) were 110, 163, respectively, and 50–70 cells were used in the lateral direction depending on binder thickness. The typical height and depth of the computational domain above and below the burning surface were 3.5 and 7.1 mm, respectively. The typical time step size utilized was 0.1 μs. The grid and time step size were arrived at after a grid and time step independence study. The thickness of the AP slab used in all cases was more than 1.1 mm, which is close to the thickness of AP utilized in experiments.

5. Results and discussion

The predicted gas phase reaction rate contours for the two diffusion flames and the AP decomposition flame at 0.092 MPa pressure are as shown in Figs. 4A and B for a binder thickness of 120 and 400 μm, respectively. With the increase in binder thickness from 120 to 400 μm, the base of the final diffusion flame appeared split. Similar behavior was observed at higher pressures with the above phenomenon occurring at lower binder thicknesses with increasing pressure. This has been discussed earlier in Section 2.4, and Brewster and co-workers [5,6] have reported the splitting of the base of the flame with increase in binder thickness at a particular pressure. The diffusion length scale at a particular pressure was determined by the thickness of the binder. As the thickness of the binder increased, the distance the fuel vapors will have to traverse before they get in touch with the oxidizer stream also increased.

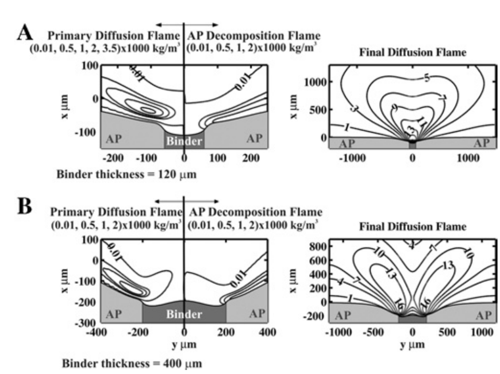

Fig. 4. Predicted gas phase reaction rate (kg/m³) contours at pressures of 0.092 MPa for (A) binder thickness of 120 μm, (B) binder thickness of 400 μm.

Therefore, a region with no reactions was formed in the vicinity of the binder surface near the $y = 0$ region (refer Fig. 4B). This resulted in a split at the base of the final diffusion flame with the increase in binder thickness. The other aspect to observe in Figs. 4A and B is that the final diffusion flame appeared more spread out with the increase in binder thickness. This has also been corroborated by experiments (refer Fig. 3 and [5,6]). With increase in binder thickness and the Damkohler number being constant (pressure constant), the excess fuel vapors released need a larger volume (area in the current case) to be consumed. Thus, the qualitative behavior of the diffusion flames experimentally observed has been correctly predicted.

The gas phase reaction rate contours for the AP decomposition reaction are shown in Figs. 4A and B. The peak reaction rates indicated here are at least one-hundredth of the values obtained at pressures in excess of 1.4 MPa (refer Fig. 3 of [11]). The contribution from these reactions towards the gas phase heat release is quite small.

The gas phase and condensed phase temperature profiles for a thick (400 μm) and a thin (120 μm) binder at a pressure of 0.092 MPa are shown in Fig. 5. The gas phase temperature profiles show that with the increase in binder thickness, larger areas are seen to be at higher temperatures due to larger areas occupied by the final diffusion flame at the higher binder thickness, as described earlier in this section. *Peak temperatures are achieved at around 1 mm from the surface in comparison to these being achieved at around 100 μm at pressures in excess of 1.4 MPa (refer Fig. 3 of [11]).* The region of activity of the primary diffusion flame (refer Figs. 4A and B) coincides with a small region in the gas phase close to the regressing surface near the AP–binder interface where the gradients are steep (indicated by the closeness of the contour lines). This leads to a larger gas phase heat flux to the regressing surface near the AP–binder interface, indicating the importance of primary diffusion flame at pressures close to atmospheric pressure.

In the condensed phase contours, the AP–binder interface region is at a higher temperature, and the heat flows laterally from the AP–binder interface region to the AP side. For the sandwich to burn, the heat from the gas phase flame to the AP–binder interface region must be equal to, or higher than, the heat transferred to AP side. If the heat supplied from the gas phase flame to the AP–binder interface region is less than the heat transferred to the AP side, it leads to quenching of the sandwich. The quantitative substantiation of the above process is useful; it involves maintaining an accurate heat conduction record at a junction and observing the same over the period of time during which the quenching takes place. It is not discussed here.

The variation of burn rate of a sandwich with time for a quenched case is shown in Figs. 6C and D. The other two plots in the same figure (Figs. 6A and B) correspond to a burning case. In the quenched cases, in contrast to regressing ones, the instantaneous burn rates at all sections fall sharply beyond a certain time period. The convergence criteria utilized here has been presented in [11]. From Fig. 6, it is evident that for all cases only regions close to the AP–binder interface are regressing, while a large portion of AP far off from the AP–binder interface is hardly regressing. The operating pressures discussed in this paper are all below 2.0 MPa, which corresponds to the Low Pressure Deflagration Limit (LPDL) of AP. Thus, a strong AP monopropellant flame is absent (as discussed earlier in this paper), causing the regions of AP far off from AP–binder interface to protrude. This is in conformity with the experimental results (Fig. 3), which show that only regions in the vicinity of the AP–binder interface are regressing. Thus, only regions close to AP–

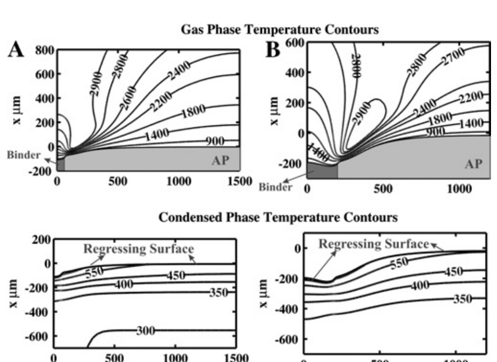

Fig. 5. Predicted gas phase and condensed phase temperature contours for a binder thickness of 120 μm (A) and 400 μm (B) at 0.092 MPa.

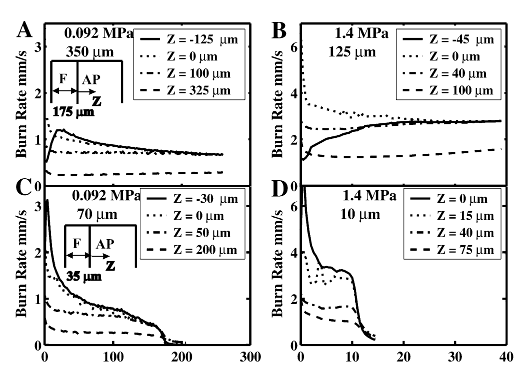

Fig. 6. Predicted burn rates at different cross-sections on the surface parallel to AP–binder interface (distances measured from AP–binder interface) for various cases as indicated.

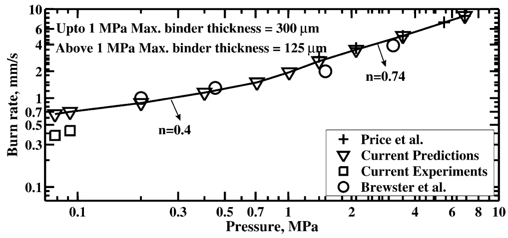

Fig. 7. Predicted variation of burn rate with pressure at large binder thickness (indicated) for sandwich propellant along with experimental results.

binder interface are considered, while deciding on the convergence criterion at all pressures studied in this paper. The successful prediction of regression of sandwich propellant below LPDL of AP and the prediction of quenching of sandwiches consistent with the experimental observations indicate the maturity of the model. This was possible by the inclusion of surface liquid layer model for AP and the unsteady condensed phase heat transfer.

The predicted burn rate variation with binder thickness is shown in Fig. 2 along with the experimental variation. The predicted burn rate is higher than the experimental values. HTPB binders utilized in the experiments are known [7] to form melt, which tends to flow onto adjoining AP. This causes the pyrolysis rates of AP adjoining the binder to be lower, and hence could lower the overall sandwich regression rates. The predictive model utilized here has no provision to account for binder melt formation and flow, and consequentially could be overpredicting the burn rates. The model predicts the quenching of sandwiches as the binder thicknesses are reduced. The predicted quenching occurs at binder thicknesses lower than those experimentally observed. The heat loss from the sandwich, which is not incorporated in the model, is a factor suggested as being responsible for the difference between the experiments and the prediction.

The variation of burn rate with pressure at large binder thickness for a sandwich propellant along with experimental results is shown Fig. 7. It shows that the predictions are in reasonable agreement with the experimental results of Price et al. [1,2], and Brewster and co-workers [5,6]. The possible reasons for the predicted burn rate being higher than the experimental values at pressures close to atmospheric pressure have been explained in the previous paragraph. This predicted variation shows that the combustion of sandwich has two pressure indices, at pressures below 0.7 MPa a low pressure index of 0.40 and at pressures above 0.7 MPa an index of 0.74. The change in pressure index indicates the relative importance of various flames in the different pressure regimes. At the low pressure end, the primary diffusion flame is important. With an increase in pressure, the importance of the final diffusion flame increases, while that of the primary diffusion flame diminishes. The AP decomposition flame assumes relevance above a pressure of 2.0 MPa corresponding to the LDPL of AP. A similar result obtained experimentally by Chorpening and Brewster [6] shows a pressure index of 0.31 at pressures below 1.5 MPa and an index of 0.66 from 1.5 to 3.2 MPa. The reasons for the lower index of 0.31 at pressures below 1.5 MPa have already been discussed in the preceding paragraphs. The lower pressure index reported by them [6] at pressures above 1.5 MPa could be due to issues related to melt flow associated with HTPB binder as described by Price [7].

6. Conclusions

Experiments along with the numerical studies have been carried out on sandwich propellant with HTPB as binder at pressures close to atmospheric pressure to get an understanding of the processes that govern the combustion of sandwiches at these pressures. Numerical studies of the periodic sandwich propellant geometry were carried out with two-dimensional unsteady gas and condensed phases, a non-planar regressing surface along with a kinetic model of three reaction steps in the gas phase. The thickness of the binder utilized in the experimental studies varied from 100 to 550 μm, and in computational studies it varied from 10 to 400 μm. The experiments were conducted at pressures of 0.078 and 0.092 MPa, while numerical calculations were carried out over pressures ranging from 0.078 to 1.4 MPa. The predicted burn rate at pressures of 0.078 and 0.092 MPa was around 0.45–0.7 mm/s, which was higher than the experimentally obtained values of around 0.4–0.5 mm/s. The absence of a heat loss model and a model to account for the binder melt flows associated with the thick HTPB binder utilized here are suggested as reasons for the difference between experiments and prediction. The splitting of the base of the flame observed at large binder thicknesses was successfully captured by the numerical study. The quenching of sandwiches was experimentally observed and was successfully predicted as well. This was attributed to the inclusion of a surface liquid layer model for AP and the unsteady condensed phase heat transfer. The predicted dependence of burn rate on pressure was in reasonable agreement with the experimental results. The predicted pressure index of combustion of sandwiches at pressures up to 0.7 MPa was 0.4, and for pressures greater than 0.7 MPa it was 0.74. The primary diffusion flame controlled the combustion at the low pressure end while the final diffusion flame along with the AP decomposition flame controlled the combustion at the high pressure end.

Acknowledgment

This work was partially funded by the Brain Korea 21 project.

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Comment

Oleg Korobeinichev, Russian Academy of Sciences, Russia. The authors performed a great deal of work, especially with regard to calculations, which allowed computation of the sandwich flame structure. Could you please indicate the values of such parameters such as width of reaction zone in flame and burning surface temperature in cross-section corresponding to the center of binder layer? How do these parameters conform to what is available in literature experimental data on the thermal flame structure of sandwiches based on AP and binders? What is the reason for the considerable difference between observed and calculated shape of the burning surface profile in the combustion of the sandwich?

Reply. The experimentally measured surface temperatures at the center of the binder layer during regression for a polymeric fuel are reported in (Ref. [1] in paper). They are 733 and 500 K for polystyrene and polyformaldehyde as binder, respectively, at 1.0 MPa pressure. As seen, the experimentally measured surface temperatures vary over a wide range depending on the type of binder. The computed surface temperature at the center of the binder (HTPB) layer at 1.0 MPa pressure case is 750 K, which is in the same range as the experimentally measured temperatures.

The height of the diffusion flame above the regressing surface has been obtained experimentally by Brewster and co-workers (Refs. [5,6] in paper) utilizing ultra-violet emission imaging technique with back lit surface profiles. The values reported by them are as follows; at around 0.4 MPa it varies from 1200 to 1400 μm and at around 0.2 MPa it varies from 1300 to 1500 μm depending on the binder thickness. For similar conditions, the computed final diffusion flame heights above the regressing surface are; 900–1100 μm at 0.4 MPa and 1000–1300 μm at 0.2 MPa. The computed results although slightly lower are in the same range as the experimental results. The difference between the two could be attributed to detailed chemistry (not included in the modeling), which as pointed out in the paper is computationally prohibitive to undertake at present.

The experimental profiles were obtained after around 20 s of regression. It is computationally prohibitive to carry out computations for such a long time and is not necessary. Regression as seen in Fig. 5 is restricted to an area close to the AP-binder interface. The computed burning surface profile was obtained after calculations were carried out for around 200 ms, during which the regions close to the AP-binder interface had reached a steady state as seen in Fig. 5. The difference in the regression rates between the regions close to the AP-binder interface and the regions near the edge of the AP slab when extrapolated to around 20 s would yield a profile similar to those experimentally observed.

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