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HYBRIDS REVISITED

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Abstract

This paper reexamines the hybrid rocket in light of several important unanswered questions regarding its performance. The well-known heat transfer limited burning rate equation is quoted, and its limitations are pointed out. Several inconsistencies in the burning rate determination through fuel depolymerization are explicitly discussed. The resolution appears to be through the postulate of (surface) oxidative degradation of the fuel. Experiments are initiated to study the fuel degradation in mixtures of nitrogen/oxygen in the 99.9%/0.1% to 98%/2% range. The overall hybrid combustion behavior is studied in a 2"-diameter rocket motor, where a PMMA tube is used as the fuel. The novel results of this study include detailed, real-time infrared video images of the combustion zone. Space- and time-averaged images give a broad indication of the temperature reached in the gases. A brief outline is shown of future work, which will specifically concentrate on the exploration of the role of the oxidizer transport to the fuel surface, and the role of the unburned fuel that is reported to escape below the classical time-averaged boundary-layer flame.

Nomenclature

\[ \begin{align*}
  a, b & \text{Coefficients of the regression rate} \\
  B & \text{Mass transfer number; coefficient of reaction} \\
  C_f & \text{Local skin-friction coefficient} \\
  C_p & \text{Mean specific heat} \\
  C_H & \text{Stanton number} \\
  D & \text{Depolymerization energy} \\
  E & \text{Activation energy} \\
  h & \text{Enthalpy} \\
  k & \text{Heat conductivity} \\
  M & \text{Molecular weight} \\
  \text{Re} & \text{Reynolds number}
\end{align*} \]

\[ \begin{align*}
  \theta & \text{Reduced activation energy} \\
  \mu & \text{Viscosity} \\
  \rho & \text{Density} \\
  \epsilon & \text{Emissivity} \\
  \alpha & \text{Absorptivity} \\
  \tau & \text{Shear stress} \\
  \sigma & \text{Stefan-Boltzmann constant}
\end{align*} \]

Subscripts

\[ \begin{align*}
  e & \text{Free stream flow} \\
  \text{o} & \text{Without blowing} \\
  \text{\theta} & \text{Solid phase} \\
  \text{ox} & \text{Oxygen} \\
  s & \text{Stagnation state} \\
  \text{TD} & \text{Degradation} \\
  \text{w} & \text{Condition at wall} \\
  \infty & \text{Free stream}
\end{align*} \]

Introduction

A controllable, flexible, and safe propulsion system is needed for space missions. As compared with solid and liquid rockets, the hybrid rocket has become a very important candidate for use as a propulsion system. The hybrid rocket is potentially important because it has the promise of combining many of the advantages of both liquid and solid rockets. The configuration of the hybrid rocket engine is basically similar to that of a solid rocket, except that the former uses solid fuels instead of solid propellants. Also, in the hybrid rocket, the oxidizer is stored in the tank in liquid form.

Solid rocket boosters have failed catastrophically in 1985 and 1986 during launches of the Titan and STS-Challenger. The failures were caused by defects in case bonding and a leak in the combustion chamber wall, respectively.\(^1\) In the hybrid propulsion system, the combustion chamber contains only the solid fuel, while the liquid oxidizer is stored in a tank and injected through a feed system into a
combustion channel inside the solid fuel. The hybrid rocket does not rely at all on case bonding.

In solid rockets, a small leak in the chamber wall results in the immediate ignition (followed by self-sustained combustion) of all propellant surfaces along which the leakage gases flow. The same situation in hybrids would cause an extremely fuel-rich flow, with hardly any widening of the leakage flow path, because hybrid combustion occurs along well oxidizer-ventilated surfaces only. Therefore, the hybrid is much safer than solids. Because of the volatility and flammability of liquid fuel (such as liquid hydrogen) in the liquid rocket, it is not hard to imagine how much more dangerous the liquid rockets are than the hybrids would be.

The controllability (including restart) of the propulsion system is very important for space missions. In the solid rocket, it is almost impossible to stop or restart the combustion after the ignition of the rocket. Since the oxidizer and fuel are not cured together in the hybrid rocket as in the solid rocket, where the oxidizer is stored in a tank, we may control the combustion of the hybrid rocket by controlling the flow of the oxidizer. Also, we may achieve stop and restart of the hybrid rocket. It is well known that achievement of controllability of the liquid rocket is gained at a great loss of simplicity in liquid rocket systems. Consequently, the comprehensive property of controllability, flexibility, and safety makes hybrid rockets a very important, promising propulsion system for use in future space missions.

Selection, formulation, and processing of fuel alone are far simpler tasks than the same for solid propellant binders, where the interactions with various solid ingredients (oxidizer particles) must be considered. In addition, the fuel requirements are relaxed for the hybrid; this means that many variations are possible. All of these ultimately translate into cost savings. Since the oxidizer is a very well studied and abundantly available liquid/gaseous component (contrasted with specially prepared solids like AP), the cost comparisons have shown a dramatic factor of 30 improvement compared to state-of-the-art solid propellants.$^1$

A completely different stimulus for the study of hybrids is provided by studies of future space missions that intend to use local in-situ resources (ISRU). Efforts are underway to manufacture/extract oxygen at extraterrestrial sites. The utilization of this oxygen in the simplest form, a gas generator, is likely to be a simple hybrid device. Another stimulus has recently come from the applicability of a hybrid motor as a test bed for materials testing; materials compatibility, high-temperature stability, nozzle survivability, liner/insulation performance, etc., can all be tested with a hybrid as a gas generator. Wide variations in gas temperature, composition, and oxidizer/fuel are possible; also, wide variations in pressures and flow rates are easily achieved without the inconveniences/dangers of instability, extinction, or costly propellant tailoring programs (that will be necessary if we were to rely on solid propellant rockets for these purposes).

These advantages of controllability, safety, reliability, wide-tolerance fuels, cost, and potential instability-free combustion have not gone unrecognized. Programs to exploit these advantages are underway.$^2-5$ It is apparent that solving many of the remaining problems can quickly result in easy acceptability of the hybrids. Attempts at building operational hybrids, without really understanding their fundamentals, can lead to unfortunate setbacks,$^6$ besides casting needless doubts on the fundamental technological feasibility itself. Many of these types of unnecessary negative images will dissolve away in a well-planned program that clearly identifies specific deficiencies in our understanding of hybrids. One possible matrix that identifies the specifics in one, albeit important, aspect of hybrids (namely, the fuel burning rate or, more generally, combustion) is shown in Table 1. It is seen that simple theories based upon gas-phase heat transfer limited combustion can explain the experimentally observed performance at low flow rates and high pressures (see, for example, Marxman and Gilbert$^7$ and Marxman$^8$), but fail at higher flow rates and lower pressures.$^9,10$ Invoking slow gas-phase chemical kinetics$^8,11$ can explain the pressure dependence, but is hardly the final resolution since unrealistic numerical values are needed for this process. Similarly, thermal degradation of the fuel polymer in an inert atmosphere (not the hybrid environment) can be treated in detail and can be shown to match experimental data trends and numerical values as long as the experiments are conducted in an inert atmosphere (hot plate, for example).$^{12}$ Earlier skepticism$^{13,14}$ concerning the applicability of these low heating rate data (from hot plate pyrolysis studies) to high heating rate environments in hybrids was allayed through
Table 1. Hybrid theories.

<table>
<thead>
<tr>
<th>Theories Based Upon</th>
<th>Can Explain</th>
<th>Cannot Explain</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Gas-phase heat transfer</td>
<td>Burning rate at low flow rates</td>
<td>Burning rate at high flow rates</td>
</tr>
<tr>
<td>( r \propto (\rho U)^{0.8} )</td>
<td>high pressures</td>
<td>low pressures</td>
</tr>
<tr>
<td>• Gas-phase kinetic postulates</td>
<td>Burning rate at low pressures (with unreasonable constants)</td>
<td>Burning rate at low pressures (with known constants)</td>
</tr>
<tr>
<td>( \dot{m}'''' \propto [F] [O] P^n Ke^{-E/RT} )</td>
<td>Pyrolysis rate in inert atmospheres</td>
<td>Pyrolysis in reactive atmospheres</td>
</tr>
<tr>
<td>• Condensed-phase (fuel) thermal degradation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \frac{dN}{dt} = -NB e^{-E/RT} )</td>
<td>Fuel burning rate in reactive atmospheres</td>
<td>&quot;Saturation&quot; effect</td>
</tr>
<tr>
<td>• Oxidative degradation of fuel</td>
<td>Pressure sensitivity</td>
<td>Unburned fuel</td>
</tr>
<tr>
<td>( \frac{dN}{dt} = -[O]NB e^{-E/RT} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• [ ]</td>
<td>Full hybrid range</td>
<td>[ ]</td>
</tr>
<tr>
<td></td>
<td>Scale-up rules</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Transients</td>
<td></td>
</tr>
</tbody>
</table>

systematic use of the fundamental data in accurate mathematical formulations rather than in simple-minded "extrapolations." Introduction of oxidative degradation as a pyrolysis augmentation mechanism at the fuel surface not only explained the possible burning rate phenomenon but also accounted for the pressure sensitivity at high flow rates. Despite its "consistency checks," a quantitative theory including oxidative degradation has not yet been developed. Many recent studies (see, for example, Korting et al.)15 have added valuable experimental data to the hybrid literature, but have not developed the complete picture. For example, one self-consistent theory should be able to explain the fuel pyrolysis behavior in both inert and reactive environments, explain the burning rate behavior at low and high flow rates and low and high pressures, and predict verifiable scaling rules, besides accurately predicting the combustion efficiency (unburned fuel fraction). We should not have to resort to different theories, or mechanisms, to explain different facets of the same phenomenon.

After identifying the various facets of the hybrid rocket, the "big picture" is shown in Fig. 1. The most important unanswered question is, "What is the rate of oxidizer transport to the fuel surface at various values of pressure and flow rates?" Also important is the question of time-averaged flame temperature in the boundary layer at various pressures and flow rates. These will be input to a comprehensive theory of hybrid operation and will be verified quantitatively through experiments on static rockets of several scales.

In 1963, Marxman and Gilbert7 proposed a heat transfer limited model for the hybrid rocket combustion (Fig. 2). In the heat transfer controlling model, the mass transfer number of Spalding16, \( B = (\rho v \nu)/(\rho_u u) \cdot 1/2 C_f \), is a very important parameter which represents the effect of mass addition on the velocity profile, the Stanton coefficient, and the boundary thickness in the boundary layer. It is very hard to determine this important number in Marxman and Gilbert's model.

In the heat transfer model, the diffuse process is considered as the key process that will control the hybrid combustion. However, it has long been recognized that, in certain situations, the kinetics of gas-phase, heterogeneous, or solid-phase reaction may influence or even control the burning rate.7,17 The experimental results, particularly those of Smoot and Price,9,10 have delineated the conditions under which the diffuse-limited model (heat transfer limited model) becomes inadequate. Much work has been done on the importance of
AIMS: BETTER UNDERSTAND
HYBRIDS, DEVELOP ECONOMICAL
DESIGN TOOLS

EVOLVE BEST USE OF OXIDIZER IN ISRU

FUEL TAILORING
- BASIC TGA, DSC STUDIES
- "SEED" FUEL WITH ADDITIVES
- QUALITY CONTROL CRITERIA

TURBULENT B-L THEORY
- 5-0-A 3-D CODES
- CONCEPT OF "LOCAL" (MICROSCALE) COMBUSTION
- CONCEPTS OF TRIPLE CORRELATION AND LOCAL EXTINCTION

FUEL COMBUSTION
- PYROLYSIS THEORIES
- 2-D EFFECTS
- OXIDATIVE DEGRADATION

ROCKET EXPERIMENT

MODERN DIAGNOSTICS
- COLOR CODED IR VIDEO
- MICRO FIBEROPTICS AND MICROCHIPS IN FUEL
- IMAGE PROCESSING

OUTPUTS
- COMBUSTION EFFICIENCY
- DETAILED r VS X PLOTS
- EFFICIENT IGNITION OF FUEL
- HYBRID AS A TEST-BED GAS GENERATOR (THROTTLEABILITY, DIFFERENT GASES, ...)
- MATERIALS COMPATIBILITY
- BETTER HIGH-TECH DESIGNS

SCALE-UP RULES
- ECONOMY, SAFETY

Fig. 1 Hybrid rocket research plan.
What we want to do is to explore the role of the oxidizer transport to the fuel surface and the role of the unburned fuel that is thought to escape below the classical time-averaged boundary layer flame in order to obtain detailed distributions of the concentration and temperature in the boundary layer. We also want to find a better way of explaining the pressure dependence of the regression rate so the predicted regression rate can be compared with experimental results. This will then enable the design of a better hybrid propulsion system.

At present, we are working on an experimental hybrid rocket that consists of two plexiglass tubes. The inner one is used as the fuel tube, and the outer tube as a holder which fixes the inner tube and takes the pressure. The gaseous oxidizer is fed into the combustion channel of the inner tube from the head of the rocket. The fuel tube can be various polymeric fuels; for the time being, we just use PMMA as the fuel tube because it is easy to make comparisons with the extensive early data.

In order to understand the effect of the existence of oxidizer near the solid surface on the degradation of the solid fuel, we begin a TGA experiment using the mixture of nitrogen/oxygen in the range 99.9%/0.1% to 98%/2%. As pointed out by Marxman and Gilbert,7 the flame zone is the temperature discontinuity. In this paper, we intend to investigate the temperature distribution inside the boundary layer under different pressures using an advanced real-time infrared camera. These images are easily computer processed for high-lighting zones.

In light of all the limitations of the present work, the worthwhile contributions are thought to be as follows: the experimental investigation of the degradation of the PMMA under small concentrations of oxidizer, which is helpful for grasping the key process in the hybrid combustion, and the use of a real-time infrared camera for understanding the transportation process in the boundary layer.

**Hybrid Combustion Theory**

The heat transfer limited model, based on an idealized turbulent boundary layer combustion, was presented by Marxman and Gilbert7 in 1963. It is assumed that combustion occurs in a relatively thin flame zone within the boundary layer above the sublimating surface (Fig. 2). Because of the reaction in the boundary layer flame zone and the mass addition from the solid surface, the flow is easily transferred from laminar flow to turbulent flow. Therefore, the hybrid boundary layer was treated as turbulent over the entire length.

By assuming that the hybrid regression rate is controlled by the heat transfer from the flame to the fuel surface, it is shown that

\[ \rho_f \dot{r} = (\rho v)_w = \dot{Q}_w / \Delta H, \]  

where \( \rho_f \) is the density of solid fuel, \( \dot{r} \) is the linear regression rate of the fuel surface, \( (\rho v)_w \) is the gas phase mass flux of fuel at the fuel surface, \( \dot{Q}_w \) is heat transfer per unit area to the wall, and \( \Delta H \) is the effective heat of gasification of the solid fuel; and

\[ \dot{Q}_w = \frac{h}{C_p} \frac{\partial h}{\partial y} \bigg|_w = C_{H0} \frac{C_H}{C_{H0}} \rho_c U_c (h_{cs} - h_{wg}). \]

where \( C_{H0} \) is the Stanton number in the absence of blowing, \( U_c \) is the axial mass flux at the combustion layer, \( h_{cs} \) is the stagnation enthalpy at the flame, and \( h_{wg} \) is enthalpy at the wall in the gas phase.

The reduction in heat transfer to the wall caused by blowing is accounted for by the ratio \( C_H / C_{H0} \). The relation between \( C_H / C_{H0} \) and the mass transfer number B is as follows:

\[
C_H / C_{H0} = \begin{cases} 
1.2 B^{-0.7} & 5 < B < 95 \\
\ln(1.0 + B)/B & B < 5 
\end{cases}
\]  

In the diagram:
Let \( L_e = P_f = 1 \). Reynold's analogy then holds across the entire boundary and is expressed by the equation

\[
- \frac{\dot{Q}}{\partial \tau} = \frac{\tau}{\partial U/\partial y},
\]

where \( \dot{Q} \) is heat flux and \( \tau \) is shear stress. Therefore, the relation between the Stanton number and the friction coefficient, consistent with the combustion, is obtained as

\[
C_H = \frac{1}{2} C_f \left( \frac{\rho_e U_e^2}{\rho_c U_c^2} \right). \tag{5}
\]

Marxman then postulated that the friction coefficient in the hybrid combustion is approximately the same as that for an ordinary boundary layer with equivalent blowing. Therefore,

\[
C_{t0} = 2cRe_x^{-0.2} Pr^{-2/3} \tag{6}
\]

and for \( Pr = 1.0 \)

\[
C_{H0} = cRe_x^{-0.2} \left( \frac{\rho_e}{\rho_c} \right) \left( \frac{U_e}{U_c} \right)^2, \tag{7}
\]

where \( c \) is a function of mainstream Mach number, which is about 0.03 for the low Mach numbers expected in the hybrid.

Combining equations (2) through (7), the closed form for the regression rate is obtained as follows:

\[
\dot{r} = \frac{cGRe_x^{-0.2}}{\rho_f} \frac{C_H}{C_{H0}} \frac{U_e}{U_c} \frac{h_{ce} - h_{wx}}{\Delta H}
+ \frac{\sigma_{\infty} (\varepsilon g T_c^4 - \varepsilon g T_w^4)}{\rho_f \Delta H}. \tag{8}
\]

The last term on the right-hand side is the result for consideration of radiation heat transfer in the boundary layer.

The regression rate expression reflects the fact that convective and conductive heat transfer to the surface is governed by the aerodynamics of the turbulent boundary layer. It is shown that the regression rate is proportional to \( G^{0.8} \) and is also a function of the position along the tube, but not of pressure. From the measured result, \(^9\) it is not hard to see that the model works well in the low specific mass flux region but cannot match the experimental result at high mass flux.

Ramohalli and Stickler\(^{12}\) proposed a pressure sensitive model for the hybrid combustion. In this model, it is thought that the solid fuel will be depolymerized into small fragments instead of monomers. So, the concept of fragment size vaporizing (FSV) arises. The determination of FSV as shown by Ramohalli\(^20\) is

\[
FSV = \frac{32.8}{M} p^{-0.2615} \exp(3.67 \times 10^{-3} T_w). \tag{9}
\]

He postulated that the regression rate is governed by the surface degradation. The reaction subsurface thermal depolymerization is supplemented by surface depolymerization by active species. These active species may be unburned oxidizer that was transported to the surface through bulk turbulent eddy transport across the classical time-averaged "flame sheet." The pressure enters the control function through its effect on the concentration of the active species near the surface.

Based on the energy and backbone conservation equations,

\[
\frac{d}{dx} \left[ k \frac{dT}{dx} + \rho c \frac{dT}{dx} \right] = D \rho NB_{TD} \exp(-E_{TD}/RT) \tag{10}
\]

when \( x = 0, T = T_w \); when \( x = \infty, T = T_0 \)

\[
- \frac{dN}{dt} = NB_{TD} \exp(-E_{TD}/RT) \tag{11}
\]

when \( x = 0, N = N_{w} \); when \( x = \infty, N = 1.0 \).

the regression rate for the hybrid combustion for the large activation energy fuel is obtained as follows:

\[
\dot{r} = \left[ \frac{k}{\rho c} B_{TD} \exp(-E_{TD}/RT_w) \right] \left[ \frac{D}{c(T_w - T_0) + 1} \right] \tag{12}
\]

\[
\cdot \left[ \frac{E_{TD}}{RT_w} \left[ \frac{D}{c(T_w - T_0) + 1} \right] \right]^{1/2},
\]

\[
\cdot \log \left[ \frac{FSV}{FSV - 1} \right] \frac{D}{c(T_w - T_0)FSV} \]

\[
\cdot \left[ \frac{E_{TD}}{RT_w} \left[ \frac{D}{c(T_w - T_0) + 1} \right] \right]^{1/2}.
\]
From this expression, the pressure dependence of the regression rate is easily seen through the pressure dependence of FSV.

In this pressure sensitive model there is no region of hybrid combustion that can be considered fully pressure independent. The dependence relationship of the reduced regression rate, \( r = \frac{\dot{t}}{\dot{t}_\infty} \frac{G_\infty^n}{G^n} \frac{\rho_n (P_{Tf}/P_\infty)}{\ln[(P_{Tf})/(P)]^{1/2}} \) and reduced mass flow rate \( \dot{G} = \frac{G}{G_\infty} \frac{P_\infty}{P_{ox}} \) is shown by Ramohalli and Stickler\(^{12}\) (their fig. 6). It is shown that \( \dot{r} \) is constant in the conventional pressure-independent region and that \( P \) is linear in the conventional full-pressure region and decreases with the reduced mass flux \( \dot{G} \).

For the comparisons of the heat transfer limited model and the pressure sensitive model, we calculated the dependence of \( \dot{r} \) on \( T_w \) (Fig. 3). From these results, it is seen that there is serious inconsistency between the two methods, which leaves us a lot of opportunity to develop and perfect the hybrid combustion theory. It is challenging to study the depolymerization of the solid fuel under small concentrations of active species.

In order to study the boundary layer in detail, an adequately thick boundary layer is desired. In our design of the hybrid rocket, the thickness of the turbulent flow is about 10 mm for the wide variations of working conditions. A schematic of the rocket is shown in Fig. 4. In this rocket, a wide range of specific mass flux is achieved through the adjustment of the throat diameter of the nozzle. The range of the mass flux is 0.01 lb/sec-in\(^2\) to 0.4 lb/sec-in\(^2\). The corresponding pressure is 20 to 70 psi. The throat diameter may be adjusted if a wider range of pressure is needed.

Fig. 4 Schematic of the experimental rocket.

**Procedure and Measurement System**

Once the apparatus was actually constructed, the main experimental procedure was to make sure everything was connected and tight. The outside of the burned tube was coated with silicon grease so that it would not bond with the larger tube, as happened before. Also, some coating is needed for the nozzle throat in order to prevent erosive damage.

When the oxidizer flows over the solid surface, the oxidizer will diffuse through the boundary layer and the vapor of solid fuel after
sublimation will diffuse toward the oxidizer free stream, also. There is a combustion zone in the boundary layer. Temperature discontinuity was assumed by Marxman and Gilbert. Here, we use an infrared camera to measure the temperature distribution in the boundary layer. We also use two pressure transducers, which are mounted on the head and aft to investigate the history of the pressure during the rocket firing. The measurement system is shown in Fig. 5.

Fig. 5 The measurement system.

**Results and Discussion**

It is thought that the chemical kinetic rate of degradation of the fuel PMMA in the presence of small concentrations of oxidizer species may hold the key to a complete understanding of hybrid combustion. The experiments were initiated to study this degradation in the mixture of nitrogen/oxygen in the range of 99.9%/0.1% to 98%/2%. The temperature in the experimental sample of PMMA was kept at 600 to 700°K, which is the temperature in the rocket firing. At the present time, only two experimental results are available which cannot be explained convincingly.

As the preliminary study for the mechanism of the hybrid combustion, it was necessary to investigate the species concentration and temperature distribution. An advanced infrared camera was used to measure the temperature under different chamber pressures, which could be changed from 20 to 70 psi. Due to the difficulty of transparency of the PMMA to infrared waves, the results were not satisfactory. Hopefully, we may obtain more successful results after more trials.

At the time of this writing (April 1990), the following sub-tasks have been accomplished:

1. The motor has been designed and built.
2. Cold flow tests have been completed.
3. Initial runs have been made.
4. Infrared pictures have been taken.
5. PMMA degradation tests have been made.

**Summary and Future Work**

Based on the experimental investigation of the hybrid rocket, we can make the following conclusions:

1. The experimental system can achieve wide working conditions of pressure, specific mass flux, and oxidizer and fuel composition.

2. The time-averaged temperature in the boundary layer is independent of the mean oxidizer flow rate and the operational pressure (Table 2).

3. The observations tend to support the view that in hybrid combustion the surface reaction (in the small concentration of oxidizer) is important to the regression rate of the solid fuel.

4. A convincing mechanism of the full hybrid operation has not been developed yet.

Future work includes the investigation of the distribution of the small concentration of oxidizer near the solid surface and the investigation of the transport of the oxidizer in the boundary layer in order to determine the effect of the oxidizer on the pyrolysis of the solid fuel. Through these investigations we will hopefully get a clear understanding of the mechanism of the hybrid combustion and be able to propose a better design of the hybrid rocket.

**Acknowledgments**

The authors are grateful to Milton Schick for his help in the construction of the hybrid rocket. We are indebted to Dr. Shadman and Yi Zhao for their work on the measurement of the PMMA degradation in small concentrations of oxygen, and to the Department of Aerospace and Mechanical Engineering, The University of Arizona, for their support.
Table 2. Boundary layer mechanics.

<table>
<thead>
<tr>
<th>Species Transport</th>
<th>Heat Transfer</th>
<th>Oxidizer</th>
<th>Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>• To fuel surface from combustion zone</td>
<td>• To combustion zone from free stream</td>
<td>• To combustion zone from surface</td>
<td></td>
</tr>
<tr>
<td>• Convection</td>
<td>• Radiation</td>
<td>• To fuel surface across time-averaged &quot;flame&quot; zone</td>
<td></td>
</tr>
<tr>
<td>• During transients</td>
<td>• Ignition</td>
<td>• Unburned and escape below time-averaged &quot;flame&quot; zone</td>
<td></td>
</tr>
<tr>
<td>• Instability?</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

References


