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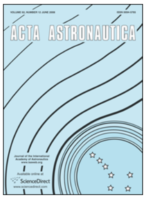

Measurement of regression rate in hybrid rocket using combustion chamber pressure

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ABSTRACT

An attempt was made in this paper to determine the regression rate of a hybrid fuel by using combustion chamber pressure. In this method, the choked flow condition at the nozzle throat of the hybrid rocket was used to obtain the mass of fuel burnt and in turn the regression rate. The algorithm used here is better than those reported in the literature as the results obtained were compared with the results obtained using the weight loss method and was demonstrated to be in good agreement with the results obtained using the weight loss method using the same motor and the same fuel and oxidizer combination. In addition, the O/F ratio obtained was in good agreement with those obtained using the weight loss method. The combustion efficiencies obtained were in good agreement with the average values.

1. Introduction

A hybrid rocket is basically the combination of solid and liquid rocket engines. In this fuel is in solid phase and oxidizer is either in liquid or gaseous phase. It has many advantages over solid and liquid rocket engines, which has been explained in Sutton and Biblarz [1], Altman and Holzman [2] and also available in the review paper by Pastrone [3].

In a hybrid rocket, regression rate is the key parameter and the measurement of regression rate itself is a matter of concern, which needs major attention. It is due to non-linear burning of fuel with burn time. Various methods have been used by the researchers to determine the regression rate of hybrid rocket fuel such as ultrasonic technique [4–12], X-ray radiographic technique [7,9,13–15], and weight loss method [16–27]. In an ultrasonic technique, an array of transducers will be needed to get the complete regression rate, which would increase the overall cost and complexity of the set up. The X-ray radiographic technique uses sophisticated equipment and requires skilled man-power for its operation. These increases the overall cost of the system. The weight loss method [16–27] is the most widely used method to determine the regression rate. The drawback of this method is that to get a complete trend line of regression rate vs G_{ox}, a series of experiments need to be carried out.

An alternate method has been conceived by researchers [28–31,12] to obtain the regression rate of a hybrid fuel, which could be simpler and accurate. Here, the combustion chamber pressure is used to obtain the regression rate of the fuel. It has advantage over the weight loss method such that in a single experiment, it can give the complete trend line of regression rate vs oxidizer mass flux (G_{ox}). In this method, the relations for the chocked flow through the nozzle are used to obtain the regression rate using

$$\dot{m}_{ox} = \frac{c_{ds} P_s A_{ts}}{C^{\star}_{ox}} \tag{1}$$

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Nomenclature

A_t	throat area of nozzle at combustion chamber, m^2
A_{ts}	throat area of nozzle at settling chamber exit, m^2
a	empirical constant
c_{ds}	coefficient of discharge at the exit of the settling chamber
$C^\star$	characteristic velocity, m/s
$C^\star_{ox}$	characteristic velocity of oxidizer, m/s
$C^\star_{expt}$	experimental characteristic velocity, m/s
$C^\star_{theo}$	theoreitical characteristic velocity, m/s
d_p	port diameter, mm
d_t	nozzle throat diameter, mm
$d_p(i)$	port diameter at the ith time step,, mm
$d_{p(i+1)}$	port diameter at the $(i+1)$th time step, mm
G_{ox}	oxidizer mass flux, g/cm^3 s
L_g	length of fuel grain, m
$L^\star$	characteristic length, m
M_f	total mass of fuel burnt, g
M'_f	total mass of fuel burnt calculated, g
$\dot{m}_f$	mass flow rate of fuel, g/s
$\dot{m}'_f$	mass flow rate of fuel after first iteration, g/s
$\dot{m}_{ox}$	mass flow rate of oxidizer, g/s
$\mathcal{M}_p$	molecular mass of burnt product
$\mathcal{M}_{ox}$	molecular mass of oxidizer
n	mass flux exponent
O/F	oxidizer to fuel ratio
P_s, P_1, P_2	settling chamber pressure, bar
P_c, P_3	combustion chamber pressure, bar
$\overline{p}_c$	average chamber pressure, bar
R_u	universal gas constant
$\dot{r}$	regression rate, mm/s
T_c	combustion chamber temperature, K
T_{ox}, T_s	settling chamber temperature, K
V_c	combustion chamber volume, m^3
ρ_f	density of fuel, kg/m^3
Δt	time step, s
ϕ	equivalence ratio
ϕ'	equivalence ratio after any iteration
γ_{ox}	specific heat ratio of oxidizer
γ_p	specific heat ratio of burnt product
η	combustion efficiency

$$C^\star_{ox} = \frac{1}{\Gamma_s(\gamma_{ox})}\sqrt{\frac{R_u T_{ox}}{\mathcal{M}_{ox}}} \tag{2}$$

$$\Gamma_s(\gamma_{ox}) = \sqrt{\gamma_{ox}}\left[\frac{2}{\gamma_{ox}+1}\right]^{(\gamma_{ox}+1)/2(\gamma_{ox}-1)} \tag{3}$$

$$\dot{m}_f = \frac{P_c A_t}{C^\star} - \dot{m}_{ox} \tag{4}$$

$$C^\star = \frac{1}{\Gamma_c(\gamma_p)}\sqrt{\frac{R_u T_c}{\mathcal{M}_p}} \tag{5}$$

$$\Gamma_c\left(\gamma_p\right) = \sqrt{\gamma_p}\left[\frac{2}{\gamma_p+1}\right]^{(\gamma_p+1)/2(\gamma_p-1)} \tag{6}$$

$$\dot{r} = \frac{\dot{m}_f}{\pi \rho_f d_p L_g} \tag{7}$$

$$G_{ox} = \frac{4\dot{m}_{ox}}{\pi d_p^2} \tag{8}$$

$$d_{p(i+1)} = d_{p(i)} + 2\dot{r}\Delta t \tag{9}$$

Eq. (4) is used to calculate the mass of fuel burnt knowing the combustion chamber pressure, $C^\star$, nozzle throat area, mass flow rate of oxidizer (Eq. (1)) and it is further used to calculate the regression rate using Eq. (7).

Earlier, this method was used by Osmon [28] to obtain the regression rate of lithium aluminum hydride fuel using a motor of length 500 mm. He had used Eqs. (4) and (7) to determine the regression rate. The $C^\star$ used by him was an averaged value for the entire burn time, but in an actual case it changes with burn time as the O/F ratio changes. Wernimont [29] had used a method similar to the one used by Osmon [28] to get the regression rate of polyethylene fuel. They attempted to compute the variation of $C^\star$ with burn time by assuming a linear change in throat area with burn time. The regression rate obtained by them does not follow any trend line and they even observed a decrease in regression rate with the increase in oxidizer mass flux. George et al. [30] used this method to obtain the regression rate of HTPB based fuel. Their algorithm is an improvement over that used by Osmon [28], in which they account for the variation in O/F ratio with burn time by calculating the $C^\star_{theo}$ based on the instantaneous value of O/F. They also have taken the additional care of matching the mass loss of fuel obtained from their calculation with those experimentally obtained at the end of combustion. Fig. 1 shows the comparison of regression rates for HTPB and oxygen combination obtained by various investigators [23,1,9,30–34,14,20]. The geometry of the motor used is a significant contributor to the variation seen in Fig. 1. Considering this, it would be appropriate if the comparison of the regression rate obtained by using the pressure time curve is made against an accepted technique using the same motor. But George et al. [30] have not compared it in this fashion but have compared their results with those obtained by Strand et al. [32]. This does not look appropriate, as results obtained by Strand et al. [32] were at lower G_{ox}($3–8\ g/cm^2$ s) and most of the results obtained by George et al. [30] are at higher G_{ox} ($6–32\ g/cm^2$ s).

Apart from this, the mass flux exponent (n) reported by them for pure HTPB fuel was 0.53, which is close to 0.5. This means that the O/F ratio is nearly a constant with burn time. But the O/F ratio reported for this case by George et al. [30] shows a variation from 5.5 to 7.5 with burn time.

Risha et al. [31] have used an alternate method to determine the regression rate using combustion chamber