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Thrust Modulation in Hybrid Rocket Engines

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An experimental investigation of hybrid rocket engines (HRE) is performed to study the throttling performance within a thrust range of 10:1. In order to improve the throttling properties over the entire thrust range, the method of secondary gas injection (gasification) was used. The injection gases were reactive (O_2) and inert (N_2). High-pressure tests were carried out up to 70 bar to increase the burning rate and the specific impulse. The standard fuel in this study was a composition of aromatic and cyclic amine with red fuming nitric acid (RFNA) as the oxidizer. Controllable, stable, and reproducible throttling properties were demonstrated down to 10% of thrust. The performance with gasification demonstrated the general feasibility of wide-range throttling with fixed-injection geometry. The paper outlines a method for calculating the ballistic behavior of hybrid propellant combinations that is based upon the regression characteristic and the effects of gasification.

Nomenclature

a	= regression constant
A	= area
c^*	= characteristic velocity
F	= thrust
$G = \dot{m}/A$	= mass flux
I_s	= specific impulse
$\dot{m}$	= mass flow
$O/F = \dot{m}_o/\dot{m}_f$	= mixture ratio
p_c	= chamber pressure
$\dot{Q}_{con}$	= convective heat flow
$\dot{Q}_{rad}$	= radiative heat flow
$\dot{r}$	= regression rate
t	= time
α	= pressure exponent
β	= mass flux exponent
γ	= characteristic velocity exponent
$\eta = c^*_{exp}/c^*_{th}$	= c^*-efficiency
ρ	= density

Subscripts

dp	= design point
exp	= experimental
f	= fuel
opt	= optimal conditions
o	= oxidizer
p	= fuel port
s	= fuel surface
th	= theoretical
t	= throat
tot	= total
$'$	= with gas injection
$\bar{}$	= averaged

Introduction

THE oxidizer and the fuel for an HRE are normally in different physical states. Usually the fuel is solid and the oxidizer is liquid. Hybrid rockets possess different characteristics than the pure liquid or pure solid motors that in some instances supply the motivation for their development. The mechanically simple hybrid motors have inherently good safety aspects of handling and operation since the grain is inert and has good mechanical properties. However, the HRE is somewhat more complicated than the solid-propellant rocket motor and its performance cannot match the performance of the liquid-propellant rocket, especially if the chamber pressure is lower than the level in the pure liquid rockets.

In this work, high-pressure tests up to 70 bar were conducted to improve the specific impulse and to observe the regression rate at high chamber pressures. Literature review revealed that no experiments have specifically been conducted at a pressure higher than 40 bar.

Thrust modulation, the main attraction of HRE, is much easier than in pure-liquid rockets since it can be controlled by varying only the oxidizer mass flow. The throttling range limits are defined by the appreciable performance losses that occur when operating at other than the design oxidizer flow rate. The losses are caused by variations in the oxidizer-fuel ratio and in the decrease of combustion efficiency when the operating conditions are changed.

In this study, an injection method was used that was very successful in improving the efficiency over a wide throttling range. The concept was to improve the atomization of the liquid oxidizer at reduced mass flows by introducing a secondary gas in the injection system (gasification). Beside the improvement in atomization, there are significant changes in the flow pattern. The ensuing strong turbulence causes increased mixing of the reactants with a corresponding improvement in combustion efficiency. The objectives for our investigation were to measure the efficiency improvement and the behavior of the mixture ratio with throttling.

The combustion process in a hybrid motor can be distinguished in two different regimes. The first regime at the entrance region is governed by fuel ablation and heterogeneous combustion at the interface[1-3] (Figs. 1 and 2). The second regime is characterized by homogeneous gas-phase reactions within the turbulent boundary layer.[4,5] Convective and radiation heat flux from the flame zone and the hot core to the solid surface fixes the fuel evaporation rate while the diffusion of the oxidizer and the fuel vapors to the combustion zone regulate the reaction products rate and the amount of heat released by the chemical reaction.

It is evident that a good knowledge of the overall regression rate of the solid fuel and its dependence on flow conditions, pressure, and temperature is mandatory for the design, performance prediction, and understanding of HRE.

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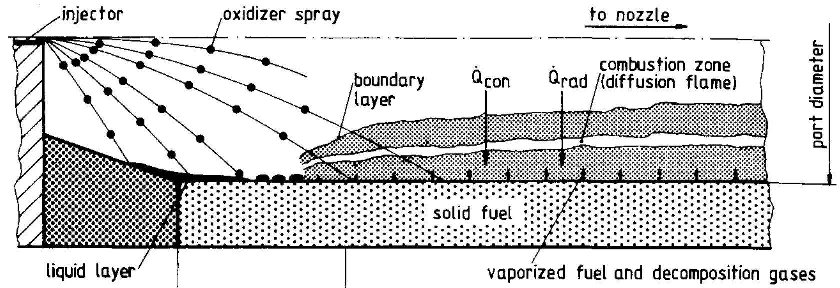

	entrance region	main combustion region
Dominant physical phenomena 1,2,3,4,5	non-equilibrium heterogeneous surface (degradation) reaction erosive ablation Langmuir adsorption desorption equilibrium	homogeneous gas-phase reactions in turbulent shear layers
Regression controlling mechanism	Reaction controlled pressure, temperature dependant	diffusion (transport) controlled mainly mass flux dependant

Fig. 1 Mode of combustion process in HRE.

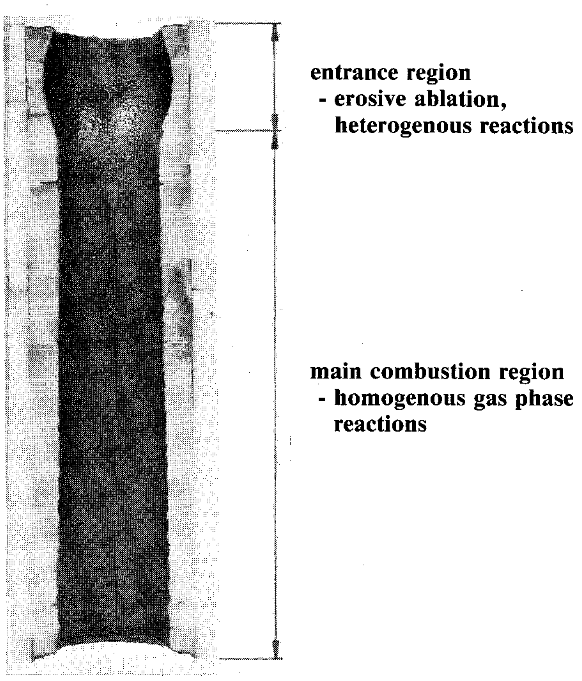

Fig. 2 Shape of the fuel grain after firing.

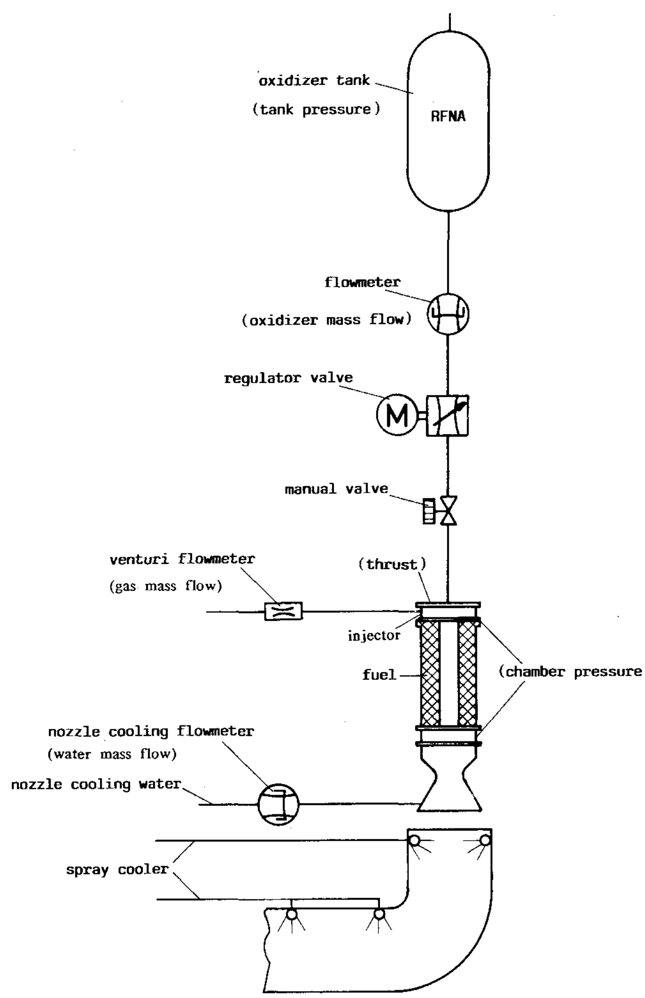

Fig. 3 Schematic of the test stand.

Experimental Hardware

Principal Components

The test hardware principal components consisted of an experimental HRE with the required auxiliary feed system and appropriate instrumentation for recording the data for test evaluation. Instrumentation consisted of pressure transducers, thermocouples, flow meters, and thrust transducers (Fig. 3).

The HRE is shown schematically in Fig. 4. The choice of materials for the apparatus was dictated mainly by the corrosive nature of the liquid oxidizer red-fuming nitric acid (RFNA) so that the components were fabricated of stainless steel. The exhaust nozzle was a water-cooled copper nozzle with a thin chromium layer that provided protection against the RFNA.

To provide good oxidizer atomization a swirl-injector design was chosen (Fig. 5). The atomizing gas could be varied from 0 to 0.3 $\dot{m}_o$.

Propellants

The first tests were conducted using the fuel UPTII. The composition is shown in Table 1. This fuel contains a toxical ingredient p-Toluidin with a high vapor pressure. Because there were no possibilities of isolating personnel from direct contact during production, this fuel type was eliminated as not desirable for baseline investigations.

UPTII without p-Toluidin, now called UTII, showed satisfactory behavior and was utilized for the final tests with gasification.

Results and Discussion

Regression Rate

The important parameter for the performance of a hybrid rocket motor is the fuel mass flow, which is determined by the area of the burning surface, the density of the fuel, and the regression rate

$$\dot{m}_f = A_s \cdot \rho_f \cdot \dot{r} \tag{1}$$

The regression rate is influenced by the combustion pressure, the total mass flux, and the temperature. Based upon these observations an empirical power law for the regression rate was formulated:

$$\dot{r} = a \cdot p_c{}^{\alpha} \cdot G_{\text{tot}}{}^{\beta} \cdot c^{*\gamma} \tag{2}$$

In many investigated propellant systems, the influence of pressure and temperature was neglected ($\alpha = 0$, $\gamma = 0$); in that case Eq. (2) may be reduced to a very simple form that is often used in the literature. These investigations show a particularly strong pressure influence. Thus, the pressure term in Eq. (3) is required:

$$\dot{r} = a \cdot p_c{}^{\alpha} \cdot G_{\text{tot}}\beta \tag{3}$$

Throttling Without Gasification

A problem with throttling is that the fuel flow from the grain does not vary in direct proportion with the flow of the oxidizer injected at the entrance. Consequently, the oxidizer-fuel flow ratio O/F will not remain constant over the throttling range. Because optimum performance occurs at a single given value of $O/F(O/F)_{\text{opt}}$, then, subsequently, a performance loss results from throttling.

The extent to which the fuel flow rate changes with the oxidizer flow rate is given by the regression characteristic [Eq. (3)]. This expression shows how the exponent values α and β affect the fuel flow and, hence, affect the performance. A detailed investigation of the interaction between the regression exponents is given in Ref. 6.

Figure 6 shows the regression rate for the first-investigated propellant system UPTII/RFNA. The empirical power law was obtained by a least square fit and the result listed in Table 1. For that fuel combination, throttling by reducing the oxidizer mass flow resulted in an increasing O/F value (Fig. 7). The performance subsequently decreased and the propellant remained unreacted in the combustion chamber.

Another important problem due to throttling is the decrease in combustion efficiency (Fig. 8). The diminished atomization at a lower oxidizer mass flow and the smaller turbulence level within the combustion chamber (low-mixing) result in a strongly reduced c^*-efficiency. For a 5:1 decrease in thrust magnitude, there results a nearly 40% decrease in c^*-efficiency that is intolerable.

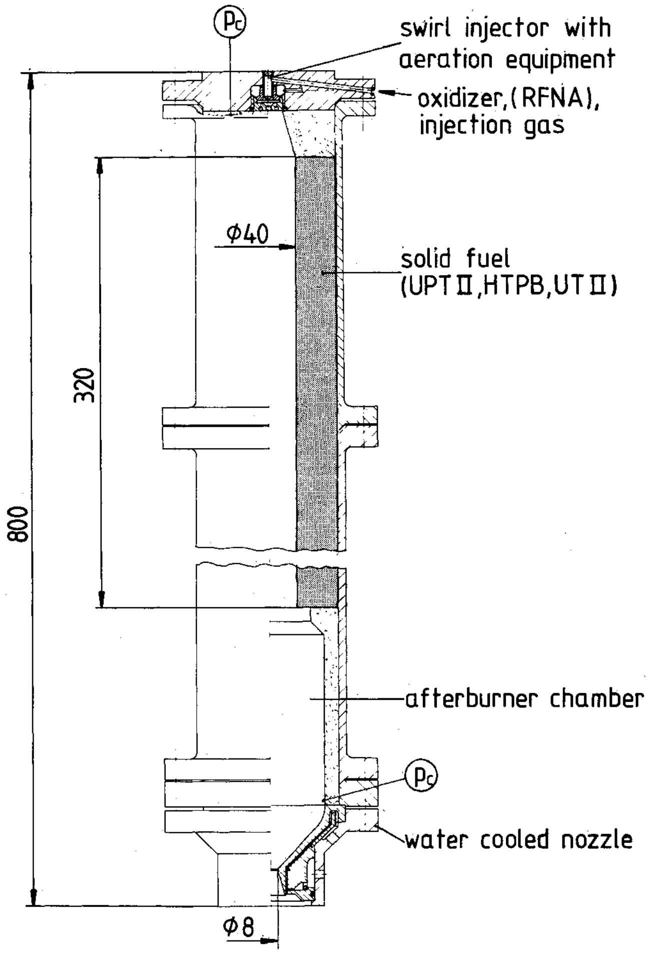

Fig. 4 Hybrid rocket motor schematic.

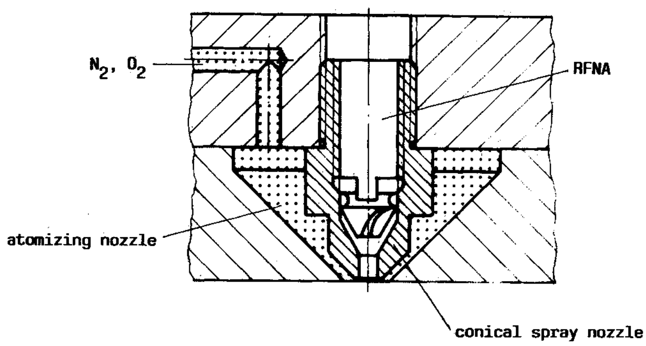

Fig. 5 Oxidizer injector.

Table 1 Propellant system and regression rate data

$\dot{r}$ (mm/s) /	p_c(bar) /	G_{tot} [g/(cm$^2\cdot$s)] /		$I_s(s)$ Standard expansion
Fuel	Oxidizer	Stoich. mixture ratio	Specific impulse	Regression-rate approximation
UPTII: 76% Urotropin 16% p-Toluidin 3% Ferrocen 5% Araldid	RFNA: 84% HNO_3 14% N_2O_4 2% H_2O	3.4	260	$\dot{r} = 0.022 \cdot p_c{}^{0.6} \cdot G_{\text{tot}}{}^{0.5}$
UTII: 92% Urotropin 3% Ferrocen 5% Araldid	RFNA: 84% HNO_3 14% N_2O_4 2% H_2O	3.2	262	$\dot{r} = 0.026 \cdot p_c{}^{0.55} \cdot G_{\text{tot}}{}^{0.5}$

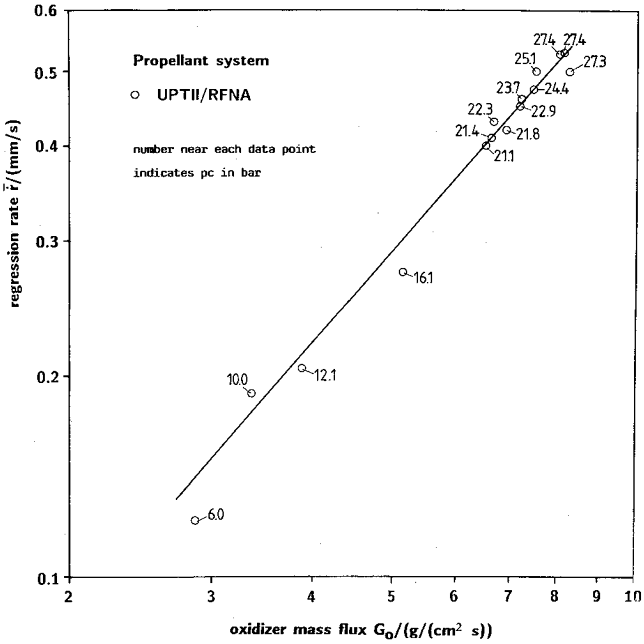

Fig. 6 Fuel regression characteristic due to throttling.

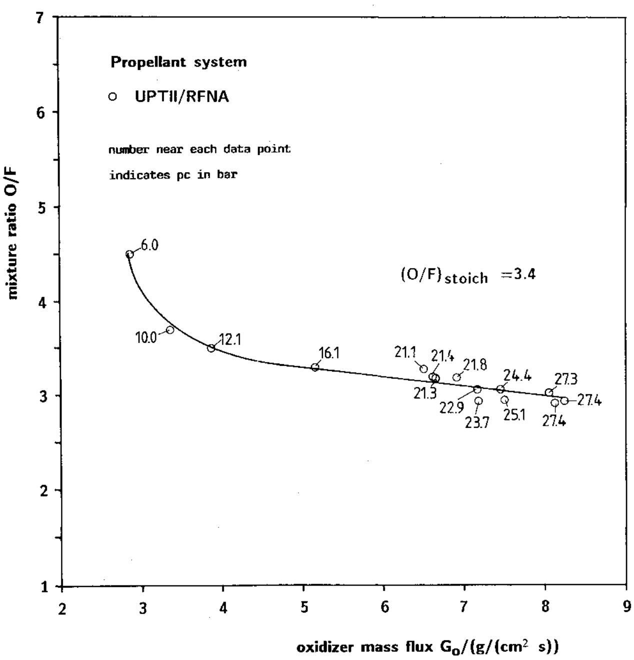

Fig. 7 Mixture ratio shift due to throttling.

Throttling with Secondary Gas Injection

The loss in c^*-efficiency during thrust modulation can be diminished or even avoided by injecting a gas at high speed together with the liquid oxidizer. The ensuing stronger turbulence level caused a high degree of flow mixing and improved atomization. In Fig. 9, the improvement due to increasing gas injection is shown in the spray pictures.

The effect of gasification also greatly increases the combustion efficiency. When gasification is started at a low-thrust level the c^*-efficiency is not much different from the design point, whereas without gasification a considerable loss in efficiency is observed (Fig. 10). The amount of injection gas necessary to improve efficiency depends on the mass flow of the liquid oxidizer. Above a certain amount of injection gas flow, which was quite small, there was no further improve-

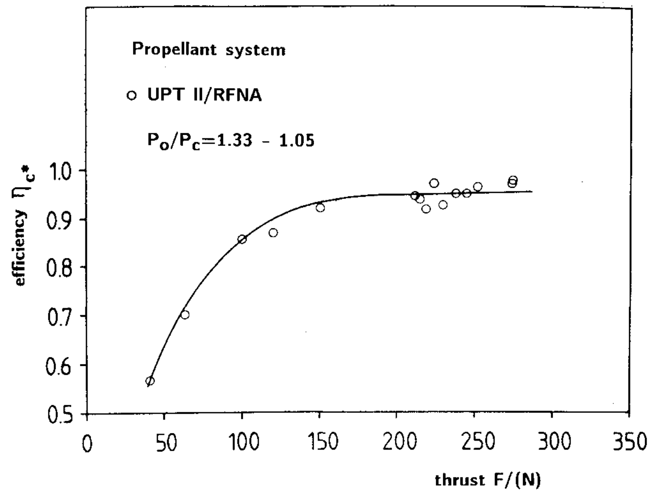

Fig. 8 c^*-efficiency reduction due to throttling.

ment in c^*-efficiency. For the investigated low throttling range, the maximum gas to oxidizer ratio was 0.2. The effect of different atomizing gases on c^*-efficiency showed no influence between introducing a reacting (O_2) and an inert (N_2) gas. The gas acts mainly on the oxidizer spray pattern. Reaction kinetic effects are apparently secondary.

Figure 11 shows the effect varying gasification during a test run. The pressure difference caused by stopped and restarted gasification can be split into two main parts, 1) the pressure increment caused by the additional mass flow and the change in the characteristic velocity,[7] and 2) the most important part, the pressure increment caused by a rise in c^*-efficiency. The improvement measured from the pressure step achieves nearly 30% in c^*-efficiency.

As another consequence of gasification, the flow parameters (velocity, temperature, concentration) have a flat profile (turbulent pipe flow). The resulting higher heat flux to the fuel surface increases the amount of fuel released. Tests with gasification show a regression rate up to 50% higher than without gasification (Fig. 12) that affects a shift of the mixture ratio (Fig. 13). For our test system, which tended to become oxidizer-rich (without gasification), there was a compensating effect. The ideal case would be that the mixture ratio remains constant or becomes the optimal value $[(O/F)_{opt}]$.

In connection with the thrust modulation, high-pressure tests were carried out. The reasons for increasing the chamber pressure were to increase the regression rate [see Eq. (2)] in addition to the improvement in specific impulse. An enhanced fuel release would be very advantageous for HRE design objectives because hybrids are regression-rate limited. Experimental tests with metal-loaded fuels[8,9] (greater pressure sensitivity) show that increasing the chamber pressure increases the regression rate until a certain limit is reached, at which point further increases in pressure have little or no effect. In order to find this region for the system UTII/RFNA, high-pressure tests were conducted up to the level of 70 bar (limitation of the experimental equipment). The results of the tests show only a weak decrease in pressure sensitivity so that the empirical power law for calculating the regression rate, which was first approximated at lower pressures, was still valid over the whole extended pressure range. The upper limit, where the pressure influences regression rate, was not reached.

Theoretical Investigation

Hybrid Internal Ballistics

The fuel mass flow may be expressed as

$$\dot{m}_f = \rho_f A_s \cdot a \cdot p_c^{\alpha} \cdot G_{tot}^{\beta} \cdot c^{*\gamma} \tag{4}$$

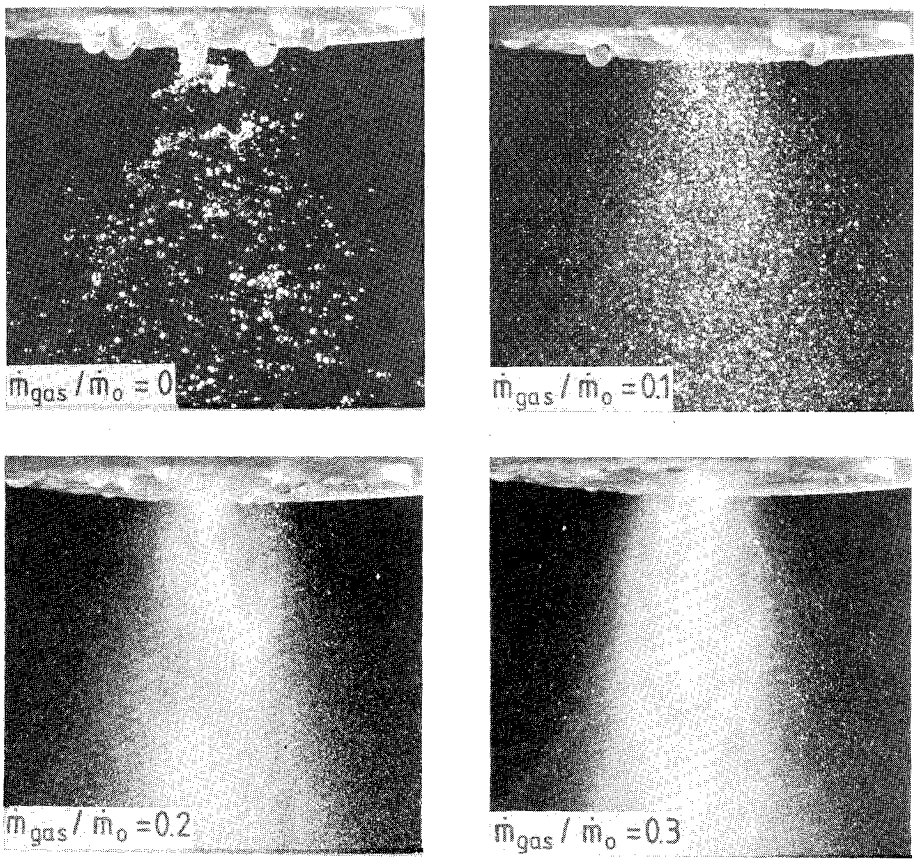

Fig. 9 Spray pattern evaluation for various injection gas ratios ($p_o - p_c \simeq 0.5$).

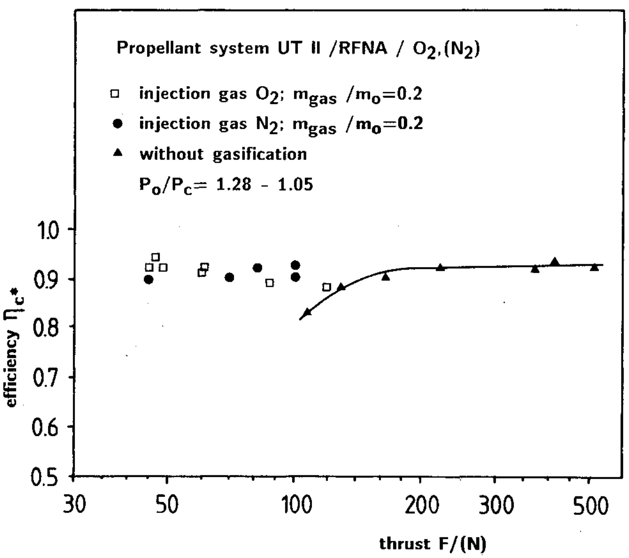

Fig. 10 Improvement in c^*-efficiency with gasification.

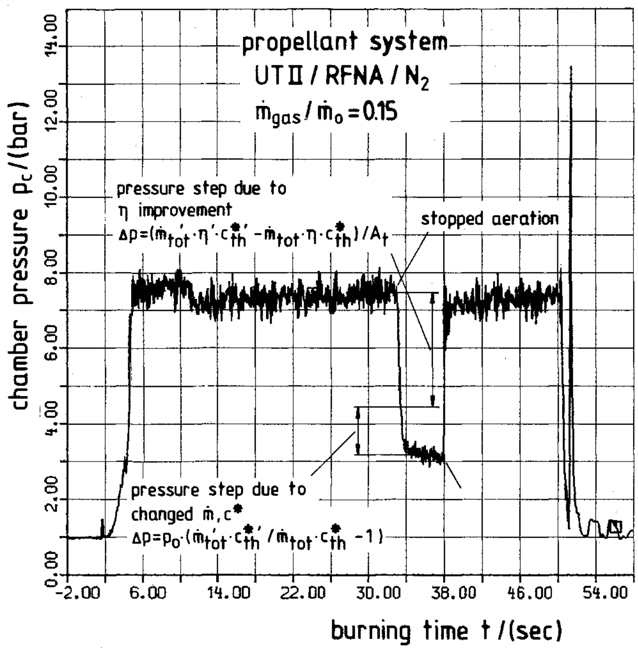

Fig. 11 Pressure-time history with stopped and restarted gasification.

by combining Eqs. 1 and 2 with

$$c^* = f(O/F, p_c, m_{gas}/m_o, \eta)$$

The characteristic velocity c^* for a given propellant system is dependant on the mixture ratio, the chamber pressure, the injection-gas portion, and the c^*-efficiency. The theoretical value $c^*(\eta = 1)$ can be computed with a thermodynamic equilibrium program.[10]

The mass balance between the supplied and exhausted mass flow becomes

$$\dot{m}_o + \dot{m}_f + \dot{m}_{gas} = \frac{p_c \cdot A_t}{c^*} \tag{5}$$

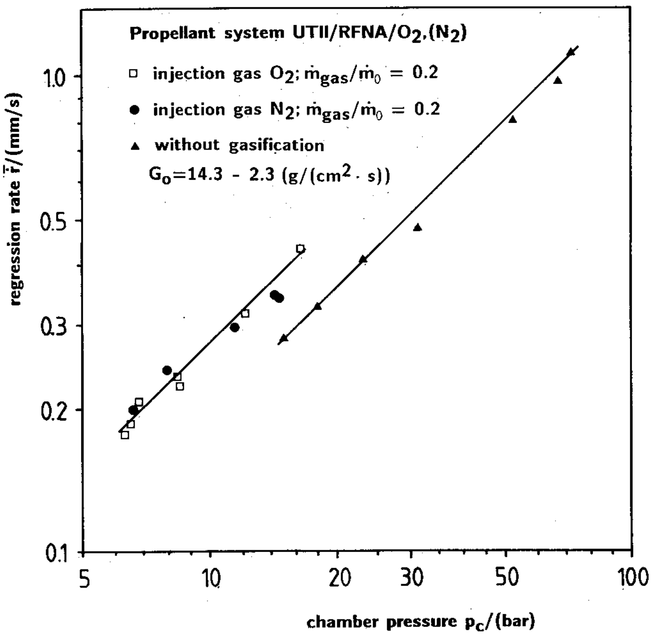

Fig. 12 Fuel regression characteristic including gasification effects.

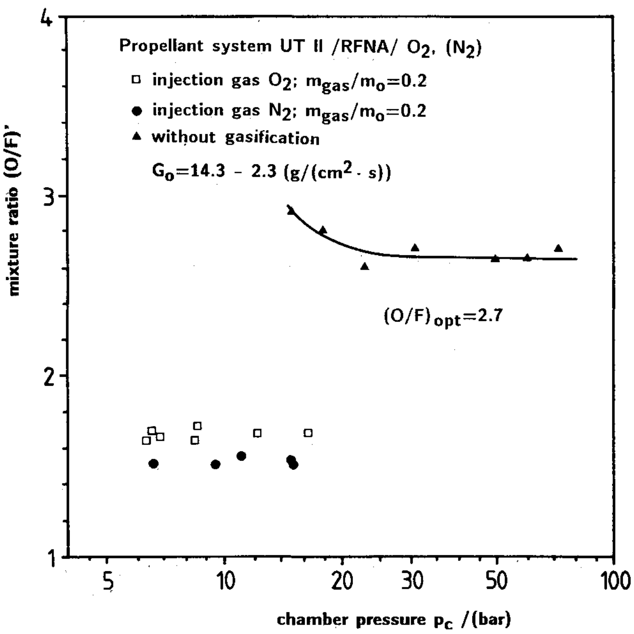

Fig. 13 Mixture ratio effect due to gasification.

With the definition of the mixture ratio O/F and Eqs. (4) and (5), the global ballistic behavior of an HRE can be described as follows.

Mixture ratio dependency:

$$O/F = \frac{1}{a}\cdot {p_c}^{1-\alpha-\beta}\cdot {c^*}^{1-\beta+\gamma}{}_{-1}$$

Mass flow condition:

$$\frac{\dot m_o}{A_t} + \rho_f a\frac{A_s}{A_t}\left[\frac{A_p}{A_t}\right]^{-\beta} c^{*\gamma-\beta}\, p_c^{\alpha+\beta} = \frac{p_c}{c^*}$$

The solution of the equations requires an iterative solution procedure.

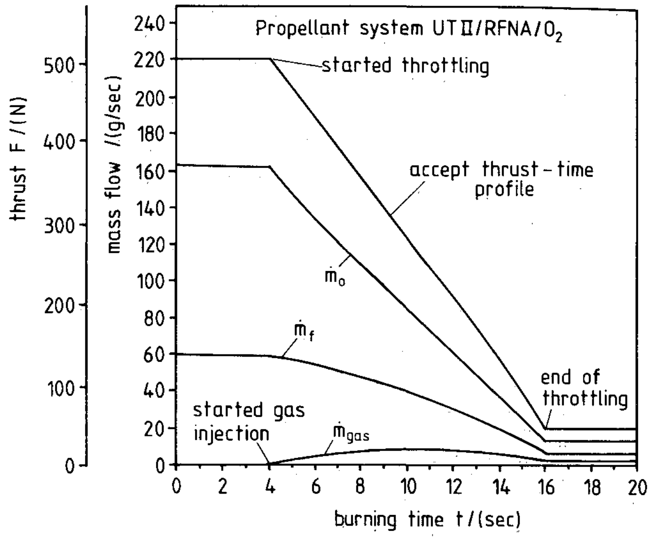

Fig. 14 Calculated mass flows for a hypothetical thrust-time profile.

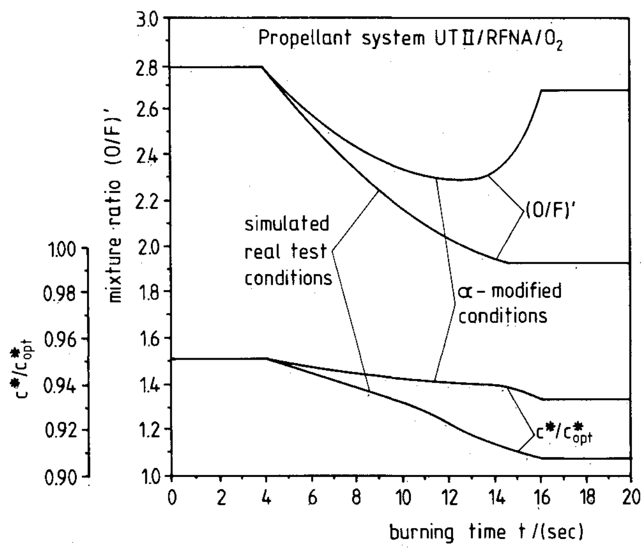

Fig. 15 Improvement in performance for an α-modified propellant system.

Computing Example

The aim of the theoretical calculation was to simulate the experimental test behavior and from this knowledge to improve the loss in performance caused by mixture ratio shifting for an assumed thrust time profile (Fig. 14). The experimental input to simulate real conditions during 10:1 throttling are as follows:

1) See regression characteristic from UTII/RFNA as listed in Table 1.

2) The regression increases linearly due to the effects of gasification from zero at the design point (no gasification) to 50% increase at the lowest throttled point (highest gasification).

3) The relationship of gas mass flow to the oxidizer mass flow is also linear. At the design point the value is zero; at the lowest throttled point the value $\dot m_{gas}/\dot m_o$ becomes 0.2.

4) The characteristic velocity is nearly constant $\eta = 0.95$ (see Fig. 10).

One way to influence the internal ballistic behavior is through the regression characteristic represented by a, α, and β.[11] The most practical parameter that could be changed is the pressure sensitivity α (this can be achieved through metal loadings or loading the fuel with catalytical ingredients). By varying α, the fuel release due to the regression characteristic can be changed, and it is possible to improve the total mixture ratio shift (Fig. 15). The interaction between fuel flow fixed by the regression characteristic without gasification, the additional fuel released by effects of gasification, and the amount of injection gas affects characteristics of the O/F ratio. The improved curve has a better balance between the different mass flows and, therefore, an improved performance as shown by the c^*/c^*_{opt} in Fig. 15.

A constant O/F value was not achieved. The example does show how it is possible to modify an existing fuel type with the aim of increasing the performance for throttling concepts.

Conclusions

Experimental results indicate that gasification has a drastic influence on the throttling performance. Multiple injection can enhance the atomization and mixing process of the oxidizer thus effecting a higher combustion efficiency.

Successful theoretical design of a throttleable system can be achieved by balancing the interaction of the complicated internal ballistic effects such as regression characteristics, c^*-efficiency, the influence of the injection gas, and the design weight of the system.

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