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# SOLID FUEL RAMJET REGULATION BY MEANS OF AN AIR DIVISION VALVE

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## Abstract

An analytical study was conducted, developing a theoretical model for the regulation of solid fuel ramjets by means of an air division valve. The solid fuel ramjet motor is the simplest air-breathing propulsion means for supersonic flights. However, the variable flight conditions over the operating envelope of altitudes and velocities significantly affect the motor performance. Regulation requirement was defined in this study as the motor capability of operating at a constant, desirable fuel to air ratio over a wide range of flight conditions. The adopted method is based on an air division valve, which drives a part of the incoming air from the diffuser through a bypass to the aft-mixing end of the combustion chamber. The model takes into account the parameters that influence the burning rate of the solid fuel (air mass flow, port diameter) and formulates a general regulation law for the division valve. The method was checked for specific cases, considering different trajectories. The control law provided a good regulation by means of the division valve, determining the instantaneous opening state of the valve that assures a constant optimal fuel to air ratio over the operating envelope.

## Nomenclature

$A$ = area
$d$ = diameter
$f$ = fuel to air ratio
$G$ = air mass flux
$H$ = inlet step
$h$ = heat transfer coefficient; altitude
$L$ = fuel grain length
$n$ = mass flow rate or mass flux exponent
$M$ = Mach number
$m$ = temperature exponent
$\dot{m}$ = mass flow rate
$\dot{q}$ = heat transfer rate
$\dot{r}$ = fuel regression rate
$T$ = temperature; air temperature
$T_0$ = stagnation air temperature
$t$ = time
$\gamma$ = specific heat ratio
$\Delta H_v$ = heat of gasification
$\rho$ = density

Subscripts
$a$ = air
$b$ = bypass
$c$ = combustion
$f$ = fuel
$in$ = inlet
$max$ = maximum
$min$ = minimum
$nom$ = nominal
$p$ = port
$t$ = throat
$w$ = wall

## Introduction

The solid fuel ramjet (SFRJ) is one of the simplest air-breathing engines. The use of solid fuels in conventional engines provides many advantages: high-energy density resulting in a more compact system, simplicity (there is no need for fuel-control, fuel storage and feeding systems comprising pumps and valves), safety and easy storage. Another benefit of SFRJ motors is the high degree of combustion stability, as experienced at United Technologies Chemical Systems[1], USA, in over 2500 test firings with a variety of combustor sizes and configurations; the uniformity of the energy release, due to the mainly diffusion-controlled combustion process, is believed to minimize combustion instability problems.

Because of their high specific impulse (3-4 times than that of solid rocket motors), SFRJ motors are particularly suitable for long range missile and projectile propulsion at supersonic flights (between Mach 2 and 4); at lower Mach numbers turbojet motors with after-burner are still preferable.

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Of the three types of ramjet engines, the liquid fuel ramjet, the ducted rocket, and the solid fuel ramjet (SFRJ), the SFRJ represents the simplest design solution due to the absence of any moving parts and the simple combustor configuration[2].

The SFRJ consists of an air intake system, a combustor and an exhaust nozzle. The combustor comprises a sudden expansion (inlet step) serving as a flame holder, an igniter and the solid fuel grain, often of a hollow cylinder shape (Fig.1). The SFRJ operation can be described by three basic stages: aerodynamic compression through the diffuser, sudden expansion of the incoming air and combustion of the fuel with the air, and finally conversion of the combustion gases thermal energy into kinetic energy through the exhaust nozzle. The aerodynamic compression takes place in the diffuser where the incoming flow slows down from a supersonic to a subsonic speed, passing through a series of oblique shocks and a normal shock wave and increasing the air pressure and temperature. The air enters the combustion chamber and flows through the port of the fuel grain. Flame stabilization is achieved by the sudden expansion of the incoming air. A recirculation zone is formed at the entrance of the combustion chamber by the inlet step, and its length is generally proportional to the step height. Flame stabilization has been studied in small SFRJ motors by Netzer and Gany[3]. Three parameters may influence flame stabilization: the port to inlet area ratio $A_p/A_{in}$, which is an equivalent parameter to the relative step height, determines the dimensions of the recirculation zone. The fuel port to nozzle throat area ratio $A_p/A_t$ establishes the Mach number inside the fuel grain. Finally, flight conditions (Mach number and altitude) determine stagnation temperature and pressure of the incoming air to the diffuser. It is possible to describe flameholding limits of an SFRJ combustion chamber as a function of the parameters above on a map, as shown schematically in Fig.2.

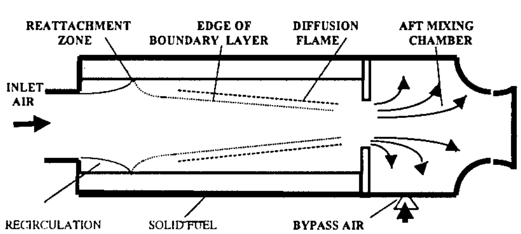


**Fig.1 SFRJ combustor geometry and flow field.**

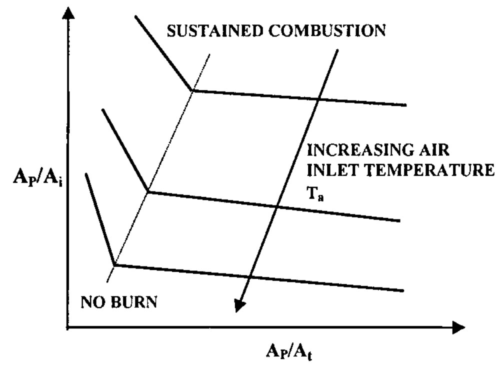


**Fig.2 Flammability limits.**

For a given stagnation temperature of the incoming air, any operating point (indicated by certain $A_p/A_{in}$ and $A_p/A_t$ ratios) above the sustained flameholding limit enables combustion , while points below that limit do not assure stable operation. The figure shows that an increase in inlet air temperature, an increase in the $A_p/A_t$ area ratio (equivalent to a reduced flow velocity inside the combustion chamber), or an increase in the $A_p/A_{in}$ area ratio (equivalent to the increase of the step height and consequently of the recirculation zone), either of the above can provide a larger envelope of sustained combustion. The higher the flight Mach number, the higher the stagnation temperature of the air, and the easier the flame stabilization. Similar results have been reported by Schulte[4], who conducted flameholding experiments in different air temperatures, fuel grains and port diameters.

The combustion process of the solid fuel consists of the thermal decomposition and gasification of the fuel surface due to heat transfer from the hot flow, and combustion of fuel vapor with the air in the gas phase [5,6] (Fig.1). The fuel vapor passes by diffusion to the shear layer developed between the incoming airflow and the recirculation zone. In this region a part of the fuel vapor is burned with the air, and the combustion products, together with the unburned fuel vapor, flow over the solid fuel surface.

From the reattachment point of the flow, at the end of the recirculation zone, a turbulent boundary layer develops over the solid fuel surface, where diffusive combustion takes place between the fuel vapor from the wall and the oxygen from the flow core[7]. The end of the combustor usually does not contain solid fuel and is used as an aft-mixing chamber in order to complete the reaction between fuel vapor and air. Sometimes the aft-mixing chamber is fitted with a bypass air injection.

The fuel used in the SFRJ is primarily of a polymeric hydrocarbon type, e.g., polybutadiene, polyethylene, polymethylmethacrylate, providing high heat of combustion, good mechanical properties, good regression characteristics and high combustion efficiency over a wide range of conditions. It is possible to increase both the gravimetric and the volumetric heat release of solid fuels by using certain metal additives.

It is important to note that combustion temperatures in SFRJ motors are lower than those in rocket motors, so that dissociation problems in the combustion process are significantly reduced, enabling the exploitation of almost all the chemical energy potential.

The advantages listed above make the SFRJ motor a very attractive propulsion system from many points of view. However, the use of a solid fuel complicates the internal ballistics and the design of a desired working point, as there is no way to establish directly the fuel flow rate, which depends on physical and chemical properties of the matter, on the incoming airflow rate, and on the geometry (basically the diameter) of the combustion chamber[8,9]. In order to assure effective motor operation over the entire flight envelope, it is necessary to control the combustion process allowing motor operation at optimal conditions over the desirable operating range. Such an optimal operation requirement may be the motor capability of operating at a constant, desirable fuel to air ratio, over a wide range of flight conditions. This requires the regulation of the fuel mass flow rate during flight, due to changes in the air mass flow rate because of variable flight conditions (altitude and Mach number) as well as the increase in fuel port diameter due to solid fuel burning. A higher flight velocity or a lower altitude both increase the air mass flow rate, causing a reduction of the fuel to air ratio, which may affect motor performance significantly. The increase in the fuel port diameter with time also reduces fuel to air ratio by diminishing the fuel mass flow rate.

SFRJ motors do have some "self-throttling" characteristics that enable them to partially overcome this problem: the dependence of fuel regression rate on air flow rate and temperature implies that at lower flight altitudes, which result in higher flow rate and stagnation temperature of the incoming air, the fuel flow rate increases as well, and vice-versa. However, this "self-throttling" characteristic of the SFRJ is not complete in itself, and additional suitable methods for the control of fuel mass flow rate should be applied. This control can be achieved either by a bypass control of the inlet air or by a regression rate control of the fuel. The first method has been already adopted in many operating systems other than SFRJ (e.g., YF-12 and Concord aircraft use bypass control of inlet air): this method consists of bypassing a required quantity of inlet air into the atmosphere, without participating in combustion. The second method is relatively new and is peculiar to the SFRJ: the fuel regression rate is controlled by varying the effective air mass flow rate over the fuel surface. The "tube-in-hole" method[10] is based on the regression rate control concept. This method uses a tube co-axially placed in the grain port hole (Fig.3). The tube divides the inlet air into two parts, one directed along the annular passage over the fuel surface and the other through the central tube directly to the aft-end. In the first position (Fig.3a) the entire air flows through the annular passage producing the highest regression rate; in the second position (Fig.3b) the tube splits the air flow and the air mass flow rate over the fuel surface is reduced, producing a lower regression rate. In the third position (Fig.3c) most of the air flows through the tube and only the least amount of air necessary for sustained combustion is directed to the fuel port. Philmon George and Krishnan[11] conducted recently a parametric study adopting the "tube-in-hole" method for certain typical configurations of SFRJ gun launched projectiles, varying fuel grain lengths, inlet diameters and launch angles.

The objective of the present work is to propose and investigate the possibility of regulating the solid fuel ramjet operation, and to determine the effectiveness of such a regulation over a wide range of flight conditions.

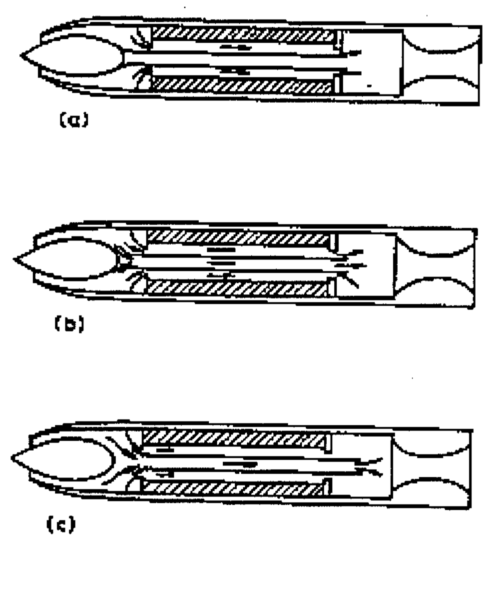


**Fig.3 "Tube-in-hole" technique[11]**

The work focuses on a method which seems to offer very good control capabilities and control range. This method is based on an air division valve, which divides the incoming airflow from the diffuser into two separate flows; a part of the air (the principal airflow) is drawn directly into the combustion chamber through the port of the solid fuel grain and determines the fuel flow rate, while the other part (the bypass airflow) flows through a bypass to the aft-mixing end of the combustion chamber (Fig.4).

An analytical study has been conducted, characterizing a general regulation law for the air division valve.

## Analysis

### Fuel regression rate

The fuel regression rate in the SFRJ is known to be a result of thermal degradation and gasification of the solid fuel[12,13] . For a typical polymeric fuel, the regression rate is proportional to the heat flux to the surface according to:

$$\dot{r} = \frac{\dot{q}_w}{\rho_f \Delta H_v} \propto \dot{q}_w \qquad (1)$$

It can be shown that for a relatively high activation energy of the polymer decomposition process, the fuel regression is a quasi-equilibrium process, with a practically constant value of the heat of gasification.
The heat transfer mechanism is assumed to be dominated by forced convection through the turbulent boundary layer. The heat flux to the fuel surface is:

$$\dot{q}_w = h(T_c - T_w) \qquad (2)$$

It can be assumed that both the wall temperature and the diffusion flame temperature are more or less constant, then

$$\dot{q}_w \propto h \qquad (3)$$

In a developed turbulent boundary layer the heat transfer coefficient can be expressed by Reynolds analogy. Under such conditions it can be correlated in terms of the air mass flux through the port G and the port diameter d:

$$h \propto G^{0.8} d^{-0.2} \qquad (4)$$

where

$$G = \frac{\dot{m}_{a,p}}{\left(\pi d^2 / 4\right)} \qquad (5)$$

Substituting Eqs.(1) and (3) in Eq.(4), and generalizing the power law one obtains:

$$\dot{r} \propto G^n d^{n-1} \qquad (6)$$

In terms of the mass flow rate through the port (or the principal airflow rate), Eq.(6) becomes:

$$\dot{r} \propto \dot{m}_{a,p}^n d^{-(1+n)} \qquad (7)$$

The fuel regression rate model gives a general scheme that can be replaced by test data or other correlations, if available.

An additional parameter which can be taken into account is the total temperature of the incoming air, $T_0$, which is known to influence fuel regression rate. The more comprehensive model can then include this effect:

$$\dot{r} \propto \dot{m}_{a,p}^n d^{-(1+n)} T_0^m \qquad (8)$$

where the total air temperature can be expressed in terms of flight Mach number and ambient air temperature, T (depending on flight altitude):

$$T_0 = T \cdot \left(1 + \frac{\gamma - 1}{2} M^2\right) \qquad (9)$$

### The airflow division concept

Using an air division valve, the incoming air can be divided into two parts prior to entering the combustor: the principal (port) airflow and the bypass airflow (see Fig.4 ), where

$$\dot{m}_a = \dot{m}_{a,p} + \dot{m}_{a,b} \qquad (10)$$

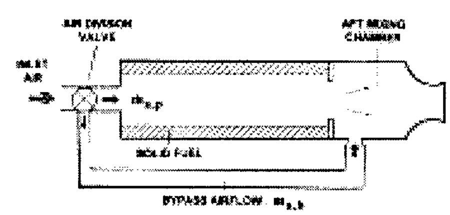

**Fig.4 Schematic description of the combustion chamber showing the air division valve concept.**

The airflow division concept is based on the fact that the fuel mass flow rate is directly dependent on the principal airflow rate, which flows through the fuel port, and is independent of the overall airflow rate coming through the inlet. On the other hand, the overall fuel/air ratio, f, is related to the overall incoming airflow $\dot{m}_a$:

$$f = \frac{\dot{m}_f}{\dot{m}_a} = \frac{\dot{m}_f}{\dot{m}_{a,p} + \dot{m}_{a,b}} \quad (11)$$

It is possible to find a relation between the fuel mass flow rate and the principal (port) airflow rate, which enables us to control the fuel to air ratio via regulating the port to overall airflow rate ratio $\dot{m}_{a,p}/\dot{m}_a$. For a cylindrical combustion chamber, the fuel mass flow rate is determined as follows:

$$\dot{m}_f = \pi d \rho_f L \dot{r} \quad (12)$$

For a given fuel grain length (and a constant fuel density):

$$\dot{m}_f \propto d \cdot \dot{r} \quad (13)$$

Making use of Eq.(8), the fuel mass flow rate can be expressed as a function of the principal airflow, the port diameter, and the total temperature:

$$\dot{m}_f \propto \left(\frac{\dot{m}_{a,p}}{d}\right)^n \cdot T_0^m \quad (14)$$

**Control law**

Regulation of the SFRJ operation may be very significant particularly for maintaining a desirable performance level in typical variable ambient, flight and operating conditions encountered by the motor. As mentioned above, the desirable operating state defined in the present work is motor operation at constant fuel to air ratio. In order to fulfill this requirement, a control law is derived based on controlled variation of the port to overall airflow ratio.

The fuel to air ratio at any point in the flight envelope is compared to a nominal, desirable ratio:

$$f = f_{nom} \quad (15)$$

After substituting the fuel mass flow rate expression from Eq.(14) in the fuel to air ratios f and $f_{nom}$ in Eq.(15), the following control law is derived, defining the instantaneous opening state of the division valve as a function of air mass flow rate, temperature and port diameter, relative to some nominal conditions, at which a nominal value of fuel burning rate and a desirable nominal value of fuel to air ratio are defined:

$$\frac{\dot{m}_{a,p}}{\dot{m}_a} \propto \left(\frac{\dot{m}_{a,p}}{\dot{m}_a}\right)_{nom} \cdot \left(\frac{d}{d_{nom}}\right) \cdot \left(\frac{\dot{m}_a}{\dot{m}_{a,nom}}\right)^{\left(\frac{1-n}{n}\right)} \cdot \left(\frac{T_0}{T_{0,nom}}\right)^{\left(\frac{m}{n}\right)} \quad (16)$$

The port diameter increases as the fuel grain is burned:

$$d = d_{min} + \int_0^t 2\dot{r}\, dt \quad (17)$$

where the fuel regression rate can be expressed in the following form:

$$\dot{r} \propto m_{a,p}^n d^{-(1+n)} \cdot T_0^m \propto \left(\frac{\dot{m}_{a,p}}{\dot{m}_a}\right)^n \cdot \dot{m}_a^n \cdot d^{-(1+n)} \cdot T_0^m \quad (18)$$

The burning rate is related to the nominal conditions:

$$\dot{r} = \dot{r}_{nom} \cdot \frac{\left(\dot{m}_{a,p}/\dot{m}_a\right)^n}{\left(\dot{m}_{a,p}/\dot{m}_a\right)_{nom}^n} \cdot \left(\frac{\dot{m}_a}{\dot{m}_{a,nom}}\right)^n \cdot \left(\frac{d}{d_{nom}}\right)^{-(1+n)} \cdot \left(\frac{T_0}{T_{0,nom}}\right)^m \quad (19)$$

The air mass flow rate varies with flight Mach number and altitude:

$$\dot{m}_a \propto \rho \cdot M \cdot T^{1/2} \quad (20)$$

Making use of Eqs.(16) and (20) one can express the control law in a more general form as a function of flight conditions (Mach number and altitude) and the port diameter:

$$\frac{\dot{m}_{a,p}}{\dot{m}_a} \propto \left(\frac{\dot{m}_{a,p}}{\dot{m}_a}\right)_{nom} \cdot \left(\frac{d}{d_{nom}}\right) \cdot f(h) \cdot g(M) \quad (21)$$

where f(h) and g(M) are functions of the altitude and Mach number, respectively:

$$\begin{cases} f(h) = \left(\dfrac{\rho}{\rho_{nom}}\right)^{\left(\frac{1-n}{n}\right)} \cdot \left(\dfrac{T}{T_{nom}}\right)^{\left(\frac{1-n-2m}{2n}\right)} \\ g(M) = \left(\dfrac{M}{M_{nom}}\right)^{\left(\frac{1-n}{n}\right)} \cdot \left(\dfrac{1+\frac{\gamma-1}{2}M_{nom}^2}{1+\frac{\gamma-1}{2}M^2}\right)^{\left(\frac{m}{n}\right)} \end{cases} \quad (22)$$

The nominal opening state of the division valve takes into account the most extreme conditions over the operating envelope, where the entire amount of air should flow through the fuel port (i.e., $\dot{m}_{a,p} / \dot{m}_a = 1$). Hence,

$$\left(\frac{\dot{m}_{a,p}}{\dot{m}_a}\right)_{nom} = \frac{1}{\left(\frac{d}{d_{nom}}\right)_{max} \cdot f(h)_{max} \cdot g(M)_{max}} \tag{23}$$

## Results

The control law provides a good regulation by means of the division valve over a wide operating range, and it enables to define the opening state of the valve that assures operation at a constant optimal fuel to air ratio at any point over the operating envelope.

Some examples of possible trajectories have been numerically studied. The numerical solution has been found for a 0 to 15 km altitude range and Mach numbers from 2 to 3. The fuel grain was assumed to have internal and external diameters of 80 mm and 160 mm, respectively. The opening state of the valve represented by the mass airflow rates ratio $\dot{m}_{a,p}/\dot{m}_a$ has been defined as a function of time for two hypothetical trajectories: a linear climbing from sea level to 15 km and a linear descent from 15 km to sea level, both at a constant Mach number (M=2.5) flight.

Nominal conditions have been established as follows: the nominal flight altitude is sea level, the nominal Mach number is M=2.5, and the nominal port diameter is the initial fuel port diameter.

A parametric study has been conducted, varying initial fuel port diameter, as well as n and m (characterizing fuel regression rate), keeping a constant external fuel diameter (160 mm).

Because of the linear influence of the port diameter on the mass airflow rates ratio, the changes in the opening state of the valve are significantly reduced as the initial port diameter is increased. Yet, even with the smallest initial port diameter (80 mm), the regulation can be applied successfully in both trajectories, linear climbing (Fig.5) and linear descent (Fig.6).

Figures 7 and 8 show the mass airflow rates ratio as a function of time for different values of m (indicating the temperature influence) with a given value of n (n=0.8). The variation of the m power has a minor effect on the results: in the climbing case (Fig.7), temperature influence enhances regulation needs. A smaller m would thus be preferable. In the descent case (Fig.8), the temperature influence improves the situation of motor operation, implying a higher initial airflow rates ratio and reduced regulation needs.

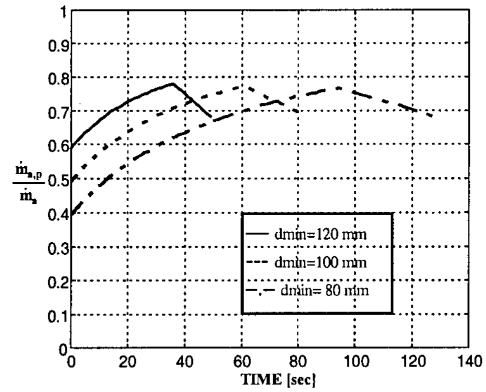


**Fig.5 The mass airflow rates ratio as a function of time for different initial port diameters at constant Mach number (M=2.5) flight and linear climbing from sea level to 15 km.**

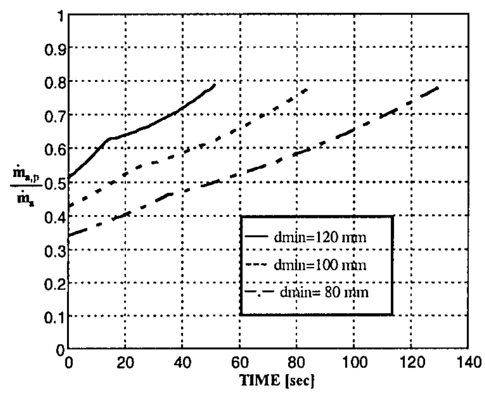


**Fig.6 The mass airflow rates ratio as a function of time for different initial port diameters at constant Mach number (M=2.5) flight and linear descent from 15 km to sea level.**

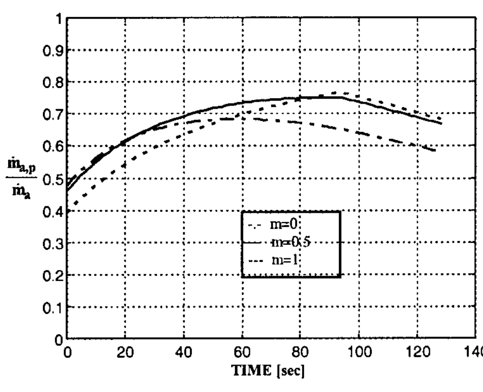


**Fig.7 The mass airflow rates ratio as a function of time with n=0.8 and different m values for constant Mach number (M=2.5) flight and linear climbing from sea level to 15 km.**

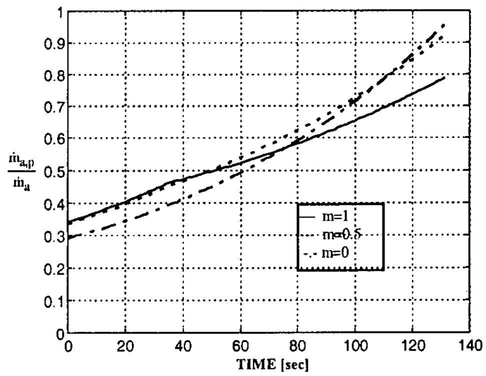


**Fig.8 The mass airflow rates ratio as a function of time with n=0.8 and different m values for constant Mach number (M=2.5) flight and linear descent from 15 km to sea level.**

Figures 9 and 10 show the mass airflow rates ratio as a function of time for different values of n (characterizing mass flow effect on fuel regression rate) with temperature influence (m=1). A reduction in the n power causes a reduction in the opening state of the valve: this is characterized by a reduction in the airflow rates ratio changes for the constant Mach number climbing case (Fig.9), and by a significant decrease of the initial opening state of the valve for the constant Mach number descent case (Fig.10), which may represent a very critical situation. In fact, at high altitudes, where the air density decreases, implying a reduction in the incoming mass flow rate, a small airflow rates ratio may cause motor extinction due to the insufficient quantity of air entering the solid fuel combustion chamber. Therefore, such a situation should be carefully checked in order to assure effective regulation with a sustained flame within the combustor.

In addition, the regulation law was applied to the same climbing and descent cases, when the trajectories and the flight characteristics were known a priori (Figs.11,12). When the trajectory is not precedently known , the possible opening range of the valve is only partially used, while for the known trajectory the mass airflow rates ratio is determined optimally so that the opening capability of the valve is fully exploited. This can be observed particularly in the climbing trajectory (Fig.11).

## Concluding Remarks

A solid fuel ramjet regulation by means of an air division valve has been modeled and analyzed yielding a regulation law. It has been demonstrated that the opening state of the valve can be successfully determined at any operating point during flight or calculated a-priori (if the trajectory is known) enabling optimal motor operation at a desirable constant fuel to air ratio. If the principal airflow is enough to sustain the flame, the use of the regulation law seems to offer good control capabilities over a wide operation range.

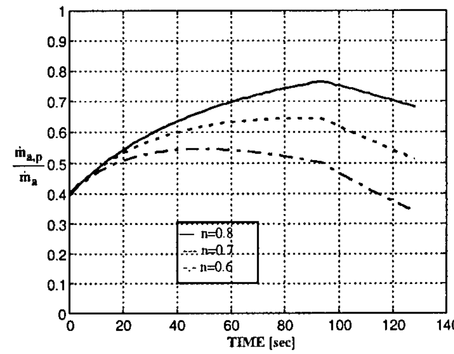


**Fig.9 The mass airflow rates ratio as a function of time with m=1 and different n values for constant Mach number (M=2.5) flight and linear climbing from sea level to 15 km.**

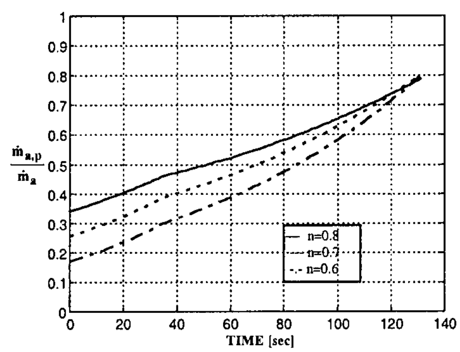


**Fig.10 The mass airflow rates ratio as a function of time with m=1 and different n values for constant Mach number (M=2.5) flight and linear descent from 15 km to sea level.**

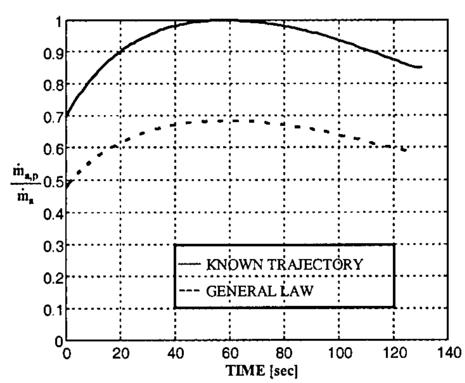


**Fig.11 The mass airflow rates ratio as a function of time (with n=0.8 and m=0) for constant Mach number (M=2.5) flight and linear climbing from sea level to 15 km.**

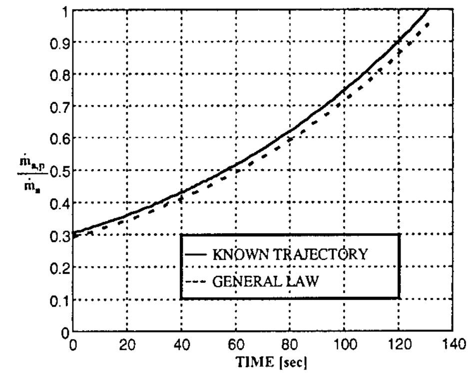


**Fig.12 The mass airflow rates ratio as a function of time (with n=0.8 and m=0) for constant Mach number (M=2.5) flight and linear descent from 15 km to sea level.**

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