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MODELLING OF MONOPROPELLANT SPACE PROPULSION SYSTEM

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ABSTRACT

Monopropellant thrusters still have a role to play in orbit insertion of small satellites whenever a sizable thrust is required. A new preliminary design analysis methodology is adopted. Two monopropellant catalyst bed reactor models are employed. The first model divides the flow into liquid, liquid-vapor, and vapor regimes. Each regime is divided into pore and free stream levels. This model is basically used off line to estimate the liquid phase regime behavior. A second model, which assumes the propellant to be readily vaporized, is used to predict the performance of the vaporized regime grossly on the free stream level. The analysis is conducted for a blow-down type feed system. A case study is presented employing hydrazine as a monopropellant. The results point out a collective impact of the tank pressure on minimum system mass. The optimum tank pressure is influenced by the bed loading and blowdown ratio. The technological complexity may have a vital impact on the choice of the bed loading and blowdown ratio.

KEY WORDS

Space propulsion, monopropellant, thruster, catalytic bed reactor

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NOMENCLATURE

A	Area	[m^2]
B	Blowdown ratio	
C_d	Discharge coefficient	
C_F	Thrust coefficient	
G	Bed loading	[kg/(s.m^2)]
g_o	Standard gravitational acceleration	[m/s^2]
I	Total impulse	[N.s]
I_{sp}	Specific impulse	[s]
K_v	Valve coefficient	[m^3/hr]
m	Mass	[kg]
$\dot{m}$	Mass flow rate	[kg/s]
P	Pressure	[N/m^2]
Q	Volume flow rate	[m^3/hr]
SG	Specific gravity	
T	Temperature	[K]
ρ	Density	[kg/m^3]

Subscripts

c	Combustion
f	Final
i	Initial
inj	Injector
L	Liquid
pr	Propellant
th	Throat
tk	Tank
v	Valve

1. INTRODUCTION

For a range of relatively low total impulse, the monopropellant system has competitive system mass regardless of having lower specific impulse than conventional bipropellant systems. The relative simplicity and low temperature gases of monopropellant systems result in a high reliability. In addition, it produces clean exhaust, and hence has low contamination hazards to other satellite sub systems.

Kesten [1] developed an analytical model for the decomposition process of monopropellant thrusters. It considers both thermal and catalytic decomposition of reactants along with simultaneous heat and mass transfer between the free streamgas phase and the gas within the pores of the catalyst beds. Sangiovanni and Kesten [2] added to the previous model capillary and viscous forces to predict the residence time of liquid reactant in the catalyst particle. Earlier, Schmitz et al [3] focused on experimentation to obtain reactor design and performance correlations.

Smith and Kesten [4] divided the flow into liquid regime, liquid-vapor regime and vapor regime. They considered the free stream and catalyst pellet levels. The model assumed heterogeneous (catalytic) decomposition in the pore of liquid, liquid-vapor regimes and at the catalyst surface of the vapor regime, but the homogeneous (thermal) decomposition of hydrazine was modeled through the voids of vapor regime only. The heterogeneous decomposition of the product ammonia was neglected in the liquid and liquid–vapor regimes, where the temperature is relatively low. The Smith model employed an implicit integral scheme. Michales [5] adopted a similar mathematical model but an iterative finite difference method was employed.

Fig. 1 shows a typical layout of monopropellant hydrazine catalytic bed reactor. The chemically reacting flow in such reactor is a very complicated multi-aspect problem, involving flow, mass diffusion, chemical reaction and heat transfer. While the use of a detailed model is warranted for the final design check, an extensive preliminary analysis may be efficiently conducted by a proper mix between simple and detailed models. Despite the lack of some absolute accuracy, it is believed that the relative difference in performance is what matters in the preliminary design phase.

It is the intention of this work to introduce a computer package based on this philosophy. To tackle such problem two models were considered with increased degree of detail and sophistication. The first model assumes the hydrazine to leave the injector in a vaporized state, whereas the second model considers the injected hydrazine to be in the liquid state [6].

2. MODELING OF HYDRAZINE CATALYTIC BED REACTOR

2.1 Vaporized hydrazine steady state 1D plug flow model

This is a one-dimensional, steady state, adiabatic, plug-flow model based on the following hydrazine monopropellant reactions

$$N_2H_4 \rightarrow NH_3 + 0.5N_2 + 0.5H_2 \tag{1}$$

$$NH_3 \rightarrow 0.5N_2 + 1.5H_2 \tag{2}$$

The liquid hydrazine is assumed to evaporate instantaneously. Four material balance-rate equations, energy balance equation, and Ergun empirical relation expressing the pressure gradient along the catalyst bed are used to describe the decomposition process [6].

2.2 General hydrazine catalytic bed model

A similar model to that of [5,7] is adopted here. However, in this model, the governing equations describing the flow in the reactor free stream and in the catalyst particle pore accounts for the conductive heat term in the fluid at the free stream. On the other hand it disregards the heat conduction in the catalyst bed structure of the reactor.

In the liquid–vapor regime the new model divides each element of that regime into two regimes: liquid regime and vapor regime consisting of a mixture of gases. Both of the homogeneous and heterogeneous decomposition of hydrazine are considered in the vapor-element and a part of the heat released from the vapor-element is devoted to vaporize the liquid-element and the remaining part raises the vapor-element temperature. This allowed the temperature, pressure, and hydrazine concentration to vary throughout this regime. The new model solves the coupled pore diffusion conservation equations with an iterative finite difference method.

3. PRELIMINARY DESIGN OF MONOPROPELLANT SYSTEM

This analysis is concerned with the preliminary design of monopropellant systems. A blowdown feed system is considered. The nature of operation dictates that the blowdown system operates in an off design mode. During its burning time the operating conditions and performance vary considerably between initial and final states. This in turn puts severe conditions on the design process since the system has to operate properly throughout a wide operating range.

The objective of this analysis is to determine the effect of the design parameters on the performance leading to an optimum selection of such parameters. The main design parameters are the initial tank pressure or initial catalyst bed inlet pressure, the tank blowdown ratio ($B = P_{tki} / P_{tkf}$) or final tank pressure, the catalyst bed geometry including length and diameter or bed loading (mass flow rate per unit catalytic bed cross sectional area), and the nozzle expansion ratio.

3.1 System Components

During the mission as the propellant is consumed the pressurant expands into the tank. This expansion is somewhere between isothermal (for very long system operation) and close to adiabatic (for very short system operation). The tank initial pressure, for a specified geometry and nozzle back pressure, determines the pressure at the various system locations. The tank volume is estimated from the volume occupied by the propellant and pressurant gas. Both are related by the blowdown ratio. At any time instant the pressure in the tank is obtained by tracing the pressurant gas volume and using the dynamic continuity and energy equations.

The feed system is presented in Fig. 2. each element produces certain pressure loss. In general, the pressure loss in the piping system is small in comparison with that encountered in the main components such as control valves, injector, catalyst bed and the nozzle.

The solenoid valve pressure loss is given by

$$\Delta P_v = (\frac{Q}{K_v})^2 SG \tag{3}$$

where, ΔP_v is the valve pressure drop in bars.
K_v is the valve coefficient as specified by solenoid valve manufacturers.

In order for the hydrazine droplets to cover the catalyst bed cross sectional area with an acceptable mass mean diameter (MMD) a circular solid cone simplex injector [8] is selected. This type has a reasonable cone angle (in the order of $50°$). In addition, to maintain injection quality (MMD< 1000 μ), a minimum pressure differential across the injector of 1.25 bar has been enforced. Such minimum takes place at the end of mission. The mass flow rate across the injector is given by.

$$\dot{m}_{pr} = C_d\ A_{inj} \sqrt{2\rho_L\ \Delta P_{inj}} \tag{4}$$

It is assumed that liquid flow pressure loss along the catalyst bed is small compared to the gaseous pressure losses. This loss is obtained using Ergun empirical equation, which evaluates the pressure gradient along the vapor regime of the bed. The stagnation pressure loss is then evaluated by integrating along the vapor regime length.

The results of the detailed model show that the liquid regime length depends on the inlet stagnation temperature, pressure and bed loading. The liquid-vapor regime length is relatively very short. The length required to achieve the maximum temperature in the vapor regime is also small, subsequently the temperature drops due to dissociation. The total bed length is estimated, as the longest length required at the most adverse conditions, fortunately these are the initial conditions. The length of the liquid regime is evaluated from the detailed model. An off-line parametric study is conducted to evaluate the dependence of the liquid regime length on the bed inlet conditions and bed loading. These parameters vary during the mission, leading to significant changes in the liquid regime length. Consequently the length of the vapor regime is estimated as the difference between the total bed length and the instantaneous liquid regime length.

3.2 System Matching

The choice of the design parameters defines the system state. However, in this case they do so in an indirect way, hence the procedure is iterative. A main 'dependent' parameter is the nozzle throat area. Based on the nozzle inlet operating conditions, the throat area is used to size the thruster in order to meet the target thrust.

Obtaining a solution for a set of design parameters is an interrelated and iterative process. Some of the dependent parameters have to be manipulated in order to meet the overall performance and constraints. The total propellant mass required to perform the mission has been initially estimated by

$$m_{pr} = I/(g_0 \overline{I_{sp}}) \tag{5}$$

where, $\overline{I_{sp}}$ is approximately given by [9]

$$\overline{I_{sp}} = I_{sp.i}(1-0.0025B) \tag{6}$$

The value obtained by equation 5 is subsequently corrected as a more accurate analysis predicts the specific impulse.

Before carrying out the full mission analysis, the initial and final state performance is checked for proper conditions within the system at these two extremes. If the results are not acceptable one or more of the dependent parameters may be altered. If the thrust is specified at the initial time, another check is conducted to ensure that the required initial thrust is met. The nozzle throat area may have to be adjusted to satisfy this requirement.

The procedure followed to satisfy the flow continuity along the system at any instant of time starts by assuming an initial value of the mass flow rate. This allows the feed system losses up to the injector to be estimated, which in turn determines the catalyst bed inlet conditions. The off line results of the detailed catalyst bed model are used to predict the inlet conditions to the 1D quasi-steady 'simple' model, which is solved for the bed outlet conditions. The nozzle mass flow rate is finally estimated and compared with the assumed value of the mass flow rate. Table 1 gives the required inputs to the main module and lists the output parameters.

Table1. Main module inputs-outputs.

Input: Design parameters	**Output: Performance parameters**
• Tank pressure • Blowdown ratio • Bed loading • Nozzle expansion ratio	• Total propellant mass • Tank volume • Mass of pressurant gas • Valve orifice diameter • Catalyst bed dimensions (length, diameter) • Nozzle configuration (throat, exit diameters, nozzle length)
	Time variation of system parameters: • Tank pressure. • Injector differential pressure. • Length of liquid and vapor regimes inside catalyst. • Catalyst bed pressure losses. • Propellant mass. • Specific impulse. • Thrust. • Mass flow rate.

After the usable propellant mass is consumed, both the transient performance and overall performance parameters are reviewed. If the total impulse is not met the propellant mass must be adjusted and the whole process is repeated.

3.3 Preliminary Design Case Study

The propulsion system mission is specified by the total impulse and initial thrust. In this case study a total impulse of 24000 N.s and an initial thrust of 10 N are considered. The preliminary design analysis investigates the effects of the design parameters on the system performance and configuration. To investigate the variations in system mass due to changes in the design parameters a reference case is chosen as:

Nozzle expansion ratio = 200
Initial tank pressure = 1 [MN/m^2]
Blowdown ratio = 2
Bed loading = 10 [kg/(s.m^2)]

The variation of any single parameter is indicated on the figures, while the remaining parameters maintain their reference values.

3.3.1 Nozzle expansion ratio

The specific impulse tends to increase with the nozzle expansion ratio. This increase is remarkable at low values of nozzle expansion ratios, and then approaches asymptotically a maximum theoretical limit. This increase reduces the propellant mass. Using basic definitions the specific impulse can be expressed as

$$I_{sp} = \left[\frac{A_{th} \cdot P_c}{\dot{m}\sqrt{T_c}}\right] \cdot \frac{C_F \cdot \sqrt{T_c}}{g_0} \tag{7}$$

The first term is basically constant due to nozzle choking. The outlet temperature demonstrates weak dependence on the remaining design parameters within their practical range. Hence, the specific impulse is highly dependent on the nozzle expansion ratio.

Assuming constant nozzle wall thickness, and since low stresses are encountered, Fig. 3 shows that increasing the expansion ratio almost linearly increases the nozzle mass. The figure also indicates the interactive effects of the remaining design parameters on the nozzle mass. This stems from their effect on the nozzle throat area required to meet the specified initial thrust.

The effect of nozzle expansion ratio on the total system mass, referred to that at an expansion ratio of 25, is presented in Fig. 4. For the combination of the other three design parameters, the effect of nozzle expansion ratio is basically similar. From this figure it is clear that, under these conditions, there is a broad optimum nozzle expansion ratio. Nozzles with high area ratio may have problems associated with very low pressures, which may invalidate the continuum flow model and/or suffer appreciable condensation. This may favor lower values of expansion ratios.

3.3.2 Tank pressure

Figure 5 shows the effect of tank pressure on tank mass, at different blowdown ratios. The tank stress and mass tend to increase with the tank pressure. However, at low tank pressures, handling and manufacturing considerations place a limit on the minimum thickness that can be used. Thus, at low tank pressure the tank mass does not change with pressure. The reduction in tank mass with the increase in blowdown ratio is due to the decrease in the pressurant gas volume.

A reduction of the tank pressure results in a reduced nozzle inlet pressure and hence the nozzle throat area must be increased to pass the required initial mass flow rate. This leads to a larger and heavier nozzle as indicated by Fig. 6. Below critical tank pressure the nozzle mass increases sharply. This takes place when the combination of inlet pressure and bed loading of the catalyst bed produces very high pressure drop across the bed, which leads to very low nozzle pressure and large nozzle throat. It can be concluded from Figs. 5 and 6 that the tank pressure must lie between high values corresponding to excessive tank mass, and a minimum corresponding to excessive nozzle mass. These two points are dependent on the blowdown ratio. An optimum tank pressure may be obtained for each blowdown ratio minimizing the sum of the tank and nozzle masses.

3.3.3 Bed loading

By its own the bed loading has insignificant effect on both the propellant and tank masses. Its most notable effects are on bed losses and injector pressure drop. The bed losses increase proportional to the square of the bed loading. Due to the imposed minimum injector pressure drop at the end of the mission, the bed loading has a pronounced effect. Assuming constant discharge coefficient and since the initial mass flow rate is nearly constant we can show that

$$\Delta P_{inj,i} \propto 1/\dot{m}_{pr.f}^{\;2} \tag{8}$$

As the final nozzle inlet pressure decreases considerably, the final mass flow rate is also reduced to match the nozzle choking conditions. The proportionality (8) indicates then that the initial pressure drop through the injector increases as shown in Fig. 8. This increase reduces the initial nozzle inlet pressure. To fulfill the required initial thrust a larger nozzle throat area must be used increasing the nozzle mass.

Fig. 8 presents the bed loading effect on nozzle mass. From catalyst bed performance, there is a minimum allowable initial tank pressure for each bed loading beyond which a steep rise in catalyst bed pressure drop takes place. This necessitates a large throat diameter and mass. This sharp rise in nozzle mass at a critical bed loading is also reflected on the total mass as indicated by Fig. 9.

Figure 8 shows that at constant bed loading and tank pressure, increasing the blowdown ratio causes the nozzle mass to increase. This is a consequence of the reduction in final tank pressure. As mentioned earlier this leads to a reduction in final mass flow rate and an increase in injector initial pressure drop, which in turn increases the pressure loss across the catalytic bed, and a larger nozzle throat is required. Hence the value of the critical bed loading for each tank pressure depends on the blowdown ratio. It may be concluded (see also Fig. 9) that the blowdown ratio shifts both the critical and optimum values of the bed loading.

Figure 10 presents the relation between the critical bed loading and tank pressure for different values of blowdown ratio. The maximum bed loading increases with tank pressure and decreases with the blowdown ratio.

The bed loading is the decisive parameter in specifying the catalyst bed diameter. Practical considerations set a limit on the minimum bed diameter to facilitate machining of bed components, with no significant gain in system mass. This may impose another limit on the maximum bed loading.

3.3.4 Blowdown ratio

Increasing the blowdown ratio the initial pressurant volume decreases and hence the tank volume and mass are reduced, Fig. 11. The figure also shows that the nozzle mass increases with the blowdown ratio. The nozzle mass being relatively small the total system mass follows the tank mass behavior.

The injector may constrain the performance in terms of coverage and atomization quality. Also, for the involved low mass flow rates, the available technology level for manufacturing the injector elements may restrict the injector dimensions. Thus, the injector port diameter is included as a measure for technological complexity level. Figures 12-a, 12-b give the variation of total system mass against the injector orifice diameter for variable blowdown ratio, bed loading and initial tank pressure. To estimate the injector orifice a constant discharge coefficient of 0.75 has been assumed.

Figures12-a, 12-b show that, for specified bed loading and blowdown ratio, there is an optimum tank pressure producing minimum system mass. The optimum tank pressure increases with the bed loading and also with the blowdown ratio.

The effect of tank pressure on injector orifice diameter is conflicting, depending on the values of the bed loading and blowdown ratio. Fig. 12-a shows that, at relatively low loading, increasing the tank pressure decreases the injector orifice diameter, whereas Fig. 12-b shows that, at relatively high bed loading and low blowdown ratios, increasing the tank pressure increases injector orifice diameter.

As indicated by proportionality 8, the initial injector pressure drop is inversely proportional to the square root of the final propellant mass flow rate. This mass flow rate is in turn proportional to ($A_{th}.P_{th.final}$). It is the variation in this term that explains the difference in behavior of the injector orifice diameter with tank pressure at different bed loading. The increase in tank pressure increases A_{th}, but $P_{th.final}$ is reduced. At high bed loading the throat area has the dominant effect, leading to higher final propellant mass flow rate and hence lower injector pressure drop. This increases the injector orifice diameter. The whole scenario is reversed at low bed loading.

Increasing the bed loading, within the relevant range, produces a small reduction in total system mass at the expense of a small reduction in injector orifice diameter and more significant reductions in bed diameter.

The blowdown ratio has a small impact on the optimum total system mass, however, it has a major impact on injector orifice diameter through its effect on final tank pressure and hence on final nozzle inlet pressure. Practical limits on injector orifice and catalyst bed diameters may restrict the choice of bed loading and blowdown ratio.

CONCLUSIONS

A preliminary design analysis of a hydrazine monopropellant thruster is conducted. A combination of two analysis models has been employed. The liquid phase length is predicted off line using a detailed model, whereas the gas phase performance is estimated on line using a simpler model. The results indicate that two critical tank pressures bind the selection, below the first the nozzle mass increases sharply, and above the second the tank mass increases sharply. The optimum tank pressure lies between these two limits and varies with both the bed loading and blowdown ratio. For each tank pressure and blowdown ratio there is a critical bed loading, which when exceeded a steep rise in bed losses take place with severe penalty in system mass. On the other hand, the bed loading has a dominant effect on the catalyst bed diameter.

The blowdown ratio has a small impact on optimum total system mass but its effect on injector orifice diameter is significant. The injector orifice diameter, considered here as a measure of technological complexity, may have a main impact on the choice of the bed loading and blowdown ratio.

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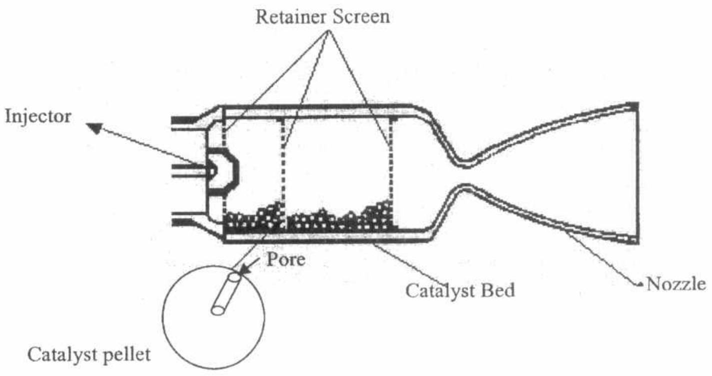
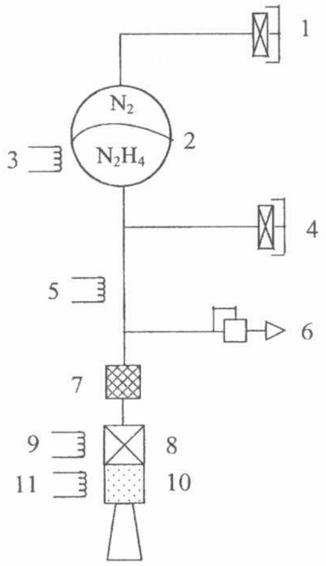


Fig. 1 Typical monopropellant catalytic bed thruster.



1	Pressurant Fill and Drain Valve
2	Tank
3	Tank heater
4	Propellant Fill and Drain Valve
5	Line Heater
6	Relief valve
7	Filter
8	Thruster Valve
9	Thruster Valve heater
10	Catalyst bed
11	Catalyst bed Heater

Fig. 2 Schematic layout of monopropellant system.

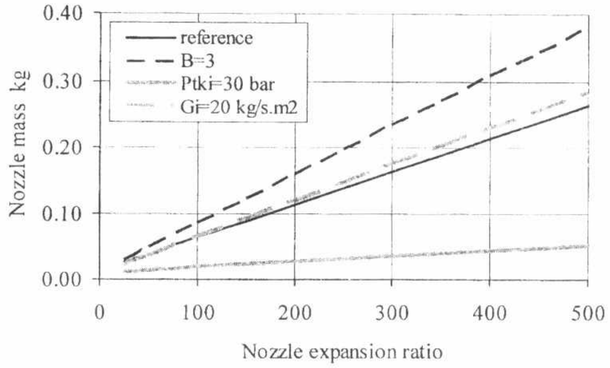


Fig. 3 Effect of nozzle expansion ratio on nozzle mass.

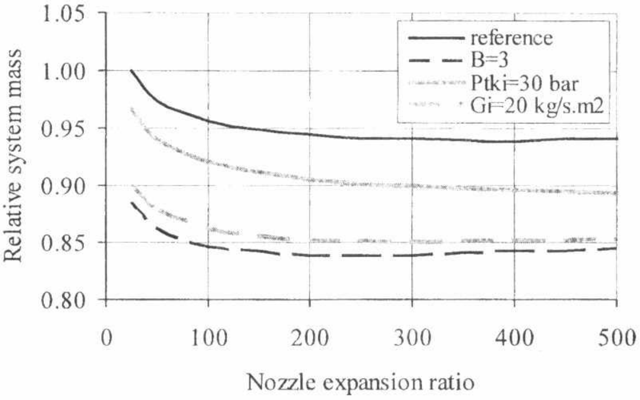


Fig. 4 Effect of nozzle expansion ratio on relative system mass.

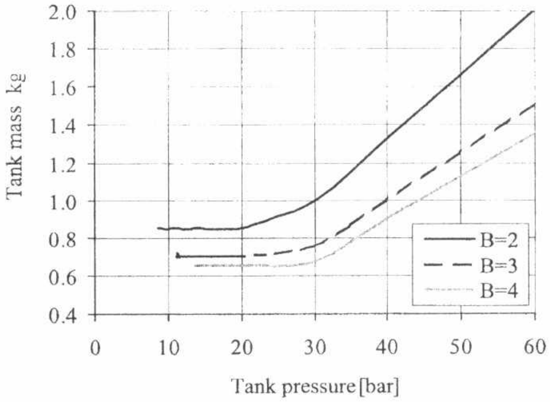


Fig. 5 Variations of tank mass, G=20 kg/(s.m^2).

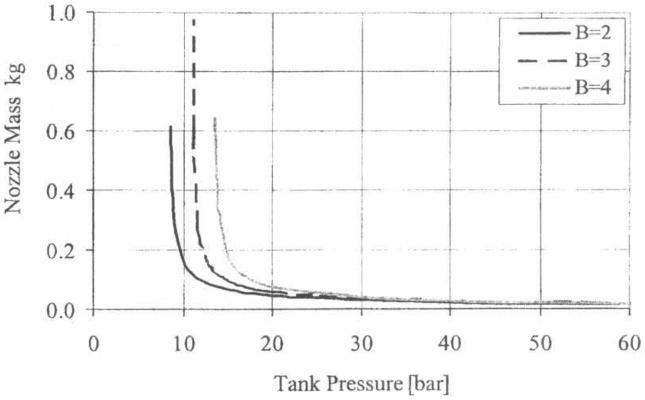


Fig. 6 Variations of nozzle mass, G=20 kg/(s.m^2).

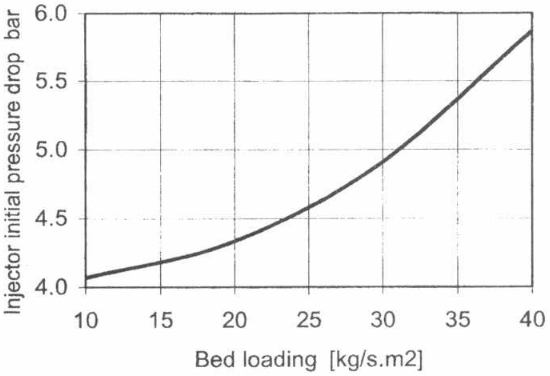


Fig. 7 Effect of bed loading on injector initial pressure drop, P_{tki}=20 bar, B=2.

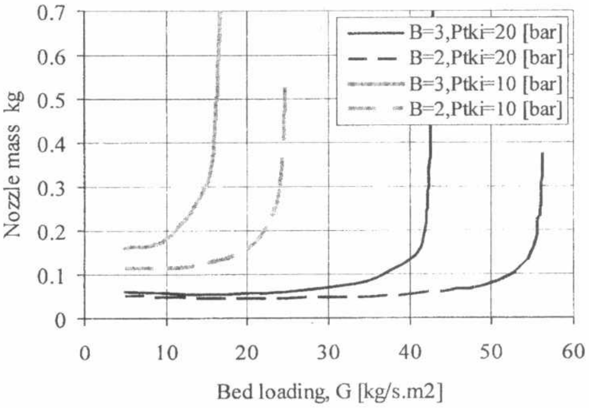


Fig. 8 Effect of bed loading on nozzle mass.

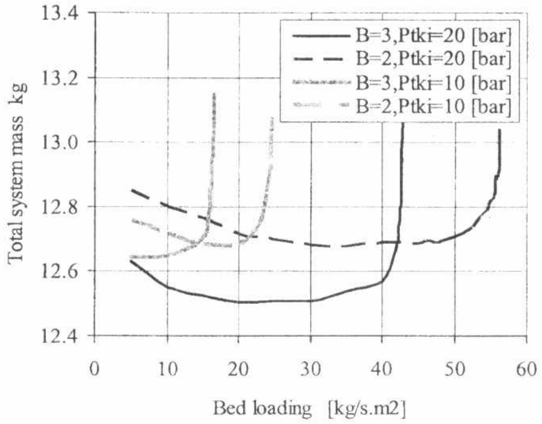


Fig. 9 Total system mass variations with bed loading.

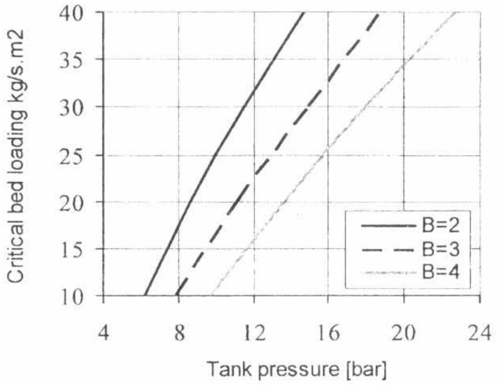


Fig. 10 Critical bed loading.

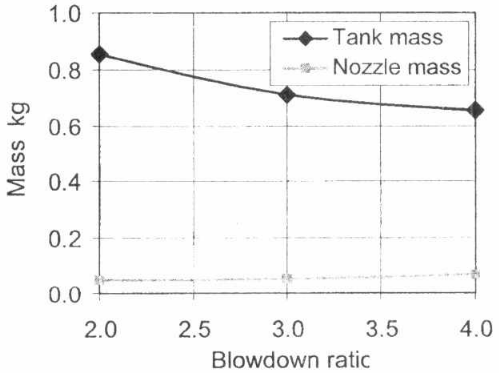


Fig. 11 Blowdown ratio effect on tank & nozzle masses, P_{tki}=20 bar, G=20 kg/(s.m^2).

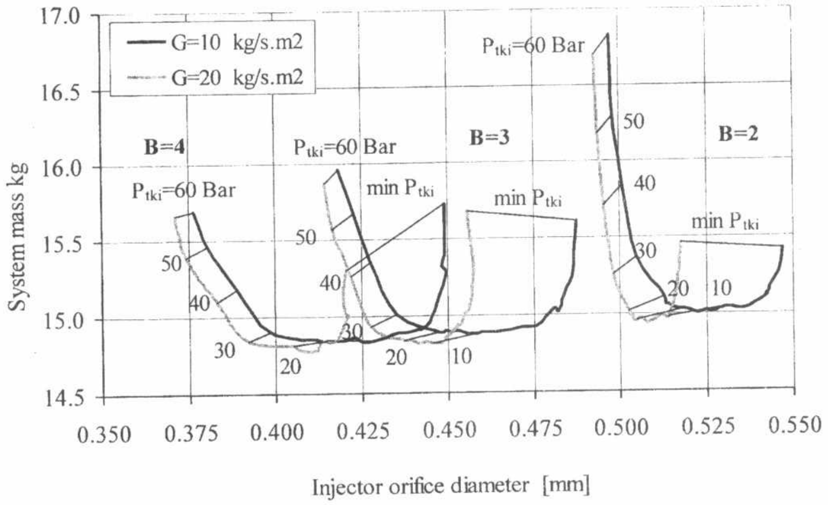


Fig. 12-a Monopropellant system design chart, G=10,20 kg/(s.m^2).

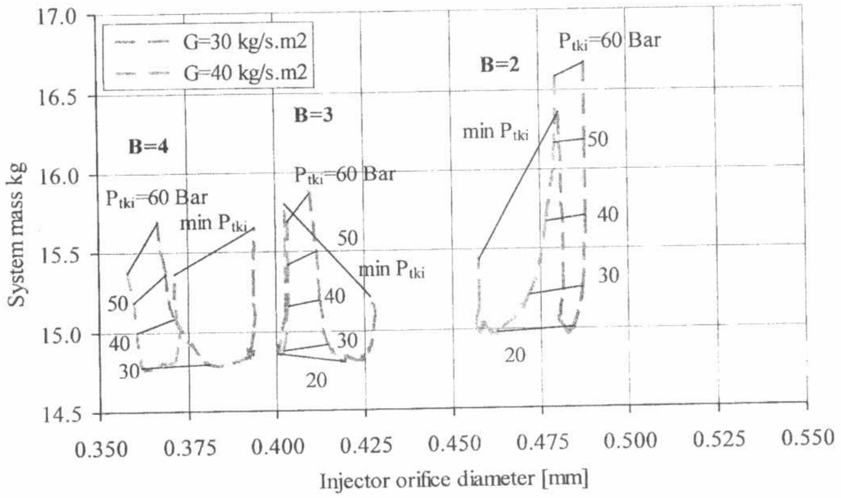


Fig. 12-b Monopropellant system design chart, G=30,40 kg/(s.m^2).