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ANALYSIS OF THE FUNCTIONING OF A SPACE VEHICLE'S FUEL SYSTEM

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23/06/2022

SPACE VEHICLE'S FUEL SYSTEM

1. INTRODUCTION

The following paper shows the analysis of the fuel system used for supply two single component hydrazine thrusters in normal and in emergency conditions.

It's needed to verify the fuel system turbopump performance in those operation states, pointing out any possible failure.

The following images shows the scheme of the space vehicle's fuel system (Figure 1) and the turbopump characteristic curve (Figure 2).

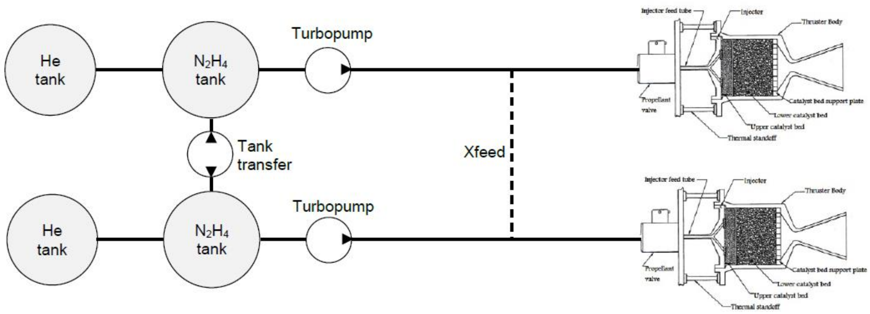


Figure 1

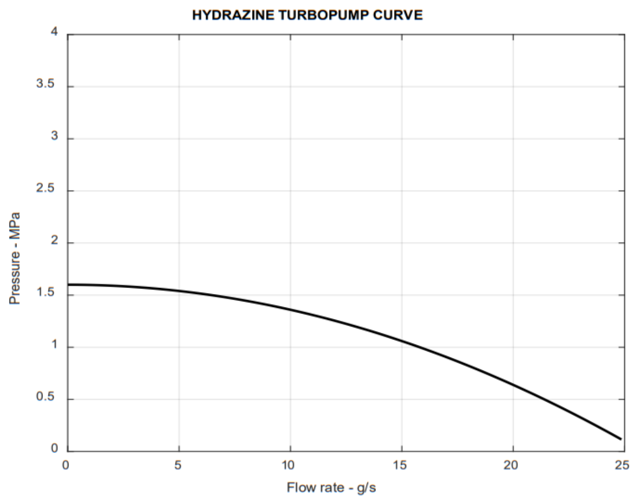


Figure 2

2. INDEX

3. SYMBOLS’ TABLE

Subscript label:

- al => referred to the alimentation pipe
- t => referred to the hydrazine tank
- p => referred to the pump
- tr => referred to the transfer pipe
- m => referred to the engine

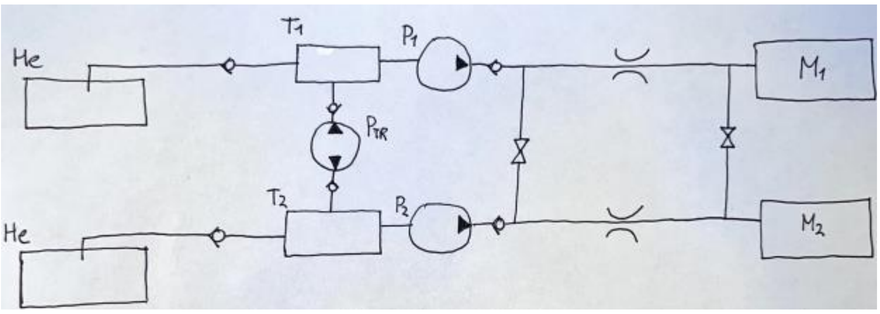
SYMBOL	**DEFINITION**	**UNIT OF MEASURE**
Q	volume flow of fuel	m^3/s
$\dot{m}$	mass flow of fuel	g/s
Re	Reynolds’ number	adimensional
v	Speed of the flow	m/s
ρ	Density of the fuel	Kg/(m^3)
μ	Dynamic viscosity of the fuel	cP
A	Pipe’s section	m^2
D	Diameter of the pipe	m
L	Pipe length	m
k	Concentrated head losses coefficient	adimensional
λ	Distributed head losses coefficient	adimensional
e	Relative roughness of the tube	adimensional

P	Pressure of the fuel at the exit of the pump	MPa

4. DESCRIPTION OF THE PROBLEM AND RESOLUTION METHOD

The analysis begins with discussion of the fuel system used by the vehicle.

4.1. FUEL SYSTEM STRUCTURE



In the scheme are represented the two analysed crossfeed line positions, even tough the system is equipped with only one crossfeed line.

The concerning space vehicle is powered by hydrazine (N2H4), a liquid propellent, whose isotherm reaction in the thruster generate hydrogen and nitrogen, channelled into the nozzle, and used as a boost.

In normal conditions each thruster is supplied by a hydrazine tank, which are pressurized by a helium tank, preventing reaching the vapour pressure.

The system is provided with two turbopumps, centrifugal ones, each of those must provide the entire fuel rate requested by the engine with suitable inlet pressure.

The centrifugal pump aspire fuel and by rotation raises the fuel speed and pressure; this is a fluid-dynamic pump, which accelerate the fluid and therefore are suitable for the transfer of fluid.

The fuel system is equipped with a crossfeed tube, whose position needs to be determined, which assures that both thrusters are properly fed in emergency conditions, in case of fault of one pump or leakage in one tank.

To avoid every possible momentum caused by a different volume of hydrazine in the principal tanks, the system is equipped with a secondary tank, whose fuel is constantly transferred in the principal tank by a turbopump; therefore, the principal tanks are constantly full.

In the alimentation line, in addition to the valves necessary for the required connections, there are filters and shut-off valves, which prevent the propagation in case of fire in the engine, and non-return valves, preventing any backflow.

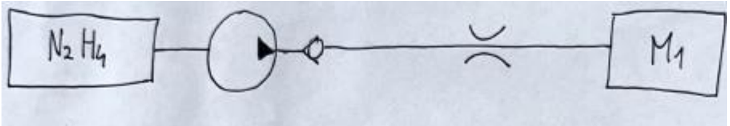
4.2. NORMAL FUNCTIONING

The thruster presents a range of fuel flow required with a suitable range of pressure. It must be verified that the turbopump is able to provide the fuel to the thruster in this range.

It's provided the minimum and max mass flow required by each thruster and the pressure range, which allows a correct functioning of the fuel system.

The system is primarily pressurized by the helium tank. The head losses may be considered negligible in the pipe part between hydrazine tank and the turbopump.

In the normal functioning the fuel, released by the tank, is pumped by the turbopump, then flows in the alimentation pipe and reaches the thruster, as the mass losses between the process could be ignored.



$$\dot{m}_T = \dot{m}_P = \dot{m}_{al} = \dot{m}_m$$

However, the head losses must be considered in the alimentation tube:

$$P_M = P_P - \Delta P_{losses} \qquad P_P = P_M + \Delta P_{losses}$$

In the pressure decrease, due to head losses, it can be identified a term of distributed head losses and a term of concentrated head losses:

$$\Delta P_{losses} = \Delta P_d + \Delta P_c$$

The distributed head losses are caused by internal friction, which increases the thermal energy of the fluid:

$$\Delta P_d = \frac{1}{2} \lambda \frac{L_{al}}{D_{al}} \rho (v_{al})^2$$

It depends by flow regime and so by the Reynolds number:

$$\lambda = \lambda(Re) \qquad Re = \frac{\rho v_{al} D_{al}}{\mu}$$

In case of laminar flow in the pipe is for Re < 2300, the friction factor is:

$$\lambda = \frac{64}{Re}$$

The losses become linear with flow velocity v.

In case of turbulent flow, Re > 3500 the friction factor is a non-linear function of Re and of the relative

roughness of the internal pipe wall, defined as the ratio between the average surface roughness and the pipe diameter.

For Re between the values above indicated there is a transition dominated by unsteady solutions.

In these cases, the friction factor trend is expressed by the Moody diagram.

The concentred head losses are caused by an obstacle in the pipeline, for many components or pipe geometries; the value of the coefficient is indicated by the constructor:

$$\Delta P_c = \frac{1}{2} K \rho (v_{al})^2$$

Their link with fluid velocity is quadratic.

Summing the two terms, the expression of total head losses in the alimentation tube:

$$\Delta P_{losses} = \left(K + \lambda \frac{L_{al}}{D_{al}}\right) \frac{1}{2} \rho v_{al}^2$$

The analysis goal is to verify that the characteristic turbopump curve is between the maximum and minimum pressure required to the pump:

$$P_{P,MAX} = P_{T,MAX} + \Delta P_{losses} \qquad P_{P,MIN} = P_{T,MIN} + \Delta P_{losses}$$

These curves are function of the mass flow supplied by the pump, so the condition mentioned before needs to be satisfied for mass flow between the minimum and maximum required to the pump.

4.3. EMERGENCY FUNCTIONING: CROSSFEED

It must be assured that the system works also in emergency conditions. In case of fault of one pump, this branch could be able to be isolated by shut off valves; therefore, the other branch must be able to supply enough fuel to both the engines.

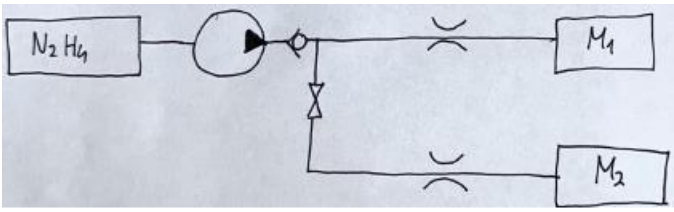
For this reason, each pump must be able to pump enough fuel for both the engines.

The space vehicle is equipped with a crossfeed line that should be properly positioned. It's possible to figure out two locations to be analysed.

In both analysis it's possible to ignore the length of the crossfeed tube and the head losses in this pipe.

In both cases it has to be verified that the turbopump curve is between the maximum and minimum pressure curve, for the appropriate rate of flow mass.

4.3.1. CROSSFEED LINE NEAR THE PUMPS



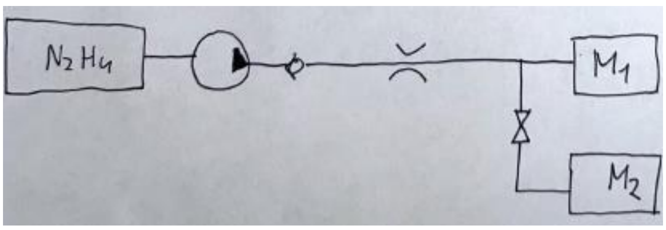
In the case of crossfeed line near the pump, the flow is immediately split into two parallel tubes:

$$\dot m_m = \dot m_{al} = 0{,}5\,\dot m_P$$

Even though the mass flow supplied by the pump is the double respect the normal functioning, the velocity of the flow in the alimentation tube is the same, as the mass flowing through the alimentation tube remains the same, therefore there are no significant increase of head losses compared with the normal functioning.

As the head losses are expected to be the same as the previous case, the minimum and maximum pressure required by the thruster is the same, but the pump flow is doubled, so it's expected that the plots of maximum and minimum pressure to be the normal condition plots stretched of a factor of 2 by the mass flow axis; also, the mass flow conditions must be doubled.

4.3.2. CROSSFEED LINE NEAR THE THRUSTERS



In this case of crossfeed line near the thrusters, the flow is split only nearby the thrusters, therefore the mass flow in the alimentation tube is doubled:

$$\dot{m}_m = 0{,}5\,\dot{m}_{al} = 0{,}5\,\dot{m}_p$$

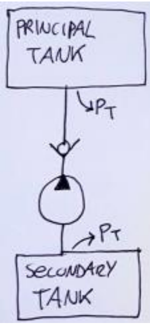
It's expected that the head losses to be the double or quadruple compared to the normal condition case, as λ depends on the flow type (Re).

As the mass flowing in the alimentation tube is equal to the one supplied by the pump, it's expected to have the same trend of the plot of maximum and minimum pressure required to the pump in normal conditions, however the mass flow conditions are doubled, as the mass required by the engines doesn't change.

4.4. TRANSFER OPERATION

To avoid any induction of undesired momentum to the vehicle due to the emptying of the principal tanks, the vehicle is provided with secondary tanks which have as major task the constant supply of fuel to the principal tanks, which need to be always full.

The transfer operation is taken possible by a turbopump, that in this vehicle is of the same type of the alimentation one.



$$P_T + \Delta P_{pump} = P_T + \Delta P_{losses}$$

$$\Delta P_{losses} = \frac{1}{2}\rho v^2 \left(K + \lambda \frac{L_{TR}}{D_{TR}}\right)$$

As the principal and secondary tanks are at the same pressure, the transfer pump should always be able to supply a difference of pressure equal to the head losses in the transfer pipeline, in a way to avoid any pressure reduction in the principal tanks.

The transfer fuel flow is determined by the intersection of the characteristic pump plot and the head losses in the transfer pipeline plot; to avoid the emptying of the principal tank during emergency operations, the transfer flow must be higher than the maximum flow required to the pump in emergency conditions.

5. DATA

Helium tanks pressure	0.4 MPa
Minimum and maximum mass flow required by each thruster	2-10 g/s
Minimum and maximum pressure required by the thrusters	0.5-2.4 MPa
Alimentation tube length	2 m
Alimentation and crossfeed tube diameter	2 mm
Crossfeed tube length	negligible
Transfer tube length	0.5 m
Transfer tube diameter	2.2 mm
Concentrated head losses coefficient Tubes relative roughness	6
Tubes relative roughness	0.001

density	1020 kg/m^3
viscosity	0.9 cP

1 cP = 1 mPa*s

6. CALCULATIONS

The task is to obtain the expression of the maximum and minimum pressure in each condition in function of the mass flow pumped; these expressions has been written in MATLAB, expressed as anonymous function, obtaining the pressure curves for the mass flow required range.

As consequence of the equation of continuity, the flow in a tube depends on the speed of the flow and the section of the tube; the tubes have circular section.

$$Q = v \cdot A$$

The characteristic pump curve has been translated for the pressurization guaranteed by the helium tank.

It has been used a MATLAB function Head_Loss, to calculate the distributed head losses coefficient, given the Reynolds number and the relative tube roughness.

All the calculation has been done for the maximum and minimum mass flow required by the engine.

6.1. NORMAL CONDITIONS

$$\dot{\mathrm{m}}_{\mathrm{p}}, min = 2\ g/s \quad \dot{\mathrm{m}}_{\mathrm{p}}, max = 10\ g/s$$

$$\dot m_P = \dot m_{al} \qquad Q_{al} = \frac{\dot m_{al}}{\rho} \qquad v_{al} = \frac{Q_{al}}{A_{al}} = \frac{Q_{al}}{\pi \frac{D_{al}^2}{4}} \qquad Re = \frac{\rho\, v_{al} D_{al}}{\mu}$$

$$\lambda = \lambda(Re, e) \qquad \Delta P_{losses} = \frac{1}{2} \rho v_{al}^2 \left(K + \lambda \frac{L_{al}}{D_{al}}\right)$$

$$P_{P,MIN} = P_{T,MIN} + \Delta P_{losses} \qquad P_{P,MAX} = P_{T,MAX} + \Delta P_{losses}$$

$$P_{P,min}(\dot m_{min}) = 0{,}5102\ MPa \qquad P_{P,min}(\dot m_{max}) = 0{,}7048\ MPa \qquad P_{PUMP}(\dot m_{min}) = 1{,}9918\ MPa$$

$$P_{P,max}(\dot m_{min}) = 2{,}4102\ MPa \qquad P_{P,max}(\dot m_{max}) = 2{,}6048\ MPa \qquad P_{PUMP}(\dot m_{max}) = 1{,}7738\ MPa$$

The pump pressure is between the values of minimum and maximum pressure for the minimum and maximum rate of mass flow; it’s expected that the pump is able to feed properly the engine in normal conditions.

6.2. EMERGENCY CONDITIONS

In these conditions as the pump need to supply a double mass flow as the normal case, the minimum and maximum flow rate need to be doubled since the previous case.

$$\dot{\mathrm{m}}_{\mathrm{p}}, min = 4\ g/s \quad \dot{\mathrm{m}}_{\mathrm{p}}, max = 20\ g/s$$

6.2.1. CROSSFEED LINE NEAR THE PUMP

The calculations are the same as 6.1, with the change that: $\dot{\mathrm{m}}_{\mathrm{p}} = 2\ \dot{\mathrm{m}}_{\mathrm{al}}$

$$P_{P,min}(\dot m_{min}) = 0{,}5102\ MPa \qquad P_{P,min}(\dot m_{max}) = 0{,}7048\ MPa \qquad P_{PUMP}(\dot m_{min}) = 1{,}9657\ MPa$$

$$P_{P,max}(\dot m_{min}) = 2{,}4102\ MPa \qquad P_{P,max}(\dot m_{max}) = 2{,}6048\ MPa \qquad P_{PUMP}(\dot m_{max}) = 1{,}0730\ MPa$$

The pump pressure is between the values of minimum and maximum pressure for the minimum and maximum rate of mass flow; it's expected that the pump is able to feed properly the engine with the crossfeed pipeline near the pump.

6.2.2. CROSSFEED NEAR THE THRUSTERS

The calculations are the same as in 6.1, as $\dot{m}_p = \dot{m}_{al}$

$$P_{P,min}(\dot{m}_{min}) = 0{,}5286\ MPa \qquad P_{P,min}(\dot{m}_{max}) = 1{,}2657\ MPa \qquad P_{PUMP}(\dot{m}_{min}) = 1{,}9657\ MPa$$

$$P_{P,max}(\dot{m}_{min}) = 2{,}4286\ MPa \qquad P_{P,max}(\dot{m}_{max}) = 3{,}1657\ MPa \qquad P_{PUMP}(\dot{m}_{max}) = 1{,}0750\ MPa$$

The pump pressure isn't between the values of minimum and maximum pressure for the minimum and maximum rate of mass flow, indeed the pump curve should crosse the minimum pressure pump before reaching the maximum flow rate required. The pump isn't able to feed properly the engine with the crossfeed pipeline near the engines.

6.3. TRANSFER

In this case is calculated the expression of the function of the head losses in the transfer pipeline in function of the mass pumped.

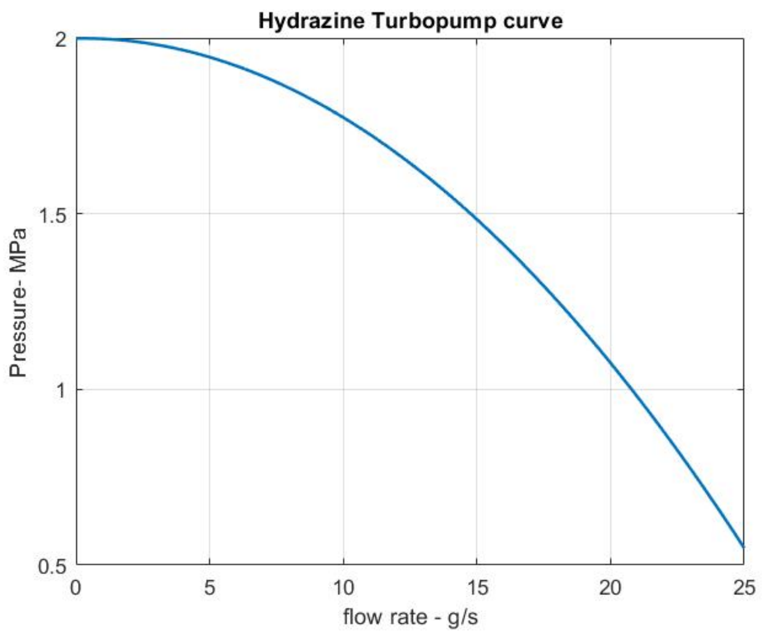
$$Q_{tr} = \frac{\dot{m}_p}{\rho} \qquad v_{tr} = \frac{Q_{tr}}{A_{tr}} = \frac{Q_{tr}}{\pi \frac{D_{tr}^2}{4}} \qquad Re = \frac{\rho v_{tr} D_{tr}}{\mu}$$

$$\lambda = \lambda(Re, e) \qquad \Delta P_{losses} = \frac{1}{2} \rho v_{tr}^2 \left(K + \lambda \frac{L_{tr}}{D_{tr}}\right)$$

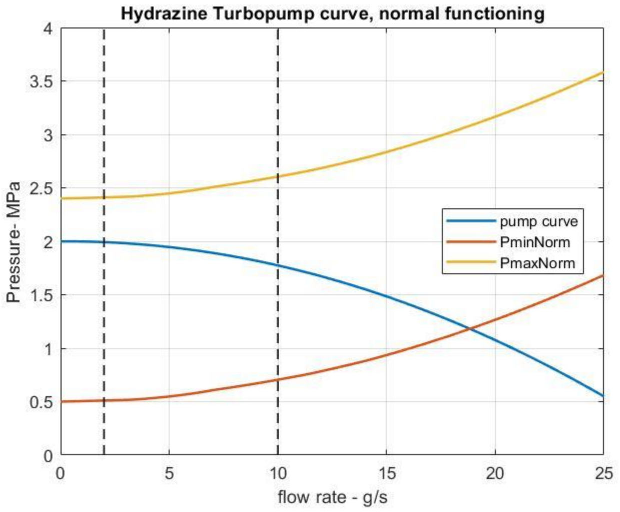
7. PRESENTATION OF THE RESULTS

It has been used Matlab to draw the plots.

It was necessary to interpolate the characteristic pump curve to analyse properly the data; it has been used the least square interpolation of grade 2, using the functions polyval and polyfit with the nodes, extrapolated empirically from the given pump curve. The curve has been translated, considering the pressurization of the hydrazine tank given from the helium tank.

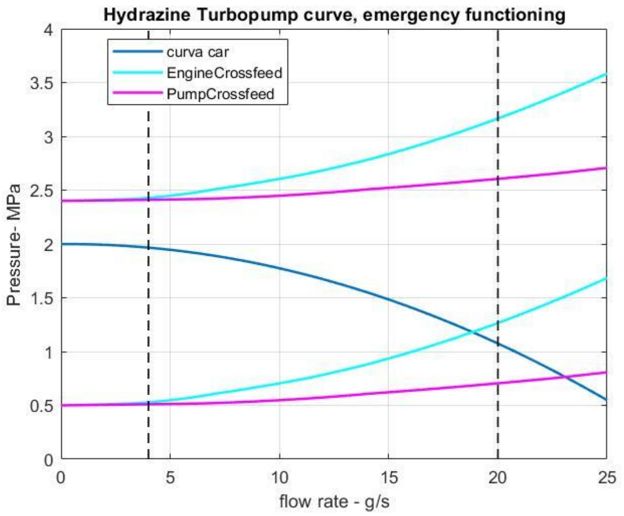


7.1. NORMAL FUNCTIONING



the turbopump guarantees the correct functioning of the space vehicle in normal conditions

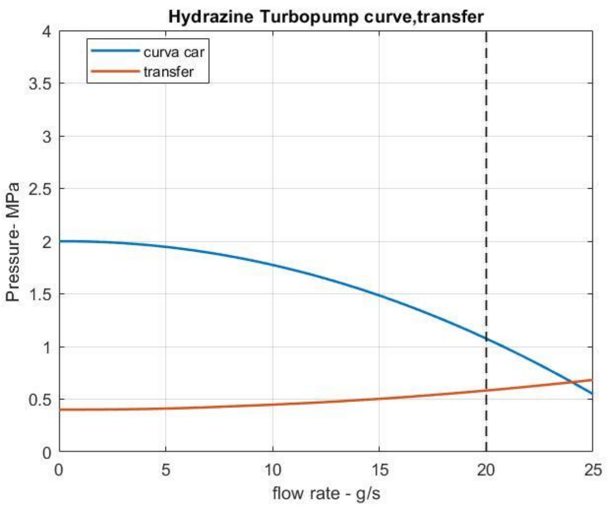
7.2. CROSSFEED



Due to head losses reasons, the crossfeed near the engines can't supply a mass flow with the minimum pressure required for the entire mass flow range.

The crossfeed near the pump, as expected, is efficient.

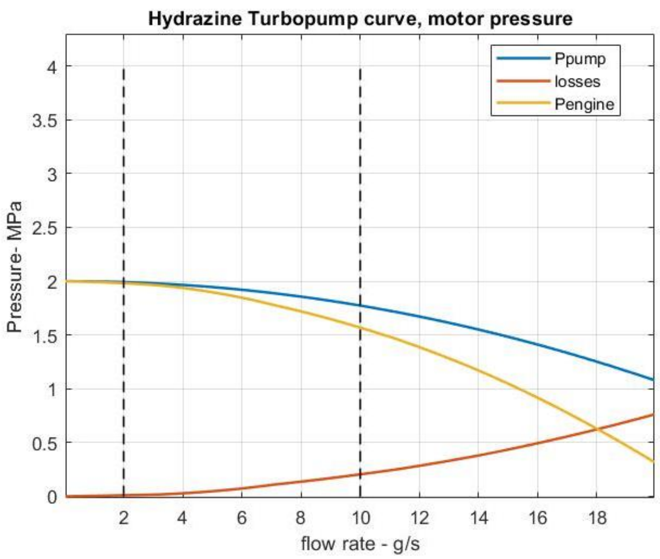
7.3. TRANSFER



The transfer head losses plot has been translated by the hydrazine tank pressurization.

The functioning point is for 24.015 g/s, bigger than the highest demand of fuel during emergency conditions.

7.4. ENGINE PRESSURE



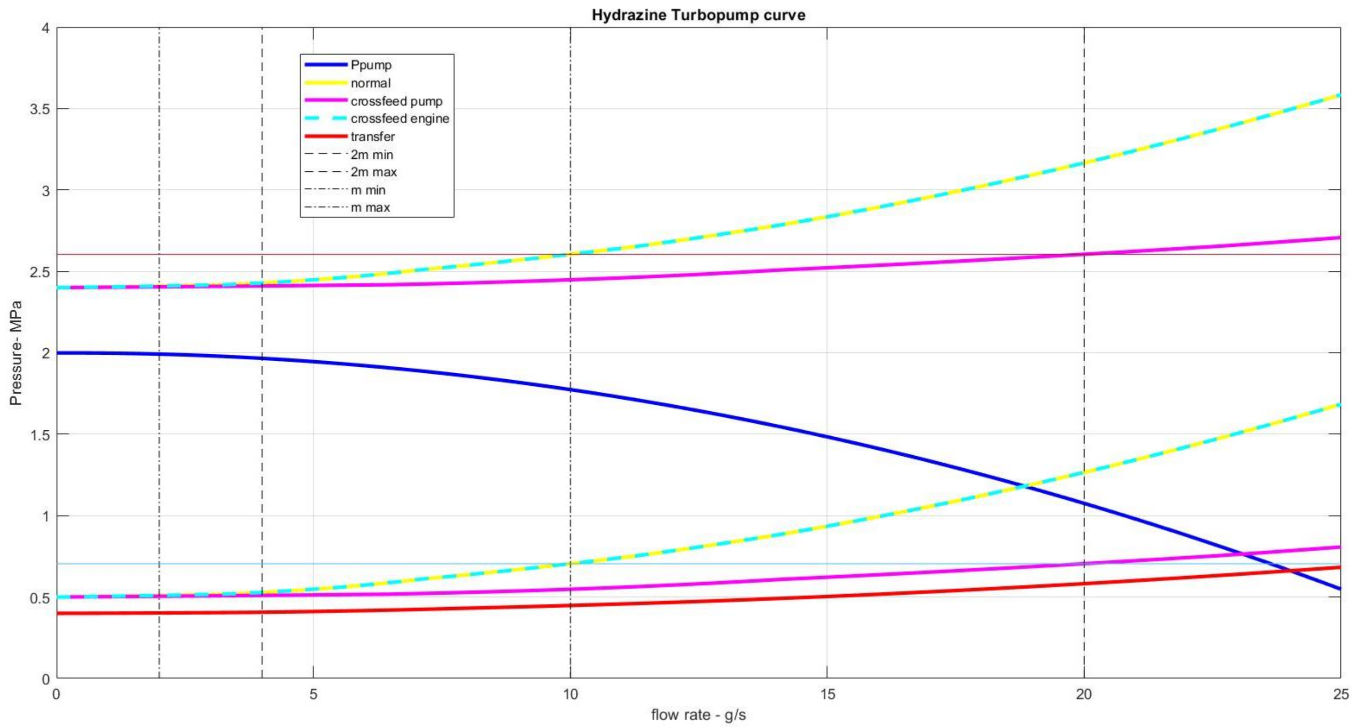
It's possible to calculate the fuel's pressure at the engine's inlet, knowing the pressure of the fuel supplied by the pump and the head losses of the fuel in the alimentation tube.

The plot is referred to normal functioning conditions.

7.5. FINAL PLOT

In this plot have been reported all the significant curves of this paper.

It's interesting to notice that the crossfeed pump curve presents the pressure values of the normal conditions for doubled mass flow, as expected.



8. CONCLUSION

The paper pointed out that the alimentation turbopump is suitable for normal conditions operations; the crossfeed pipeline must be as near to the pumps as possible, in order to decrease the head losses and guarantee the required performance; the introduction of a crossfeed pipeline near the engines needs some countermeasures as increasing the tube's diameter or the pressurization of the helium tank.

The transfer turbopump allows a continuous fulfilment of the principal tank, even in emergency conditions.