Effect of Oxidizer to Fuel Ratio on Tank Mass and Thickness for Liquid Fuel Dimethyl Aminoethyl Azide (DMAZ) with Some Oxidizers in Space Programs

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ABSTRACT: *Dimethyl aminoethyl azide (DMAZ), as a novel liquid fuel, is a good candidate for use in the upper stage of space rockets. One of the new features for the liquid fuel with conventional liquid oxidizers AK27 and nitrogen tetroxide (NT) is the dry mass estimation of tanks and thickness used for the tanks of DMAZ/AK27 and DMAZ/NT bipropellants through simple relations instead of complex relations. The oxidizer to fuel (O/F) ratio, as an important parameter, was applied for the estimations. In other words, the summation of the dry mass of tanks and bipropellants was calculated at certain values of O/F ratios. Moreover, the application of this simple method was developed for liquid fuels monomethyl hydrazine (MMH) and unsymmetrical dimethyl hydrazine (UDMH) with the liquid oxidizers. RPA software was used to find the optimum O/F ratio. The results showed that at a combustion chamber pressure of 15 bar, exit pressure of 0.001 bar, operation time of 480 seconds, and 7kN thrust, the lowest and the highest dry masses belong to NT/DMAZ and NT/MMH propellant tanks, respectively. Also, NT/MMH and AK27/DMAZ have the lowest and highest summation masses, respectively.*

KEYWORDS: *Dry mass of propellant tank; Thickness of propellant tank; O/F ratio; DMAZ; Oxidizers AK27and NT.*

INTRODUCTION

Liquid propellant rockets in space programs consist of different parts. One of the main parts is the fuel and oxidizer tanks, so about 70% of a rocket's volume is related to oxidizer and fuel tanks [1]. This is very important for the selection of fuel and oxidizer. This way, all attention is primarily on liquid propellants with high specific impulse, less ignition delay time, lower toxicity, and price [1-4]. The development history of liquid propellants confirms this [5].

Historical studies show the use of liquid fuels such as ethyl alcohol, kerosene (RP-1), liquid hydrogen, hydrazine fuels (like monomethyl hydrazine (MMH),

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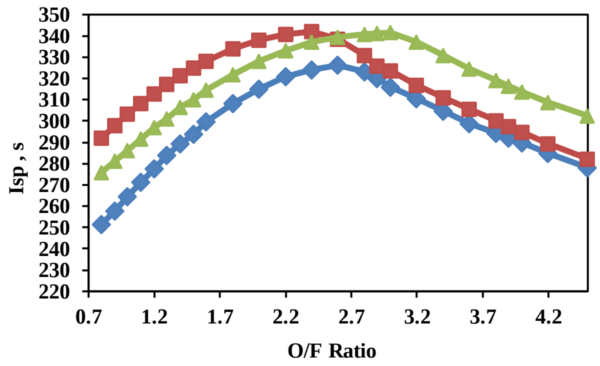

Fig.1: I_{sp} versus O/F ratio for different liquid fuels with NT oxidizer at combustion chamber pressure of 15 bar and exit pressure of 0.001 bar (NT/UDMH -▲-, NT/MMH -■-, NT/DMAZ-♦-)

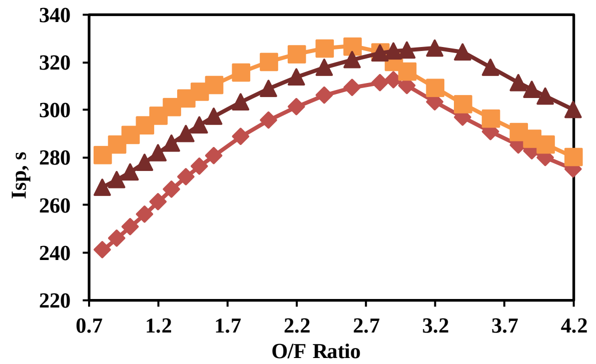

Fig.2: I_{sp} versus O/F ratio for different liquid fuels with AK27 oxidizer at combustion chamber pressure of 15 bar and exit pressure of 0.001 bar (AK27/MMH-■-, AK27/UDMH -▲-, AK27/DMAZ-♦-)

unsymmetrical dimethyl hydrazine (UDMH) and liquid mixture 50:50 of hydrazine and UDMH) in space programs. The hydrazine family is carcinogenic [6,7]. So, the green fuels are the target for space scientists and engineers. In this order, liquid fuel dimethyl aminoethyl azide (DMAZ) is new, green, and attractive [8-10]. It was introduced by the US Army [11]. Extensive studies have been performed on this fuel's chemical-physical and performance properties with different oxidizers [12-14]. However, there are no reports or documents for the tank mass of DMAZ and its corresponding oxidizer tank.

One key parameter in liquid propellant design is the Oxidizer to Fuel (O/F) ratio. The maximum specific impulse for a rocket is calculated at the optimum O/F ratio [15]. The effect of oxidizer-to-fuel mass ratio on dry and wet mass, specific impulse, propellant volume, and combustion chamber mass is impressive in comparison with chamber pressure and nozzle expansion ratio [16-18]. In other words, the mass was obtained as a function of chamber pressure, oxidizer-to-fuel ratio, required thrust, and the geometrical parameters of the engine and propellant tanks. The assessment of this dependency is carried out via complex relations and algorithms [19-21].

In this article, O/F ratio was considered as a starting point for the calculation and evaluation of propellant tank mass for novel liquid fuel DMAZ in space programs. For this purpose, liquid oxidizers used for calculations are nitrogen tetroxide (N_2O_4) and Inhibited Red-Fuming Nitric Acid (IRFNA). IRFNA is a mixture of 71 wt% HNO_3, 27 wt% N_2O_4, and balanced water. The former oxidizer is abbreviated as NT. The latter is consumed in eastern countries such as China and Russia with the symbol AK27 [22].

In other words, the dependency of DMAZ and corresponding oxidizer or oxidizers tank mass on O/F ratio will be studied easily and not in complex methods. For comparison, this will be also performed for liquid fuels MMH and UDMH.

CALCULATION REQUIREMENTS

Except for the total mass of propellant tanks, it was assumed that the mass of other parts of the space rocket (such as control and guidance systems, batteries, wings etc.) was constant or not considered. For a better understanding of the problem, in this article, the thrust of the rocket in the upper stage is considered as 7 kN. Moreover, the flight time for this stage is 480 seconds. This is close to real thrust in the upper stage of some rockets (like PSLV of India used in space programs [23]).

Liquid oxidizers used for calculations are nitrogen tetroxide (N_2O_4) and AK27. Liquid fuels in these calculations are dimethyl aminoethyl azide (DMAZ), monomethyl hydrazine (MMH), and unsymmetrical dimethyl hydrazine (UDMH).

Specific impulse is calculated via RPA software. The software is based on minimizing Gibbs free energy [24]. Knowing the thrust and Oxidizer to Fuel (O/F) ratio for each propellant, mass flow rates of fuel and oxidizer will be derived. The mass of fuel and oxidizer will be determined if the operation time of the engine is known. Therefore, the volume of tanks for fuel and oxidizer will be calculated.

RESULTS AND DISCUSSION

Performance evaluation of propellants

The combustion chamber pressure in orbital transmission block engines equipped with a gas-pressurized feed system is considered less than 30 bar. For example, in the fourth

Table 1: Maximum specific impulse at optimized O/F ratio for the liquid fuels with oxidizer NT and AK27 (at combustion chamber pressure of 15 bar and exit pressure of 0.001 bar)

Propellant	Optimized O/F ratio	I_{sp}, s
MMH/NT	2.4	342.0
UDMH/NT	3.0	341.4
DMAZ/NT	2.6	326.0
MMH/AK27	2.6	326.9
UDMH/AK27	3.0	326.7
DMAZ/AK27	2.9	312.5

Table 2: Maximum density-specific impulse at optimized O/F ratio for the liquid fuels with oxidizer NT and AK27 (at combustion chamber pressure of 15 bar and exit pressure of 0.001 bar)

Propellant	Optimized O/F ratio	I_{sp},s	$d_{propellant} \times I_{sp}$, s
MMH/NT	2.4	342.0	436.05
UDMH/NT	3.0	341.4	436.3
DMAZ/NT	2.6	326.0	423.7
MMH/AK27	2.6	326.9	429.5
UDMH/AK27	3.0	326.7	427.6
DMAZ/AK27	2.9	312.5	419.0

Table 3: propellant mass at optimized O/F ratio with oxidizer NT and AK27 at thrust 7kN and flight time 480 s

Propellant	O/F ratio	$m_{propellant}=m_{ox}+m_{f}$, kg
DMAZ/NT	2.6	982.1
UDMH/NT	3.0	984.0
MMH/NT	2.4	1030.5
DMAZ/AK27	2.9	1027.7
UDMH/AK27	3.2	1028.2
MMH/AK27	2.6	1075.2

stage of the Vega rocket (known as RD869) with a thrust 2.45 kN, the chamber pressure is 17 bar [25]. Another example is in the upper stage of Atlas 5 (known as Centaur RL-10C) in which the pressure is 24 bar. The chamber pressure in the upper stage is less than 30 bar due to entering the stage to vacuum [26].

Specific impulse (I_{sp}) versus O/F ratio for the mentioned fuels with NT and AK27 oxidizers are demonstrated in Figs.1 and 2. This is drawn for an orbital transition block with a chamber pressure of 15 bar and an exit pressure of 0.001 bar.

According to Figs. 1 and 2, the highest specific impulse with oxidizers NT and AK27, and the corresponding O/F ratio will be given in Table 1.

Pakdehi and *Shirzadi* [24] obtained an optimum O/F ratio of 2.6 for DMAZ/NT bipropellant at a chamber pressure of 140 bar. The amount of I_{sp} was achieved as 352 seconds. Increasing the chamber pressure will enhance the specific impulse. Similarly, this is true for DMAZ/AK27. In a similar way, this conclusion is true for MMH/NT, UDMH/NT, MMH/AK27, and UDMH/AK27 [13,24].

For the design of a rocket, the density-specific impulse ($d_{propellant} \times I_{sp}$) is more important than the specific impulse [1]. The specific gravity of a fuel–oxidizer mixture can be estimated by [1]:

$$d_{propellant} = \frac{\delta_{oxidizer} \times \frac{O}{F}}{1+\frac{O}{F}} + \frac{\delta_{fuel}}{1+\frac{O}{F}} \tag{1}$$

As shown in Eq. (1), the density of a propellant is a homographic function with O/F as the variable and $\delta_{oxidizer}$ and δ_{fuel} as the constants. In this function, zero O/F corresponds to δ_{fuel} for $d_{propellant}$ and a very high value for O/F corresponds to $\delta_{oxidizer}$ for $d_{propellant}$. Therefore, for next calculations, the higher O/F will achieve higher $d_{propellant} \times I_{sp}$.

The density-specific impulses at the optimum O/F ratio for the propellants are given in Table 2. The specific gravity of MMH, UDMH, and DMAZ are 880, 793, and 933, respectively [1]. Also, the specific gravity of NT and AK27 are 1440 kg/m^3 and 1482 kg/m^3, respectively [1].

Tank volume determination

Based on a thrust 7 kN and an operation time of 480 s for the upper stage, the mass flow rate of propellant is given in below [1]:

$$\dot{m}_p \, g = \frac{F}{I_{sp}} \tag{2}$$

For each propellant at optimized O/F ratios, the propellant mass is given in Table 3.

Since the propellant mass flow rate is the summation of fuel and oxidizer mass flow rates, mass flow rates are calculated for each fuel and oxidizer as below [1]:

$$\dot{m}_f = \frac{\dot{m}_t}{(1+\frac{O}{F})} \tag{3}$$

$$\dot{m}_{ox} = \dot{m}_t - \dot{m}_f \tag{4}$$

Table 4: The thickness of tanks for liquid propellants at optimized O/F ratios

Propellant	Optimized O/F ratio	Fuel tank thickness, mm estimated in this research	Fuel tank thickness, mm [35]	oxidizer tank thickness, mm estimated in this research	oxidizer tank thickness, mm [35]
AK27/DMAZ	2.9	0.789	-	0.909	-
AK27/UDMH	3.2	0.776	1.009	0.904	1.175
AK27/MMH	2.6	0.791	1.028	0.874	1.136
NTO/DMAZ	2.6	0.799	-	0.888	-
NTO/MMH	2.4	0.794	1.032	0.897	1.166
NTO/UDMH	3.0	0. 760	0.988	0.910	1.183

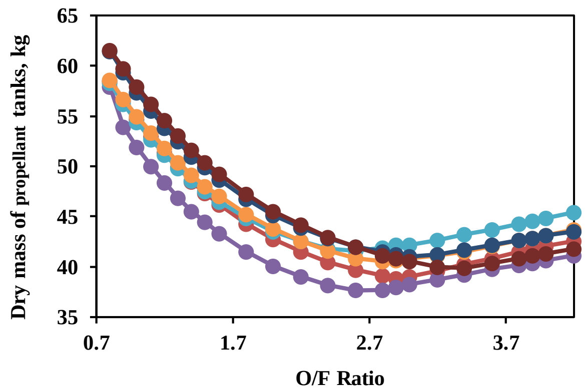

Fig. 3: Dry mass of the propellant tanks versus O/F ratios for various propellants at combustion chamber pressure of 15 bar and exit pressure of 0.001 bar and operation time of 480 seconds and 7kN thrust
(-•- AK27/DMAZ, -•-NT/DMAZ, -•-AK27/MMH, -•- NT/MMH, -•-AK27/UDMH, -•- NT/UDMH)

At an optimized O/F ratio, mass flow rates will be calculated for fuel and oxidizer. Like other chemical tanks, there is a void space in the tank measured from the top of the tank to the upper surface of the fluid. This volume is ullage. This volume is typically15% of the total volume of the tank. Keeping free space or ullage is necessary to ensure that the gas or vapor being transported is always in contact with the pressure relief valve. Secondly, this specific space is left to allow for the expansion of liquids during transportation. With the given operation time of 480 s as well as 15 vol% for ullage [27], the volumes of fuel and oxidizer tanks will be calculated.

Assessment of thickness and dry mass tank for propellants

For the propellant tanks in spherical shapes, the radius of each spherical tank leads to tank thickness calculation. Among the materials for storage of liquid fuels or oxidizers, stainless steel 316L is a good candidate [1]. If the tank material is stainless steel 316L, the allowable tension for the tank will be 170 MPa [28]. If the operation pressure of the tank plus the pressure drops from tanks to the combustion chamber is considered as 30 bar [29], the radius of each tank is given as:

$$R = \sqrt[3]{\frac{3V_{\text{tank}}}{4\pi}} \tag{5}$$

The thickness of each tank is given in below [30]:

$$\tau = \frac{2R \times P_{WP}}{2\delta} \tag{6}$$

where R: the tank radius
τ: the tank thickness
δ: the allowable tension for the tank material
P_{WP}: the operational pressure of the tank

Based on the above calculations, the results for calculations of propellant tank thicknesses are given in Table 4 at the optimized O/F ratios. A minimum tank wall thickness of 0.75mm was chosen in the preliminary design for manufacturability and practicality [31-34].

The thickness of tanks for propellants AK27/UDMH, AK27/MMH, NTO/MMH and NTO/UDMH are given in this table for comparison [35].

As shown in Table, the mean thickness of dray mass for AK27/UDMH, AK27/MMH, NTO/MMH, and NTO/UDMH tanks is more 30% than the designed thickness of this research. Therefore, the thicknesses of 1.025 mm and 1.040 mm for DMAZ tank are suggested in AK27/DMAZ and NTO/DMAZ bipropellants, respectively. Also, the suggested values for the thickness the oxidizer tank in AK27/DMAZ and NTO/DMAZ bipropellants are 1.181mm and 1.154 mm, respectively.

The dry mass of tanks is derived from the tank radius and thickness through Eq. (5) and Eq. (6). This value is shown in Fig. 3 for various O/F ratios.

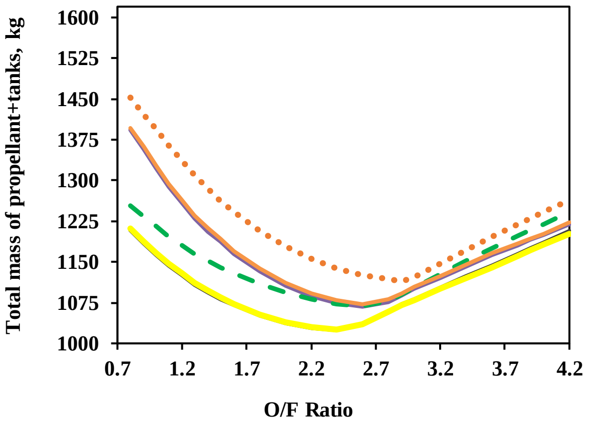

***Fig.4:** Summation of dray mass of propellant tank and propellant mass versus O/F ratio for different propellants at a combustion chamber pressure of 15 bar and exit pressure of 0.001 bar and operation time of 480 seconds and 7kN thrust (....AK27/DMAZ, —NT/DMAZ, ----AK27/MMH, —NT/MMH, — AK27/UDMH, — NT/UDMH)*

As is seen from Fig.3, all graphs have a minimum dry mass of propellant tanks at optimum O/F ratio. *Parks* [36] illustrated this graph through complex equations. He pointed there is an O/F ratio minimizing the dry mass of propellant tanks. The lowest dry mass belongs to NT/DMAZ bipropellant tanks whereas NT/MMH bipropellant tanks have the highest dry mass.

For each propellant, a summation of the dry mass of the liquid/fuel tanks and the propellant is given in Fig. 4.

Similar to Fig.3, it is shown in Fig. 4 that the summation of the dry mass of the propellant tank and propellant mass versus O/F ratio for different propellants has a minimum at the optimized O/F ratio. Also, the lowest summation mass belongs to NT/MMH bipropellant but AK27/DMAZ bipropellant has the highest value.

CONCLUSIONS

Due to a lack of data for novel liquid fuel DMAZ, a simple method for estimation of dry mass and thickness of tanks used for the fuel was applied. The application of O/F ratio idea was investigated to estimate the dry mass and thickness of tanks used for DMAZ/AK27 and DMAZ/NT bipropellants. Using the optimum ratio, found with RPA software, also leads to calculating the summation of the dry mass of tanks and bipropellants, as well as the tank thickness of both bipropellants. This idea was also applied to MMH/AK27, MMH/NT, UDMH/AK27 and UDMH/NT bipropellants. The results indicated that at combustion chamber pressure of 15 bar (as a traditional pressure in the upper stage), exit pressure of 0.001 bar (the air pressure in upper altitudes), operation time of 480 seconds, and 7kN thrust, the lowest dry mass belongs to NT/DMAZ bipropellant tanks whereas the highest dry mass belongs to NT/MMH bipropellant tanks. Also, NT/MMH bipropellant has the lowest summation masses and AK27/DMAZ has the highest.

It is recommended to study the effect of O/F ratio on the estimation of the dry mass of tanks for various cylindrical storage tanks.

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Nomenclatures

AK27	a liquid oxidizer containing 27 wt% of nitrogen tetroxide and 71-73 wt% nitric aid
DMAZ	dimethyl aminoethyl azide
$d_{propellant}$	specific density of propellant [-]
F	thrust [N]
g	gravity acceleration [m/s^2]
IRFNA	inhibited red fuming nitric acid
I_{sp}	specific impulse [s]
MMH	monomethyl hydrazine
m_f	fuel mass [kg]
m_{ox}	oxidizer mass [kg]
$m_{propellant}$	propellant mass [kg]
$\dot{m}_f$	mass flow rate of fuel [kg/s]
$\dot{m}_{ox}$	mass flow rate of oxidizer [kg/s]
$\dot{m}_p$	mass flow rate of a propellant [kg/s]
NT	nitrogen tetroxide or N_2O_4
O/F	oxidizer to fuel [-]
R	tank radius [m]
UDMH	unsymmetrical dimethyl hydrazine
V_{tank}	tank volume [m^3]
δ	allowable tension for the tank material [N/m^2]
δ_{fuel}	specific gravity of fuel [-]
$\delta_{oxidizer}$	specific gravity of oxidizer [-]
τ	tank thickness [m]

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