# RAMJET THRUSTER USING OZONE DISSOCIATION ENERGY FOR HIGH ALTITUDE OPERATION

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*We present an innovative high altitude propulsion unit using the chemical energy stored in the typical chemical compounds (e.g.: ozone) encountered at higher altitudes within the atmosphere. The ozone enters the ramjet thruster through an inlet and within the thruster the ozone is determined to dissociate chemically in oxygen. The heat generated by the dissociation accelerates the resulted oxygen through an outlet, hence, generating thrust. The amount of thrust depends on the cross section of the ramjet and the energy density stored in the upper atmosphere. A thermo-chemical estimation that takes into account the enthalpies of input and output chemical substances is shown within the paper. The thermo-chemical calculation is then coupled with one dimensional gas dynamic equation of ozone flow through the ramjet thruster. Next, the paper presents the dynamics equation for the overall thruster taking into account gravitational force, aerodynamic force and thrust force all of them being functions of mass, velocity and geometrical dimensions. The thruster can produce thrust that can overcome aerodynamic force for a given ozone density and the difference between thrust and drag is also shown as a function of speed. Connecting the ozone density with altitude by using standard high altitude atmospheric models we derive the velocities attainable at 30,000 meters altitude. One of the big advantages of such a thruster is that it allows continuous operation at high altitudes without the need of a storable fuel onboard. The boost needs to bring the ramjet within the speed operating envelope for a given altitude and then the ramjet produces excessive thrust that maintains the burnout speed. Once the velocity is reached and the ramjet is activated, it can work indefinitely from the propulsion point of view. As a future development we propose a high altitude experiment to validate some of the theoretical models and refine the results for further technological developments.*

**Keywords**: UAV, ramjet, thruster, ozone

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## 1. Introduction

The altitude band between 40 and 80 km is especially attractive for high speed flights within special application missions. The atmosphere in that altitude region is low enough such that the drag forces allow high speeds to be reached and maintained for prolonged periods of time. At the same time this altitude band is lower than the practical orbits of reconnaissance satellites and higher than the maximum practical altitude of traditional airplanes. The altitudes can be reached with balloons and rockets but while the first ones have very low speed and almost no controllability since they are carried by high altitude winds the former have high speeds but very short time of operation.

Hence one can say that reaching and maintaining high speeds (~Mach 7-9) at 40-80 km for 3-4 hours can be in some respects even more difficult than reaching the orbit due to special requirements for the propulsion unit. While the propulsion unit should have the high end velocities of rocket motors it should also have very long burn times impossible to obtain from current rocket motors. The fuel requirements for a rocket motor to reach Mach 7-9 for 2-3 hours are impractical, let aside the stress that the rocket motor should undergo in order to operate for hours burn time.

On the other side, air-breathing motors have long been studied and can offer long burn times with higher fuel efficiency than rocket motors. However, they have at least 2 drawbacks for high speed, high altitude operation:

1.) between 40 and 80 km there is not sufficient air for the air breathing motors to operate;

2.) they cannot reach Mach 7-9.

In this paper, we propose a ramjet engine that uses the energy stored in the upper atmosphere ozone layer similar to units previously proposed by other authors [1]. The energy stored in the ozone can be used through its dissociation into atomic oxygen. The main advantage is that the ramjet does not need to carry any fuel or oxidizer; only onboard power for various equipments is needed and this can be obtained through conventional batteries, solar power, fuel cells or a combination of these solutions.

In order for the ramjet solution to operate one has to propel the engine at a high initial speed at which the thrust generated by the ramjet is larger than the drag forces hence offering a positive net propulsion force. The initial speed can be obtained through the usage of a solid rocket motor booster since the acceleration especially for unmanned platforms can be high enough for a short burn time of the booster. Such an unmanned aerial vehicle equipped with the high altitude ozone ramjet (HAOR) can travel from New York to Calcutta (~12.000 km) in around 60 minutes.

In this paper we first present an atmosphere model focusing on ozone concentration existing at high altitudes. Next we present a mathematical model that evaluates through energy balance equations the amount of thrust that the proposed ozone dissociation thruster would generate. Based on the atmosphere model and the thrust model we build six degrees of freedom model that helps us understand the trajectory of the proposed high altitude UAV propelled by the ozone dissociation thruster after it separates from the booster.

The paper represents just the first step in studying this propulsion unit the authors realizing that future experiments and validations should be performed in order to implement such technology.

## 2. Atmosphere model

The atmospheric model used in this paper follows the characteristics shown in [1], [2] and [7].

The vertical distribution of ozone has been obtained through both sounding rockets and high altitude balloon flights in the past 70 years. The UV absorption observed from the ground is yet another type of measurement through which the scientists can infer the ozone layer characteristics. Both the flight measurements and the ground measurements agree with a maximum concentration of ozone at around 30,000 meters altitude. For our propulsion method concept it directly follows that the altitudes of operation at around 30,000 meters are the most desirable since the maximum energy stored in ozone should be available there. Table 1 shows the heat of formation for the ozone and atomic oxygen. The heat of formation in this case is the change in enthalpy that would occur if the molecular oxygen would be transformed in either ozone or atomic oxygen. The enthalpy changes with the temperature but in our study we assume it to be constant and equal to 270 K. This is approximately the temperature at 30 km altitude at which we study the functioning of our ozone ramjet thruster.

*Table 1*

**Heat of formation**

| Components | Heat of formation J/g-mole |
|---|---|
| Ozone | $1428 * 10^5$ |
| Atomic oxygen | $2484.72 * 10^5$ |

Considering a typical density $\rho = 6.09 \cdot 10^{-10} kg/m^3$ at 30480 meters altitude then we can compute the energy available per unit of volume by considering the enthalpies. We obtained similar values for the density throughout a series of high altitude flights that we performed both in Romania and Australia. Similarly ozone concentration was evaluated on the same flights by using a dedicated ozone sensor installed on the previous mentioned high altitude payloads.

For ozone we have the following enthalpy of formation:

$$\Delta h_{O_3} = 0 \text{ J/m}^3 \quad (1)$$

and also:

$$\Delta h_O = 0.00002189299 \text{ J/m}^3 \quad (2)$$

Finally the total atmospheric stored energy per volume unit is:

$$dW = \Delta h_O = 0.00002189299 J / m^3 \quad (3)$$

We should note that the energy computed above is only the energy available from ozone conversion to atomic and, then, molecular oxygen. Other chemical species are present in the upper atmosphere and they can also be considered for energetic transformations inside a propulsion unit and the available energy per unit volume would then increase. However, for a conservative estimation we only consider the ozone as "the reservoir of energy" for our propulsion unit. One more detail that one should note is the fact that all the measurements in the upper atmosphere represent only a snapshot at a certain moment in time. Conditions up there vary with the seasons and with the latitude and for a complete study to be performed more data covering more consequently the entire world regarding the upper atmosphere characteristics would be needed.

This way the propulsion unit performance could be studied as a function of position on the globe and, hence, a flight table could be derived that could be used when programming the flight missions.

### 3. Flight dynamics with ozone ramjet thruster

The general structure of a ramjet is shown in Fig.1

As one can see the motor consists of an inlet that has the purpose to bring the ozone into the motor. Next the ozone is passed into the combustion chamber where it dissociates in atomic oxygen and then the dissociation products are exhausted through a nozzle. An important aspect to note is that some of the atomic oxygen recombines within this chamber which decreases the overall efficiency of the motor. The less atomic oxygen recombines, the higher the efficiency of the motor.

The mass flow of air that enters the ramjet is given by:

$$\dot{m} = \rho v S \quad (3)$$

where $\rho$ is the atmospheric density, $v$ is the velocity and S is the cross section of the vehicle. Hence, the total energy stored in the air that enters the motor is given by the relation:

$$dW = \eta e \rho v S dt \quad (4)$$

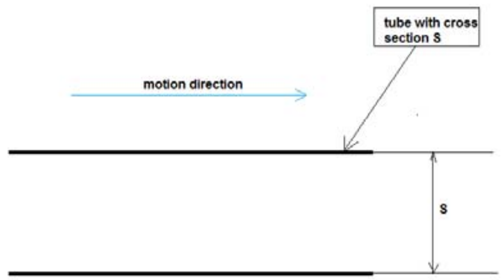


Fig.1 Ramjet conceptual schematics

where $\eta$ is the overall ramjet efficiency, $e$ is the energy density in the upper atmosphere due to potential ozone dissociation, $dt$ is the time increment.

Generally the efficiency of ramjet η depends on the geometry of the engine as well as on atmospheric conditions (if various altitudes are considered). In this paper we assumed the efficiency to be close to 90% based on the value also used in reference [1].

Next step is to evaluate the thrust of the ramjet as being given by the following relation using a methodology similar to the one found in [8]:

$$T = \eta e \rho v S dt \tag{5}$$

The entire ramjet is considered to be placed on a “rocket” shaped vehicle with short, stubby wings. In order to study the motion of the vehicle we employ two frames of reference: the body frame and the Earth frame shown schematically in Fig. 2.

The body frame is fixed with respect to the vehicle having the X axis pointing along the longitudinal axis of the vehicle while the Y axis points along the starboard of the vehicle. The Z axis is chosen conventionally to point straight down with the down being defined straight through the floor of the vehicle. The Earth reference frame is attached to the Earth (usually its origin coincides with the launch point) having the X positive axis pointing towards the North and the Y positive axis pointing towards East. The Z axis points upward indicating the local vertical. Considering the body reference frame one can describe the motion of the vehicle by using the following 6 equations (one for each degree of freedom). We follow general conventions from [3] and [4].

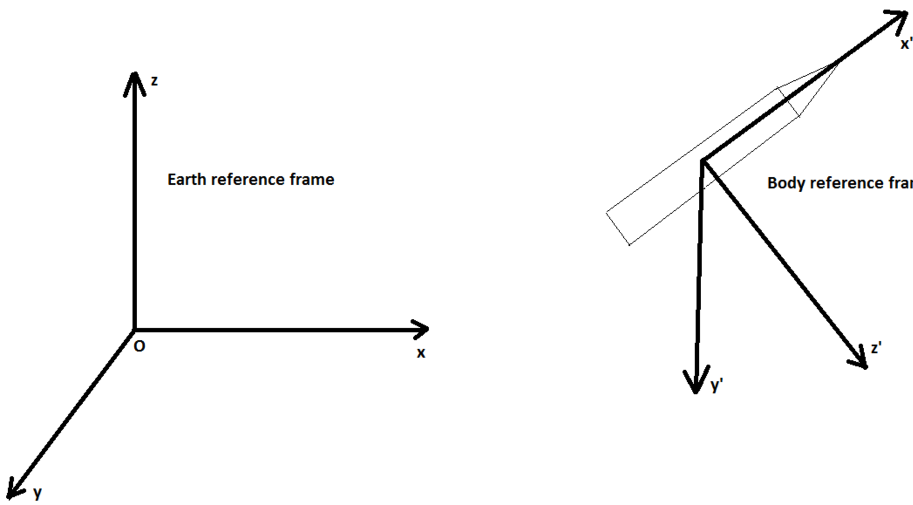


Fig.2 Earth and body reference frames

Three equations are written for the translations:

$$\dot{u} = \frac{1}{m}(T + F_{axial}) - g\sin\theta + rv - qw \tag{6}$$

$$\dot{v} = \frac{1}{m}F_{side} + g\cos\theta\sin\varphi + pw - ru \tag{7}$$

$$\dot{w} = \frac{1}{m}F_{normal} - g\cos\theta\cos\varphi + qu - pv \tag{8}$$

where $\dot{u}$, $\dot{v}$, $\dot{w}$ are the acceleration components in body reference frame, $m$ is mass, $w, u, v$ are the velocity components in the body reference frame, $q, p, r$ are the rotation rates around body reference axis, $g$ is the gravitational acceleration, $\theta, \varphi$ are the pitch and roll angles, $F_{side}, F_{normal}, F_{axial}$ are the side, normal and axial components of the aerodynamic force.

Another three equations are written for the rotation dynamics similar to ones used in [4] and [5]:

$$\dot{p} = \frac{1}{I_{xx}}[M_{propulsion} + M_x + (I_{yy} - I_{zz})] \tag{9}$$

$$\dot{q} = \frac{1}{I_{xx}}[M_y + (I_{zz} - I_{xx})] \tag{10}$$

$$\dot{r} = \frac{1}{I_{xx}}[M_z + (I_{xx} - I_{yy})] \tag{11}$$

where $M_x, M_y, M_z$ are the aerodynamic momentum components, $I_{xx}, I_{yy,} I_{zz}$ are the main body momenta of inertia.
The aerodynamic forces and moments can be computed by the following relations [6]:

$$F_{axial} = \frac{1}{2}\rho v^2 S(-C_A) \tag{12}$$

$$F_{side} = \frac{1}{2}\rho v^2 S(-C_{\gamma\beta}\beta) \tag{13}$$

$$F_{normal} = \frac{1}{2}\rho v^2 S(-C_{N\alpha}\alpha) \tag{14}$$

$$M_x = \frac{1}{2}\rho v^2 L(C_l + \frac{C_{lp} pL}{2v}) \tag{15}$$

$$M_y = \frac{1}{2}\rho v^2 L[C_{m\alpha}\alpha + (C_{m\dot{\alpha}} + C_{mq})\frac{qL}{2v}] \tag{16}$$

$$M_z = \frac{1}{2}\rho v^2 L[C_{n\beta}\beta + (C_{nr} r + C_{np} p)\frac{L}{2v}] \tag{17}$$

where $C_A$ is the axial force coefficient, $C_{m\alpha}$ is the pitching moment coefficient derivative with angle of attack, $C_{m\dot{\alpha}}$ is the pitching moment coefficient derivative with angle of attack rate, $C_{mq}$ is the pitching moment coefficient derivative with pitch rate, $C_{n\beta}$ = Yawing moment coefficient derivative with side slip angle, $C_{nr}$ is the yawing moment coefficient derivative with yaw rate, $C_{np}$ is the yawing moment coefficient derivative with pitch rate, $C_{\gamma\beta}$ is the side force coefficient derivative with sideslip angle, $C_{N\alpha}$ is the normal force coefficient derivative with angle of attack.

The above equations are written assuming that the vehicle is a rigid solid and that the Earth is flat and non-rotating.
In order to include the fact that the Earth is spherical and rotating we can generalize the above equations in the following way [3], [5] and [6]:

$$\begin{bmatrix} P \\ Q \\ R \end{bmatrix} = \begin{bmatrix} p \\ q \\ r \end{bmatrix} - T \begin{bmatrix} (\omega^E + \dot{\mu})\cos\varphi \\ -\dot{\lambda} \\ -(\omega^E + \dot{\mu})\sin\varphi \end{bmatrix} \tag{18}$$

where $P, Q, R$ are the angular rates in Earth reference frame, $\omega^E$ is the Earth's angular velocity, $\lambda$ is the latitude of the center of gravity of the body with respect to Earth's reference system, $\mu$ is the longitude of the center of gravity of the body with respect to Earth's reference system.

In the above equation T is the rotation matrix from body reference frame to Earth reference frame and it is given by the following structure:

$$T = \begin{bmatrix} T_{11} & T_{12} & T_{13} \\ T_{21} & T_{22} & T_{23} \\ T_{31} & T_{32} & T_{33} \end{bmatrix} \tag{19}$$

Where the elements of the rotation matrix T are given by the following equalities:

$T_{11} = \cos\theta\cos\psi$

$T_{12} = \cos\theta\sin\psi$

$T_{13} = -\sin\theta$

$T_{21} = \sin\varphi\sin\theta\cos\psi - \cos\varphi\sin\psi$

$T_{22} = \sin\varphi\sin\theta\sin\psi + \cos\varphi\cos\psi$

$T_{23} = \sin\varphi\cos\theta$

$T_{31} = \cos\varphi\sin\theta\cos\psi + \sin\varphi\sin\psi$

$T_{32} = \cos\varphi\sin\theta\sin\psi - \sin\varphi\cos\psi$

$T_{33} = \cos\varphi\cos\theta$

The most difficult part in numerical estimations is to obtain valid aerodynamic coefficients for the high speed, high altitude operation of the chosen vehicle. One method to obtain these coefficients is to use the dedicated software MISSILE DATCOM that can offer tabulated coefficients for a wide range of flight envelopes.

Another option is to use a semi-analytical approach and consider semi-empirical relations for each of the coefficients. The advantage of this method is the readily availability and the possibility to obtain fast results. However, the precision of the semi-analytical approach might be lower than the MISSILE DATCOM approach.

## 4. Numerical results

Two main strategies from the numerical point of view can be used.

One of them involves computing the accelerations in the body frame using equations (6) through (11).

Then the accelerations can be integrated once using Runge-Kutta 4 obtaining the velocities in the body frame. The angular velocities are transformed at this point to the rotating Earth reference frame by using relation (18). The velocity field can be rotated using the rotation matrix T and then integrated again to find the positions and the attitude angles. Another numerical strategy involves finding the accelerations by using the equations (6) through (11) without using the cross term products in the translation acceleration relations.

Hence, the new translation accelerations in the body frame are given by the relations:

$$\dot{u} = \frac{1}{m}(T + F_{axial}) - g\sin\theta \tag{20}$$

$$\dot{v} = \frac{1}{m}F_{side} + g\cos\theta\sin\varphi \tag{21}$$

$$\dot{w} = \frac{1}{m}F_{normal} - g\cos\theta\cos\varphi \tag{22}$$

The angular accelerations are not modified are still given by the equations (9) through (11).

Next, the body frame accelerations are rotated through the rotation matrix (20) to the Earth reference frame and then integrated twice by using Runge-Kutta 4. An important thing to note for this method is that the angular velocities after being transformed to the rotating Earth reference frame has to be rotated back from Earth reference frame to body reference frame and then integrated once in order to find the attitude angles. Both methods are mathematically equivalent and should provide similar results.

We used the above equations and modelled the trajectory of a proposed high altitude UAV using the ozone ramjet thruster. We considered that initially the vehicle has an upwards angle (similar to the angle it would have when leaving the launcher). This leads to an increase in altitude which leads to a further decrease in ozone concentration which in turn leads to a decrease of thrust force. Propagating the trajectory solution we observe a “wave” like trajectory being generated by the variation of thrust due to variation of ozone density at various altitudes. The oscillation of trajectory has amplitude which depends on the equilibrium relation between thrust and overall drag force. The amplitude of the trajectory damps over time due to drag forces and moments bringing the vehicle towards the “equilibrium” altitude which was assumed to be 30 km. Throughout the simulation we assume that the vehicle is trimmed “up” which creates an increasing lift force with the increase of velocity equivalent to nose-up attitude. This way at the bottom of the trajectory it is produced an effect of nose-up attitude which generates the wave-like trajectory as shown in Fig. 3.

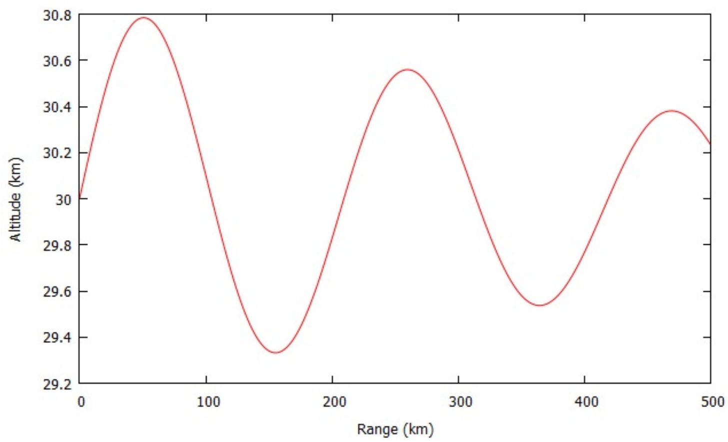


Fig.3 Wave-like trajectory

For our model in Fig. 3 we assumed that the object to be propelled has a mass of 20 kg with a wingspan of 2.5 meters. We used aerodynamic coefficients available in the literature for arrow shaped vehicles [4] and [5]. It is also assumed that the booster imparts 950 m/s to the vehicle at an inclination (above local horizontal) of 70 degrees.

Another key parameter is the needed initial velocity in order for the HAOR to start working at 30,000 meters altitude. We can estimate this velocity by considering the drag force as a function of velocity similar with (11) and the thrust force also as a function of velocity according to (2).

The initial boost can be given by boost stage using a solid rocket motor and the velocity at burnout should be enough for the HAOR to start generate thrust at a higher value than the drag. At the same time the trajectory should be chosen in such a way that the burnout velocity occurs at the right altitude (~30,000 meters).

Taking into consideration the energy per unit volume at high altitude stored in the ozone we can estimate the maximum possible speed using an estimated energy density stored in the upper atmosphere:

$$v = \sqrt{\frac{2e\eta}{\rho C_x}} \tag{23}$$

If we consider $e = 33.532 J/m^3, \eta = 90\%, C_x = 0.001$ and $\rho = 0.01204 kg/m^3$ then we obtain a maximum speed of 2238 m/s.

Higher speeds are also possible since then used value for the energy density in the upper is rather conservative. Yet another important parameter is the excess thrust defined as the difference between the net thrust and the drag force. The excess thrust as a function of velocity is given in Fig. 4.

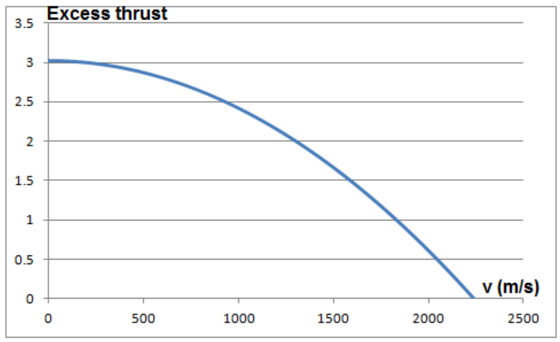


Fig. 4 Excess thrust as a function of velocity

In the above graph we assumed a conservative energy density stored in the upper atmosphere and still speeds in excess of Mach 6 can be sustained by HAOR. For not so conservative values of energy density a HAOR can reach speeds between Mach 6 and Mach 10 which represents very high velocities impossible to reach with other propulsion units except rocket motors.
It is obvious that better numerical estimations can be obtained after in-flight aerodynamic measurements which can provide a benchmark for further tuning of the numerical model.

## 5. Conclusions

In this paper we described a new propulsion method that uses the energy stored in the ozone from the upper atmosphere. The motor is based on a supersonic ramjet configuration. We provide an energy balance model that outputs a model for the thrust that is to be used within six degrees of freedom model that has the final objective to output the trajectory once the ramjet powered vehicle detaches from the booster. We also estimate the excess thrust at various velocities. The proposed ramjet can be used as a viable propulsion unit with maximum efficiency at altitudes of ~30 km and for velocities between Mach 7-12. This flight envelope was not covered before by other types of motors except the rocket motors. The advantage when compared with a rocket motor is the indefinite (from the propulsion unit point of view) flight duration together with the easiness of high altitude operation.

We intend to develop a more detailed model of the HAOR unit and then propose a flight testing programme at high altitude using our high altitude balloon flight capability proven in STRATOSPHERIUM 1 and 2 flights.

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