Introduction to Variable Specific Impulse Magnetoplasma Rocket Engines

Akhil Nair, Hindustan Institute of Technology & Sciences.
R Keshav, Hindustan Institute of Technology & Sciences.

Abstract:- To understand Electric Propulsion, we first need to understand the concept of Specific Impulse. It can be defined as the total impulse per unit weight of the propellant. It directly relates to the thruster's efficiency. In chemical propulsion we try to extract the internal energy of a propellant by combusting it and breaking bonds. But, what if we could take a propellant and supply with external energy with no theoretical limit. More the energy content more work can be done. This is the basic goal of electric propulsion.

I. INTRODUCTION

Electric propulsion, as the name suggests, uses electrical energy from an external source to heat and eject the propellant. Further, when a gas is placed in a strong electric field, its positive and negative elements split up creating a pool of charge where the positive charge is equal to the negative charge. This new physical state of the gas is called a 'Plasma' and the process is called 'Ionization'. It is fluidic like a gas, but it reacts to electric and magnetic fields since it contains charged particles and can be manipulated by these fields. So, the plasma generated by the electric field is accelerated through a magnetic field and exhausted at extremely high velocities up to 100,000 m/sec. The greater the electrical energy provided, the greater will be the current density causing a stronger magnetic field and hence a faster exhaust velocity. The concept of electric propulsion was first conceived by the father of Liquid Propulsion, "Robert Goddard" in 1906 in USA although its development started in the later part of the 19th century by NASA and ESA. Today, advanced concepts of plasma thrusters are being researched to enable deep space missions. Therefore, this paper aims to examine and review the operational advantages of high power magnetoplasma rocket.

Research is heavy in the electric propulsion department. It is a futuristic concept and can enter a larger market very soon. Recently researchers have developed an engine which can produce thrust without any propellant at all using quantum plasma. More present engines include Microwave Thrusters which do not require electrodes to generate the plasma. There are a few thrusters that fall in the grey area between thermal and MPD (Magnetoplasmadynamic) thrusters. The current popular electric engine is the VASIMR (Variable Specific Impulse Magnetoplasma Rocket) which uses RF (radio frequency) couplers to generate and heat plasma as per required thrust and specific impulse parameters of the mission. It can adapt to the mission in hand and give a longer life and reliability than the other thrusters. They can either be powered by solar panels or nuclear power.

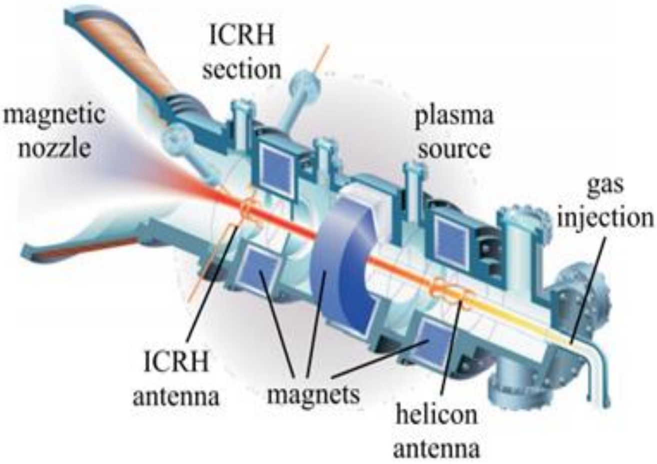


Fig 1: VSIMR Layout

There have been numerous studies on the properties of expanding magnetoplasma jets and their potential application to power generation. With the proper use of the understanding, we have about Lorentz force and with proper acceleration of the plasma we can except to see promising new advances in the field of propulsion. What makes this project even more interesting is the continuous modulation of its exhaust properties to match its operational requirements more efficiently. The plume variability allows the continuous optimization of exhaust parameters along with the motion of the ship. This process is generally known as Constant power Throttling (CPT). This is aimed at optimum utilization of engine power during various operational conditions. This will facilitate humans in completing space missions faster, which in turn is significant in reducing the deleterious physiological effects on astronauts caused by prolonged exposure to micro gravity, isolation stress and harsh radiation environments.

II. VARIABLE SPECIFIC IMPULSE MAGNETOPLASMA ROCKET

It is a highly powered, radio frequency driven magnetoplasma rocket. The plasma is produced by an integrated helicon discharge. The bulk of the plasma energy is added in a separate downstream stage by ion cyclotron resonance heating (ICRH). This is followed by the plasma acceleration by the magnetic nozzle and subsequent detachment of the same. The whole process of thrust production can be categorised as follows:

1. Injector feeds neutral gas.
2. Helicon coupler ionizes propellant.
3. Superconductor generates magnetic field that confines plasma.
4. ICH coupler heats plasma to somewhere around 1 million degrees.
5. Thrust generated as plasma escapes magnetic confinement.

It all starts with the plasma generator which is where the gas generally hydrogen or argon is injected and ionised. There are four propellants which are largely used in the VSIMR engine. The properties and parameters of these propellants play a major role in its selection for the operation.

Table 1: Propellant properties

Properties	**Argon(Ar)**	**Hydrogen(H)**	**Xenon(Xe)**	**Neon(Ne)**
Atomic Weight	39.948	1.0079	131.3	20.179
Atomic Volume(cm^3/mol)	22.4	14.4	37.3	16.7
Density(g/cm^3)	0.001784	0.0000899	0.00588	0.0009
State	Gas	Gas	Gas	Gas
Melting point(K)	83.85	14.01	161.3	24.53
Boiling point(K)	87.3	20.28	165	27.1
Specific Heat Capacity(J/gK)	0.52	14.304	0.158	0.904
Heat of Vaporization(kJ/mol)	6.447	0.904	12.636	1.7326
Heat of fusion(kJ/mol)	1.188	0.117	2.297	0.3317
1st Ionization Energy(kJ/mol)	1520.5	1312	1170.4	2080.6
2nd Ionization Energy(kJ/mol)	2665.8	-	2046.4	3952.2
3rd Ionization Energy(kJ/mol)	3930.8	-	3097.2	6121.9
Thermal Conductivity(W/mK)	0.0177	0.1805	0.00565	0.05
Cost in INR(/100g)	36.69	880.44	8804.40	33
Ionization Energy/Cost(eV)	100	200	80	150

In the injector region, a relatively cold and dense plasma is produced using a device known as a helicon. In the presence of a magnetic field, the radio waves ionize the gas. The resulting plasma flows towards the heating field where additional radio waves further energize it. In this region, the waves resonate with the natural cyclotronic ion motion around the magnetic field lines. Energy is fed into the system in the form of a circularly polarized RF signal tuned to the ion cyclotron frequency. ICRH has been chosen because it transfers energy directly and solely to the ions, which maximizes the efficiency of the engine. In the mirror machine configuration ions multiply and bounce through the ICRH RF field. In the present setup, there is no mirror chamber, and the ions make one pass through the ICRH antenna. Two stage magnetic nozzle, which accelerates the plasma particles by converting the azimuthal energy into directional momentum. ICRH is widely used for heating plasma in fusion devices. Hydrogen or deuterium and argon are the major propellants of choice for the whole process.

III. STUDY ON THE FORCES INVOLVED.

The Lorentz force on the ions in a magnetized plasma forces them to follow circular paths defined by a quantity known as the Larmor radius.

$R = mv/ qB$

where R is the Larmor radius
m is the ion mass.
q is the ion charge.
v is the component of ion velocity and is perpendicular to the magnetic field.
B is the magnitude of magnetic induction .

The frequency of the particle rotation about the lines of induction known as cyclotron frequency is given by.

$w= -qB/m$

Besides the Lorentz force, there are also minor electromagnetic effects like swirl and Hall acceleration. The Lorentz force contribution is also the way magnetic nozzles work – the forces involved can be broken into three parts:
a) Along the thruster axis – adds to the thrust.
b) Towards the thruster axis – pushes the plasma towards the centre.
c) Right angle to both these around the axis generates the swirling effect.

An ion in a static and uniform magnetic field will move in a circle doe to the Lorentz force. The angular frequency of this cyclotron motion for a given magnetic field strength B is given by.

$W= 2\pi f = zeB/M$

where z is the number of positive or negative charges of the ion.
e is the elementary charge.
M is the mass of the ion.
f is the frequency of an electric excitation signal.

Also, the mass/charge ratio is given by,

$M/z= eB/ 2\pi f$

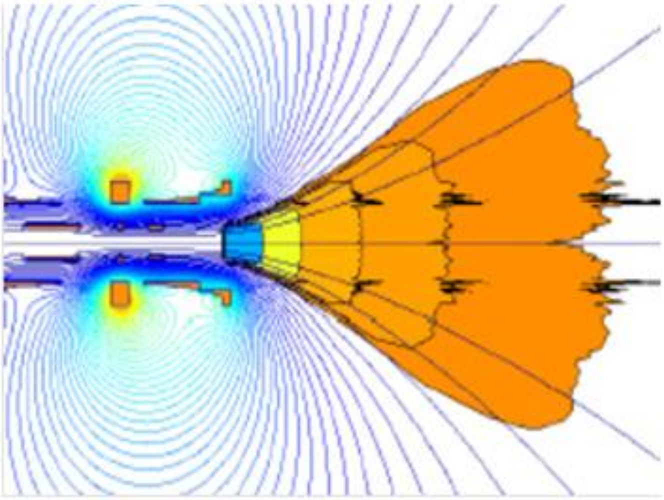


Fig 2 : Magnetic field configuration in VSIMR

In ion cyclotron resonance heating, the electromagnetic waves with frequencies corresponding to the ion cyclotron frequency is used to heat up a plasma . The ions in the plasma absorb the electromagnetic radiation and as a result of this, there is an increase in kinetic energy. Kinetic energy is deposited in the direction perpendicular to the magnetic field and must be converted to axial momentum to create thrust. This is done by the third component of the VSIMR engine, i.e., the magnetic nozzle. It must be noted that if the ions were to cling tightly to the magnetic fields, there would be no thrust. This is made sure by a phenomenon known as adiabacity where the ions keep following the field lines as long as there is no sharp curves. The intensity of magnets with respect to distance from the source also plays a major role in this process. A magnetised plasma is the one in which the ambient magnetic field B is strong enough to alter particle trajectories. Generally, magnetised plasma is anisotropic, responding differently to forces which are parallel and perpendicular to the direction of B. It has to be taken into account that a magnetised plasma moving with mean velocity V contains an electric field E = -VxB which is not affected by Debye Shielding. It is zero in the rest frame of the plasma. Finally, the detachment of the plume from the field mainly by the loss of adiabacity and the local ratio of plasma pressure to magnetic pressure. Numerous experiments are being conducted to enhance the plasma detachment and increase the efficiency of the thrust production. One of which involves a hypersonic neutral gas blanket downstream of the nozzle producing an afterburn effect. The plasma acceleration by the magnetic nozzle and its subsequent detachment are being studied and simulated to further enhance the process.

There are various ways to build MPD (magnetoplasmadynamic) thrusters : using different propellants, geometries, methods of plasma and magnetic field generation, and operation regimes, stationary or pulsed. These types of thrusters differ mainly in the way the magnetic field is generated.

Applied field (AF) MPD thrusters – endowed with permanent magnets or a Helmzholtz coil.

Self-field (SF) MPD thrusters – generates magnetic field by induction around the current travelling in the arc.

One of the most important features of this design is that it gets rid of both friction and erosion between the propellant and the body of the thruster. Since there is no physical contact, conduction cannot occur and the amount of heat that is absorbed by the thruster is limited to radiation and hence we can see a reduced thermal load on the thruster. But this does not mean that there is no need to cool the thruster. In fact, by regenerative cooling, it is possible to increase the efficiency of the thrusters. Something that makes the VSIMR different from the other types of engines is its ability to vary its exhaust velocity by changing the temperature it heats the propellant to. This in turn changes the Specific Impulse and eventually its thrust. This is why VSIMR engine can be used to travel to planets/stars more efficiently by continuously varying its thrust to optimize the trip time.

IV. TO MARS IN 39 DAYS

The following calculations will determine time of flight, coast time, distance travelled during powered flight, distance travelled during coast, propellant mass required, mass fraction, velocity increment (dV) during powered flight, velocity at start and end of powered flight, specific impulse at start and end of powered flight, acceleration at start and end of powered flight, and finally thrust at start and end of powered flight. The user can plot thrust verses time, mass flow rate verses time, velocity verses time, distance travelled verses time, specific impulse verses time, mass flow rate verses exhaust velocity, thrust verses exhaust velocity, rocket acceleration (Gs) verses time, rocket mass verses time, trajectory from Earth to destination planet.

VSIMR Thrust and Power requirements:

Input power required (P)= 200kw

Max exhaust velocity (V_{emax})= 100km/sec

Min exhaust velocity (V_{emin})= 50km/sec

Radio frequency efficiency (η) = 0.72

Number of VSIMR rockets required (N) = 60

Burn time (T_{burn})= 15 days

Initial mass of the spacecraft (M_i)= 37000kg

Total distance from Earth to planet (S_{tot}) = $1.26862.\ 10^8$ km

Number of data points describing trajectory (N_{pts})= 2000

Circular orbit of the Earth around the Sun (V_{cls})= 29.78km/sec

Total electric power

$P_{RF} = N.P = 12mW$

$Pe = \eta.P_{RF}= 8.64mW$

Time increment for flight analysis

$dt = T_{burn}/(N_{pts}-1)$

$= 7.504 \times 10^{-3}$ days

Array of time ranging from 0-tb

$K = 1. N_{pts}$
$T_k = (k-1)(T_{burn})/(N_{pts}-1)$

Optimal Isp versus time based on start and end velocity of spacecraft.

$I_{sp1} = V_{min}/g_0$
$= 5098.61sec$

$I_{sp2} = V_{max}/g_0$
$= 10197.21sec$

$I_{spk}= Is_{p1} + ((tk-t1)(I_{sp2}-I_{sp1})/(t_{npts}-t_2))$

Exhaust velocity, mass flow rate and thrust during operation.

$V_k= I_{spk}.g0$

$M_{pk} = 2Pe / (Ispk .g_0)^2$

$F_k = Ispk .g_0. M_{pk}$

Spacecraft mass, acceleration, velocity and distance travelled during operation.

$N = 1. Npts – 1$
$M_1 = M_1$
$V_1 = V_{cls}$
$S_1 = 0$ km
$Mn+1 = Mn – Mpn .dt$

$G_k = F_k / M_k$
$Vn+1 = Vn + Gn .dt$
$Sn+1 = Sn + Vn .dt$

Coast time from burnout to reverse burn.

$T_{coast} = (Stot -S_{Npts}) / V_{Npts}$
$= 24.956$ days

$S_{coast} = V_{Npts} . T_{Coast}$
$= 8.364. 10^7$ km
$N_{coast} = 100$
$k = 1. N_{coast}$

Array of time values ranging from 0 - T_{coast}

$K = 1 . N_{pts}$

$t_{ck} = (k-1)(T_{coast} + t_{Npts}) / (N_{pts} -1)$
$V_{coast} = V_{Npts}$
$S_{coast} = V_{coast} (t_{ck} – T_{burn})+ S_{Npts}$

Total mass of propellant required for the operation.

$M_{ptotal} = \sum_{k} M_{pk}. dt$
$= 4481.78$ kg

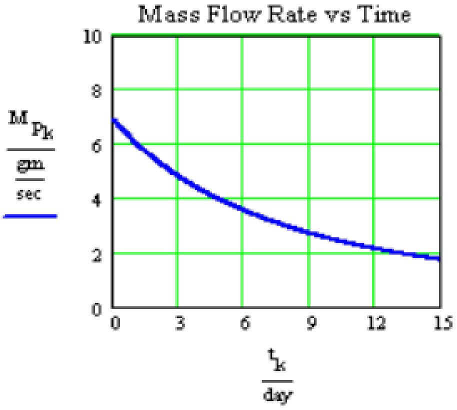
Mass fraction of total propellant mass to spacecraft initial mass

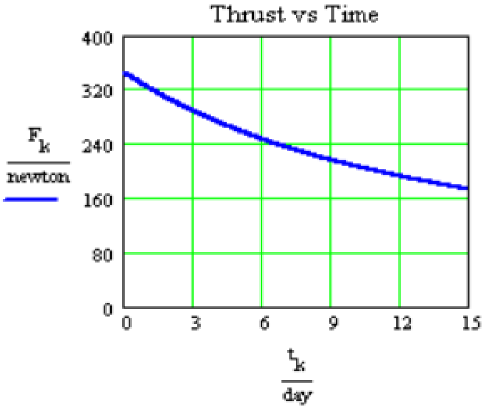
ţ $= M_{ptotal}/ M_i$
$= 0.121$

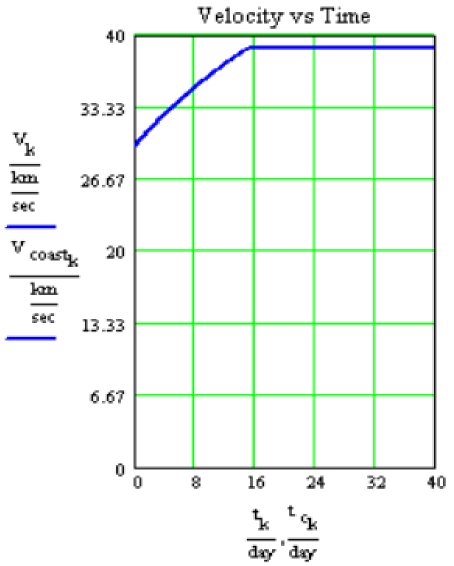
Total time from earth to mars
$S_{total}= S_{coastNpts}$
$= 1.286 . 10^8$ km

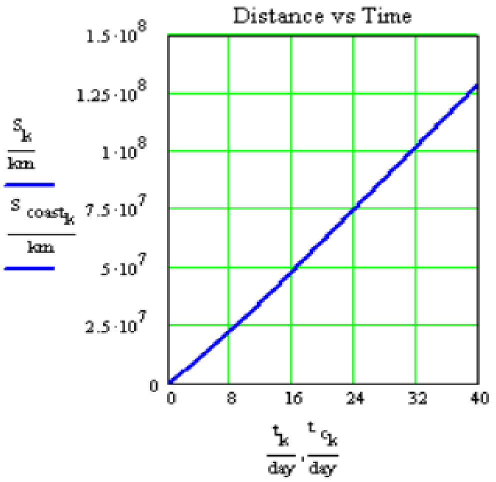
$T_{total} = T_{burn}+ T_{coast}$
$=$ **39.956 days**.

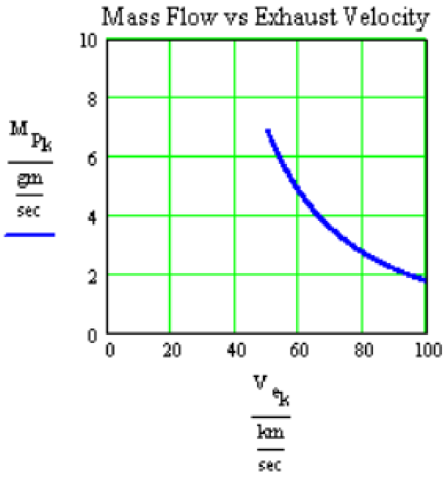
V. VSIMR PERFORMANCE PLOTS:

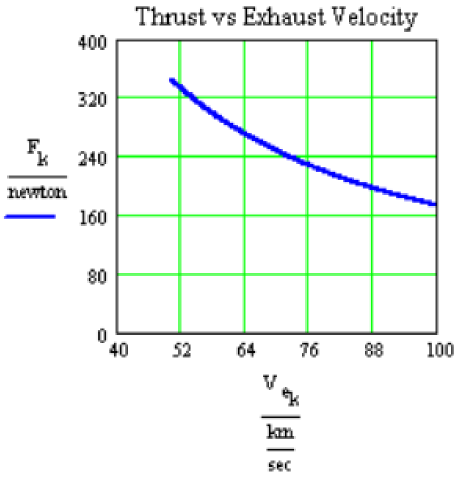


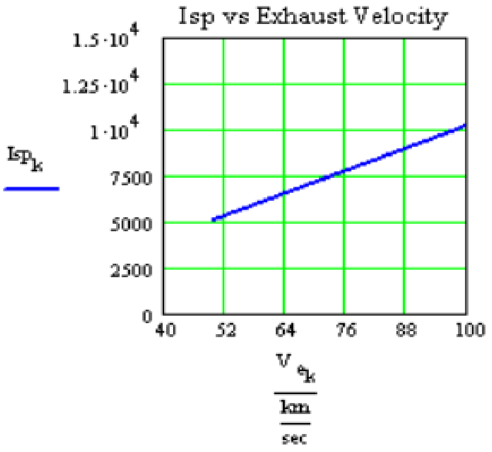


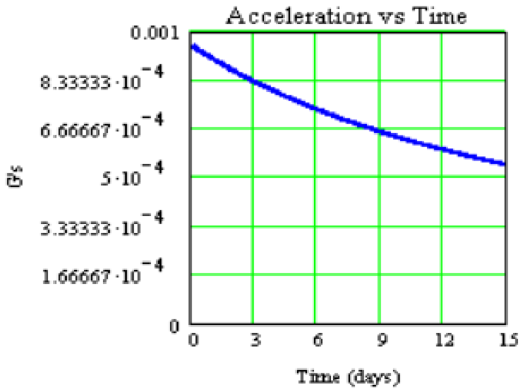

Velocity vs Time
40
33.33
26.67
20
13.33
6.67
0
0
8
16
24
32
40
V_k / km/sec
V coast_k / km/sec
t_k / day , t c_k / day


Distance vs Time
1.5·10^8
1.25·10^8
1·10^8
7.5·10^7
5·10^7
2.5·10^7
0
0
8
16
24
32
40
S_k / km
S coast_k / km
t_k / day , t c_k / day

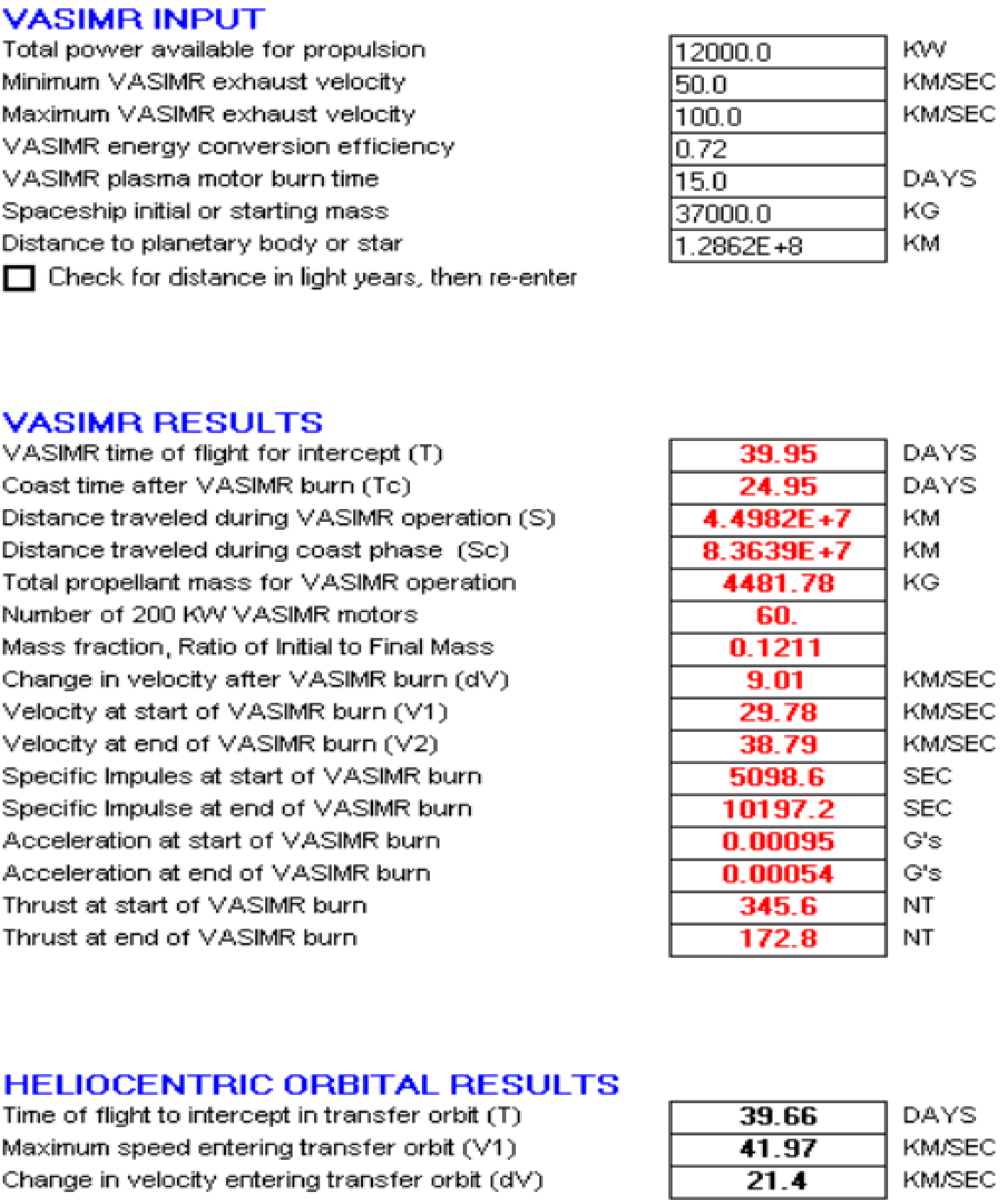

Mass Flow vs Exhaust Velocity
10
8
6
4
2
0
0
20
40
60
80
100
M P_k / gm/sec
V e_k / km/sec


Thrust vs Exhaust Velocity
400
320
240
160
80
0
40
52
64
76
88
100
F_k / newton
V e_k / km/sec


Isp vs Exhaust Velocity
1.5·10^4
1.25·10^4
1·10^4
7500
5000
2500
0
40
52
64
76
88
100
Isp_k
V e_k / km/sec


Acceleration vs Time
0.001
8.33333·10^-4
6.66667·10^-4
5·10^-4
3.33333·10^-4
1.66667·10^-4
0
0
3
6
9
12
15
G's
Time (days)

VI. RESULTS FROM STARTRAVEL 3.0 ANALYSIS:



VASIMR INPUT

Total power available for propulsion	12000.0	KW
Minimum VASIMR exhaust velocity	50.0	KM/SEC
Maximum VASIMR exhaust velocity	100.0	KM/SEC
VASIMR energy conversion efficiency	0.72	
VASIMR plasma motor burn time	15.0	DAYS
Spaceship initial or starting mass	37000.0	KG
Distance to planetary body or star	1.2862E+8	KM

☐ Check for distance in light years, then re-enter

VASIMR RESULTS

VASIMR time of flight for intercept (T)	39.95	DAYS
Coast time after VASIMR burn (Tc)	24.95	DAYS
Distance traveled during VASIMR operation (S)	4.4982E+7	KM
Distance traveled during coast phase (Sc)	8.3639E+7	KM
Total propellant mass for VASIMR operation	4481.78	KG
Number of 200 KW VASIMR motors	60.	
Mass fraction, Ratio of Initial to Final Mass	0.1211	
Change in velocity after VASIMR burn (dV)	9.01	KM/SEC
Velocity at start of VASIMR burn (V1)	29.78	KM/SEC
Velocity at end of VASIMR burn (V2)	38.79	KM/SEC
Specific Impules at start of VASIMR burn	5098.6	SEC
Specific Impulse at end of VASIMR burn	10197.2	SEC
Acceleration at start of VASIMR burn	0.00095	G's
Acceleration at end of VASIMR burn	0.00054	G's
Thrust at start of VASIMR burn	345.6	NT
Thrust at end of VASIMR burn	172.8	NT

HELIOCENTRIC ORBITAL RESULTS

Time of flight to intercept in transfer orbit (T)	39.66	DAYS
Maximum speed entering transfer orbit (V1)	41.97	KM/SEC
Change in velocity entering transfer orbit (dV)	21.4	KM/SEC

Fig3 : Simulation results of VSIMR engine using SpaceTravel 3.0 software.

VII. CONCLUSION

These technologies will give us access to greater depths of our solar system and eliminate the need for complicated mechanisms to store and deliver propellant in the case of chemical rockets. The current Vx-200 prototype is a 212kW input, 120kW thrust system, far more powerful and efficient than the original Vx-10. It is still difficult to estimate the flight systems thrust efficiency It is evident from the above results that Electric Propulsion has the capability to see humans progress into an interstellar-traversing civilization in the far future.

REFERENCES

[1]. J.F. Santarius and B.G. Logan, "Generic Magnetic Fusion Rocket Model", Journal of Propulsion and Power, 14, 519-524 (1998).

[2]. F.R. Chang-Díaz, W.A. Krueger and T.F. Yang, "Numerical Modeling of the Hybrid Plume Plasma Rocket", AIAA - 85-2058 (1985).

[3]. F.R Chang-Díaz, et. al., " A Tandem Mirror Hybrid Plume Plasma Propulsion Facility", AIAA-IEPC-88-126 (1988).

[4]. F.R. Chang Díaz, “Research Status of the Variable Specific Impulse Magnetoplasma Rocket”, Transactions of Fusion Technology, 35, 87-93 (1999).

[5]. StarTravel, VASIMR Plasma Rocket Propulsion, Retrieved on March 9th, 2021 from: www.aerorocket.com/StarTravel/StarTravel.html.

[6]. J.P. Squire, F.R. Chang Díaz, F.W. Baity, G.C. Barber, M.D. Carter, R.H. Goulding, D. Sparks, G. McCaskill, A.V. Ilin, R.D. Bengtson, R.G. Bussell, Jr., V.T. Jacobson, and T.W. Glover, “Experimental Status of the Development of a Variable Specific Impulse Magnetoplasma Rocket”, Transactions of Fusion Technology, 35, 243-247 (1999).

[7]. F.R. Chang Dfaz, J.P. Squire, R.D. Bengtson, B.N. Breizman, F.W. Baity, M.D. Carter, “The Physics and Engineering of the VASIMR Engine” , 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference 17-19 July 2000 Huntsville, Alabama.

[8]. S. W. Schwenterly, M.D. Carter, F.R. Chang Díaz, and J.P. Squire, “HTS Magnets for Advanced Space Propulsion Applications” Proceedings of CEC/ ICMC, July 13 (1999).

[9]. M.D. Carter, F.R. Chang-Díaz, A.V. Ilin, D.O. Sparks, F.W. Baity Jr., R.H. Goulding, E.F. Jaeger, J.P. Squire, “Radio Frequency Plasma Applications for Space Propulsion”, Proceedings of ICEAA99 (1999).

[10]. Chang Díaz, F. R., Hsu, M. M., Yang, T. F. "Rapid Mars Transits With Exhaust-Modulated Plasma Propulsion", NASA Technical Paper 3539 (1995).