OPITIMIZATION OF GEOSYNCHRONOUS SATELLITE SYSTEM USING ELECTRIC PROPULSION BASED ON GENETIC ALGORITHM

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Abstract: The development and application of Electric Propulsion (EP) have been emphasized by all over the world. The number of EP used by spacecraft increases rapidly in recent years. Microwave Plasma Thruster has many advantages, such as moderate specific impulse, long lifetime, slight plume contamination, and small weight. The parts of chemical propulsion on Dong Fang Hong 3 communication satellite are replaced by MPT to perform orbit transfer and north-south station keeping. Satellite’s system and its subsystem are modeled such as propulsion subsystem, power subsystem and performance. The system and mission are optimized using genetic algorithm. The system and mission results are compared with those of conventionally (chemically) propelled satellite systems and other EP. The results demonstrate that the MPT propulsion system with 60^0 burning arc can provide a reduction of propellant consumption about 21%, which means that the weight of payload will increase from 170 kg to 317 kg. Therefore, the MPT propulsion system appears to be a very attractive option to increase payload mass or increase lifetime of GEO Telecommunication satellite.

Key word: Satellite system, microwave plasma thruster, genetic algorithm, north-south station keeping, orbit transfer

1. Introduction

Electric Propulsion (EP) has many advantages of high specific impulse, long lifetime, high controlling precision. It can perform many kinds of space mission. After fifty years developed, it had been more and more applications on spacecrafts. During 2001 and year to June 2002, U.S. spacecraft manufacturing companies launched at least 8 new GEO commercial satellites with EP. Currently there are 25 in orbit using Stationary Plasma Thruster (SPT) for north-south station keeping (NSSK) respectively. These satellites have an installed total of 125 thrusters. There are 19 communication satellites in orbit with Ion Xenon Ion Propulsion System (XIPS). In addition, there are a number of satellites with Arcjet and Resistojet [1]. Within most of the previous studies electric propulsion systems are employed either only for the transfer mission segment or for NSSK tasks exclusively. In order to exploit the benefit of EP system, their application with this study is extended. They will be used the transfer mission to GEO as well we for station keeping tasks during operational mission. Hughes demonstrated the use of EP for part of orbit insertion to increase their HS-702 spacecraft payload, and The “Yamal-100” GEO satellite was successfully launched in 1999 and transferred from initial elliptical orbit to GEO with help of RSC “Energia” SPT [2].

The number of commercial telecommunication satellites on orbit in GEO is currently growing approximately linearly at about 15 new satellites/year, and the number is projected to continue increasing at a similar rate out to 2010. At the same time, need for spacecraft with larger capacity payloads, and the increased power to mass ratio in modern satellites, is motivating manufacturers to move into Orbit Transfer (OT) with EP, in addition to NSSK. Because the power levels have increased faster than the growth in mass, OT with EP can be more attractive.

Microwave Plasma Thruster (MPT) is a new type of electro-thermal thruster, which has many advantages, such as moderate specific impulse (I_{sp}), long lifetime, slight plume contamination, and small weight. It is developed in Northwestern Polytechnical University (NPU) of P.R. China at power of 1000W and 100W, is used to perform transfer and NSSK of GEO Telecommunication satellite instead of chemical propulsion [3, 4, 5]. The numerical simulation optimization of mission and platform for Dong Fang Hong - 3 (DFH-3) GEO Telecommunication satellite with MPT is presented. Both mathematical model of platform (include mass, MPT performance, power and others) and optimization method based on Genetic Algorithm (GA) are described. Various initial boundary conditions are included in the optimization problem.

2. The scheme of orbit transfer

The DFH-3 is a new generation three-axis stabilized GEO telecommunication satellite of P.R. China. After it separated from its lunch vehicle (Long March 3A) at geosynchronous transfer orbit (GTO), whose initial mass is 2 266 kg, payload weight is 170 kg, and design lifetime is 8 years. It can provide broadcast and communication covering everywhere of China. The solar arrays deliver 2 000 W of electric power at beginning of life (BOL) and 1 700 W at end of life (EOL) to provide 18 low power transponders, 6 medium power transponders, and other electric instruments.

The DFH-3 is launched to the geosynchronous transfer orbit (GTO - 209 kmX36 194 km), whose inclination angle is 28.3 degree. It is separated form LM-3A, then it is transferred to GEO through tree times maneuver of liquid apogee engine (LAE, 490N). The 14 liquid bipropellant reaction control thrusters (Bi-RCT, 10N) are used for orbit adjustment, attitude control and station keeping.

In this paper, using MPT for orbit transfer (OT) applications as well as for north-south station keeping is considered. In order to use MPT instead of the LAE and Bi-RCT to complete OT an NSSK maneuvers, the DFH-3 satellite platform must be modified. The electric power system is modified to increase electric power from 2000 W to 5250W at BOL. The propulsion system is equipped with four 1000W MPTs (T-MPT) instead of LAE and four 100W MPT (N/S-MPT) instead of 10N Bi-RCT. The modified DFH-3 satellite is entitled DFH-3 Plus.

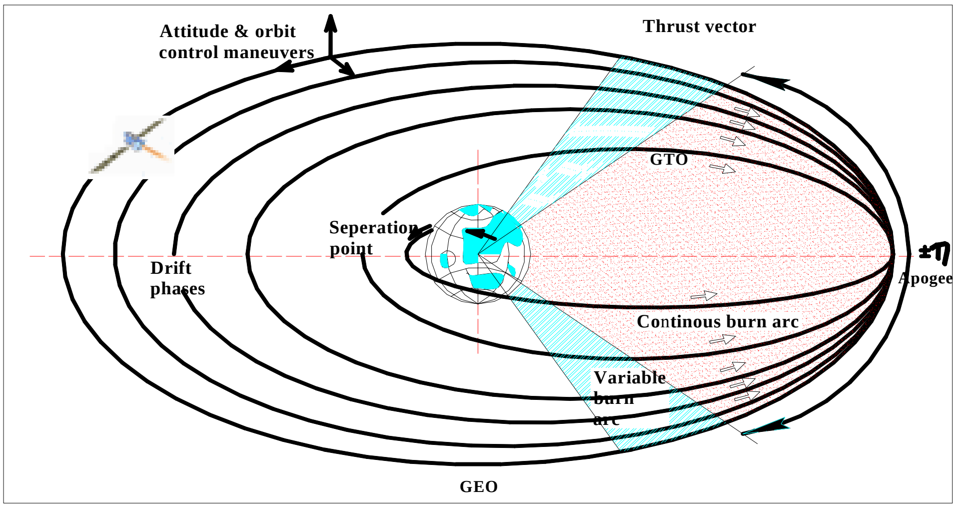

Figure 1　　Orbit transfer profile using MPT

When DFH is launched to GTO (230 km×36 194 km) by LM-3A, it is separated from the launch vehicle. Four T-MPTs are employed to spiral up the satellite to GEO by thrusting in burn-arc around the apogee. The on-orbit NSSK and repositioning maneuvers are performed by for N/S-MPT. While the yearly ΔV varies with satellite station longitude, 45.0 m/s is chosen as representative. The orbit transfer mission profile is shown figure 1.

3. System assumptions and modeling

3.1　Propulsion system

The propulsion system of DFH-3 is a unified bi-propellant system (MMH/MON), whose function is to perform all mission of the orbit transfer, position capture in GEO, attitude control, and station keeping. The propulsion system consists of a 490N liquid apogee bi-propellant engine (LAE), 14 10N liquid bi-propellant reaction control thrusters (Bi-RCT) in two redundant branches, two spherical high pressurant vessels (21.5 MPa), and other values and pipes. The fuel monomethyl-hydrazine (MMH) and oxidizer green nitrogen-tetraoxide (MON-1) are stored in two spherical propellant tanks, which inner diameter is 1 050 mm. The dry mass of chemical propulsion is 140kg, and weight of propellant is 1320kg. The performance parameters of DFH-3 chemical thrusters are shown table 1.

Table 1　　The performance of DFH-3 chemical thrusters

No.	Item	Symbol	Unit	Parameters	
				490N LAE	10N Bi-RCT
1	Thrust	F_v	N	490	10
2	Specific impulse	I_{sv}	m/s	3 030	2 744
3	Pressure of chamber	p_c	MPa	0.67	0.8
4	Maximum permanent burn time	t_{on}	h	1.5	4
5	Minimum impulse bit		mN∗s	/	<100
6	Voltage of solenoid value	V_v	V	35~42	24
7	Power of solenoid value	P_v	W	≤200	≤15
8	Respond time of solenoid value	t_{90}	ms	≤10	≤10
9	Weight	W_t	kg	4.0	0.6

For mission scenarios using on-board MPT for OT an NSSK function are considered: 1000W MPT for OT function, and 100W MPT for NSSK function. Eight years of NSSK is performed by four N/S-MPT, one pair placed on the north face and other on the south face. These thrusters are canted 18^0 from the vertical to minimize plume interaction for the solar array. According to characteristic of DFH-3 and MPT, four PPUs are mounted to support the four T- MPTs and N/S-MPTs, and fowling adaptations have to be performed. Figure 2 shows the flow schematics of the DFH-3 Plus propulsion system.

- Using four T-MPTs to replace the LAE for OT function;
- Mounting of 4 N/S-MPTs to raplace 4 10 Bi-RCT for NSSK maneuvers in GEO;
- Substitution of the 10 Bi-RCTs by 10 liquid mono-propellant thrusters (Mono-RCT);
- Installation 4 PPUs, each of them serves for one T-MPT and N/S-MPT by switching;
- Changing propellant using mono-propellant N2H2 to replace the bi-propellant MMH/MON-1;
- Simplifying propellant feed system and reduction the number of value, filters; etc. for mono-propellant;
- Modification the mass flow equipments to adapt to smaller flow rate of MPT.

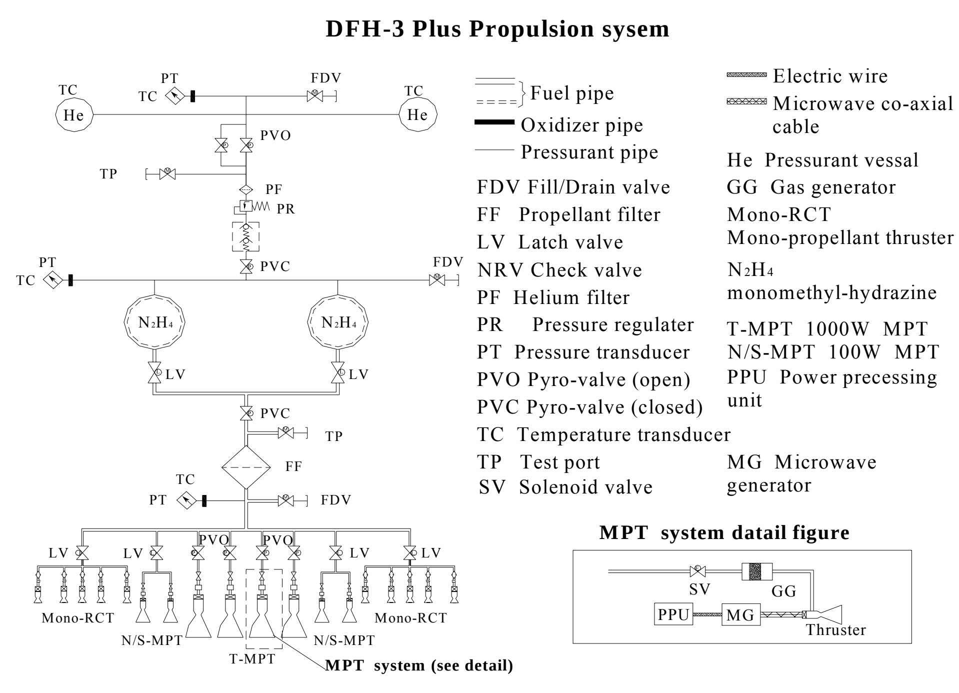

Figure 2 The flow schematics of the DFH-3 Plus propulsion system

3.2 Electric power system

In order to adapt using of MPT, it is necessary to increase electric power system (EPS) from 2000W to 5250W at BOL for DFH-3 Plus. One the one hand, the performance of EPS is increased through optimization design. On the other hand, substitution of the two groups 45A Cd-Ni storage battery by two groups 149A storage battery. The Si solar arrays, which provide payload 5250W in GEO, are assumed or for T-MPT operation power during OT since the payload is inactive during this phase. The storage battery system provides the N/S-MPT operation power during eclipse. The 5250 W electric power can provide power for T-MPT during OT phase and for transponders during on-board period. Because electric power is increased from 2000W to 5250W at BOL, the dry mass of satellite will increase 220 kg.

Table 2 The power budget of each electric load

Electric load	Symbol	Parameter / W	
		OT phase	GEO phase
Loss of EPS	P_{pow}	31	
Thermal system	P_{th}	154	
Guidance & Navigation	P_{aoc}	59	
Attitude control	P_{tt}	55	
Battery recharging	P_{ba}	401	
Solar array drive	P_{sa}	121	
Harness	P_{har}	34	
Propulsion	P_{pro}	4 520	600
Transponder	P_{pay}	0	3 446
Contingency	P_{con}	349	
Total power	P_0	5 250	

Because the time of satellite OT is relatively long, satellite crosses many times the " Van Allen Radiation Belts ". The radiation belts consist of electrons of up to a few MeV energy and protons of up to several hundred MeV energy. When the satellite moves in the radiation belts during OT using MPT, these high energy particles will damage the array and material of satellite surface. The propulsion system is penalized for long transfer time through the Van Allen Belts. Thus the arrays are assumed to have an equivalent layer of 0.4 mm protected shielding on both sides of solar array.

The requirement of power is different for each electric load at various flight phases. For example, T-MPTs consume mostly power during OT, but transponders require higher available power than others in GEO. The power budget of each electric load is shown in the table 2.

3.3 Microwave Plasma Thruster

N_2H_4 MPTs are considered in this paper, two kinds of MPT (100 W and 1000 W) is being developed in NPU under National 863 Program and National Defence Basic Research Program. There are many advantages to choose N_2H_4 as propellant, such us increasing greatly density specific impulse, combining a mixed propulsion system with Mono-RCT, and so on. The structure of propulsion system is t simplified, mass of system is reduced, and reliability of system is promoted.

N_2H_4 decomposed is by catalyst in gas generator (GG) to produce high temperature (700K) gas, then high temperature gas is injected into resonator cavity to couple with microwave at certain frequency. It is ionized to form free-floating plasma in the resonant cavity, and the plasma flow is jetted from a nozzle to produce thrust. The performance test of MPT under vacuum condition has been completed in NPU. The specific power (SP) of MPT based on experimental data.

$$SP = \frac{P_{in}}{q_m} \qquad (MJ/kg) \cdots\cdots\cdots\cdots\cdots\cdots (1)$$

Whereby SP denotes the specific power, MJ/kg. P_{in} denotes input electric power, W. q_m denotes mass flow of propellant, kg/s.

The efficiency of microwave generator is calculated as follows:

$$\eta_{gen} = \frac{P_{fow} - P_{ref}}{P_{fow}} \qquad \cdots\cdots\cdots\cdots\cdots\cdots (2)$$

Whereby η_{gen} denotes efficiency of microwave generator. P_{faw} denotes microwave forward power. W. P_{ref} denotes microwave reflected power, W.

Table3　performance parameters of MPT

No.	Performance	Symbol	Unit	Parameter	
1	Input electric power	P_{in}	W	1 100	120
2	Efficiency of PPU	η_{PPU}		0.95	0.95
3	Mass flow	q_m	mg/s	39.5	4.4
4	Specific power	SP	MJ/kg	26	40
5	Pressure of resonant cavity	p_{res}	MPa	0.30	0.32
6	Specific impulse	I_{sp}	m/s	6 191.8	5 758.3
7	Thrust	F	MN	244.7	25.5
8	Efficiency of MPT	η	%	57.5	61.3
9	Weight	W_t	kg	2.5	1.5

The performance parameters of MPT are shown in table 3. The lifetimes of 100W and 1000W MPT are assumed 1500 hours, and PPU lifetime is assumed adequate for both the OT and NSSK missions.

4. Method of Optimization

The application of MPT to perform OT and NSSK mission can be used to obtain additional increases in payload mass from reduction of propellant consumption. The goal of optimization is to maximize payload mass at constant operational lifetime and total mass of satellite.

The GA is an direct method to solve optimization problem by directly minimizing the performance index by mimicking the process of Darwinian evolution. It is chosen for the optimization process. Its robustness and the capability of avoiding local minima and inflection points, converging on the absolute minima even for discontinuous functions, make GA to adapt to orbit optimization problem.

The solution must be represented as a "chromosome" .At any stage in the solution process, a "population" or chromosome exists which contains a asset chromosomes, or candidate solutions, to the problem. Each chromosome in the population possesses a "fitness". Individuals produce offspring via defined genetic operation such as crossover or mutation, thus increasing the number and diversity of the population. At end of every generation, the individuals characterized by the highest fitness with respect to the chosen target function (The maximal GEO delivered payload) and their solution parameters (chromosome) are used to generate the individuals for the following generation. New generations are generated until convergence of the method.

The target function is shown:

$$J=\sum_{i=1}^{n}\Delta m_i(M,\Delta M,\alpha,\beta)+\Delta m_{ps} \quad\cdots\cdots\cdots\cdots(3)$$

Whereby J is maximal GEO delivered payload. Δm_i is the propellant consumption to fly around the earth one cycle (i), kg. M is mean perigee angle. α, β are vector angles of thrust.

The present optimization case is run with a length of 16 bits binary code, a population of 120 individuals, a crossover probability of 0.66, and a mutation probability of 0.01. The convergence within the specified tolerance requires about 300 generations for almost every considered case.

5. Results and discussion

According to the results of the mission optimizations, Table 4 summarizes the propellant consumption for the different steps in mission. When the burn arc half angle (η) is 60 degree and the thrust and specific impulse are constant of MPT, the propellant mass saving amounts up to 277kg equal to 21% of DFH-3. The payload mass amounts up to 147 kg (from 170 kg to 317 kg) equal to 86% of DFH-3.

Table 4 Propellant budget of the DFH-3 and DFH-3 Plus mission

Content	DFH-3				DFH-3 Plus			
Mission	ΔV (m/s)	Isp (m/s)	Propellant mass (kg)	Final mass (kg)	ΔV (m/s)	Isp (m/s)	Propellant mass (kg)	Final mass (kg)
Mass at GTO	2266				2486			
Transfer	184.2	3030	1032.2	1233.8	2170.2	6230	792.8	1 693.2
Midcourse	35	3030	14.8	1218.4	45	5800	13.08	1 680.1
Station acquisition	15	2744	4.4	1214.0	10	2157	7.771	1 672.3
NSSK	375.3	2744	155.2	1058.8	400	5800	111.5	1 560.8
EWSK	20	2744	7.7	1051.1	20	2157	14.41	1 546.4
AC	16	2744	6.1	1045.0	16	2157	11.43	1 535.0
Repositioning	30	2744	11.3	1034.7	30	6230	7.374	1 527.6
Deorbiting	8	2744	3.0	1030.7	8	6230	2.106	1 525.5
Residuum			26.0	1004.7		5800	30.00	1 495.5
Contingency	154	2744	54.8	949.9	154	2157	48.6	1 446.9
Total Propellant	1316.1				1039.1			
Helium	3.9				3.9			
Sat dry mass	946				1443			

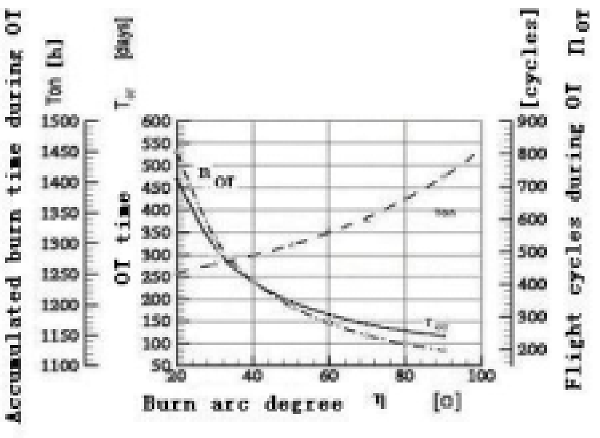

Figure 3 Transfer time, flight cycle, and accumulated burn time versus burn arc half angle η

Figure 3 shows the OT time, flight cycle, and accumulated burn times of T-MPTs with burn arc half angle. The propellant savings would increase if burn arc half angle of T-MPT decreases, but the orbit transfer time would increase. Obviously, the OT time increases dramatically if burn arc half angle decrease. Taking into account the lifetime of MPT, the maximum burn arc half angle should be smaller than 70 degree. If long

OT time is too long, the satellite will pass many times Van Allen belts, which will greatly damage solar arrays. Thus the optimal burn arc half angle is given by about 60 degree. The time of Orbit Transfer is 163 days with 60^0 burn arc half angle with four T-MPTs carrying out OT, and the cumulated firing time is 1302 hours.

The OT time can be decreased through increasing thrust of MPT, which means electric power of satellite at BOL to be increase. For example, the OT time would be decreased 96 days, when thrust per T-MPT is 445 mN, while the electric power of satellite would be increased up to 1 2000 W at BOL. Figure 4 shows OT times with thrust per T-MPT.

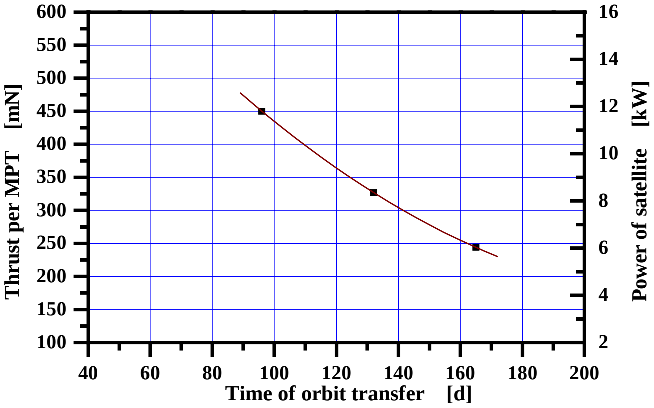

Figure 4 Transfer time versus thrust per T-MPT.

Some missions require shorter transfer time, which can be achieved through promoting perigee height and decreasing inclination angle of initial GTO. The relation of transfer times with perigee height shows in Figure5. The relation of transfer times with inclination angle shows in Figure6. When initial inclination angle is 1 degree, and perigee height is 15000 km, the transfer time would be 53 days.

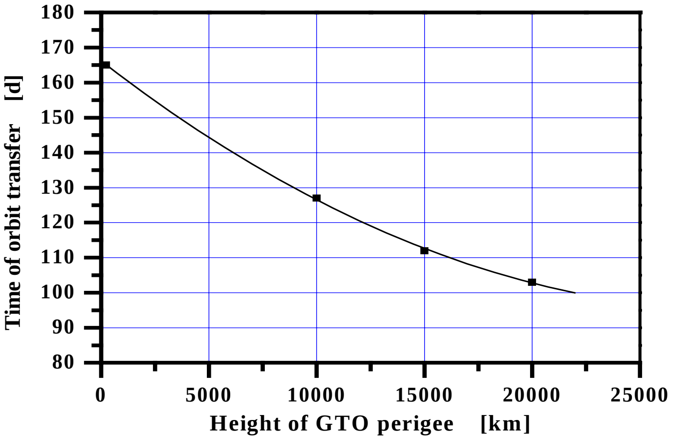

Figure 5 The relation of transfer times versus perigee height

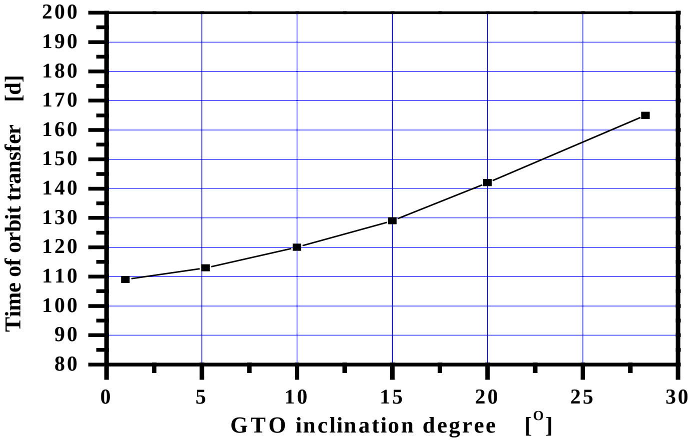

Figure 6 The relation of transfer times versus inclination angle

Comparing with other EP, such as SPT and Ion thruster, MPT has be higher the amount of thrust per unit of input electric power which is more important than I_{sp} for OT mission of GEO satellite, because the minimum transfer time is desirable. Thus the moderate I_{sp} of MPT is more nearly optimum than that of SPT and Ion thruster for OT applications. At the same time, the life time of MPT is longer than that of Arcjet.

The propulsion system of combined chemical-N_2H_4 MPT is monopropellant propulsion system, whose structure is more simple, dry weight is smaller, and reliability is higher.

5. Conclusion

Economic trends are motivating the satellite manufactures to built spacecraft with larger mass fractions and reductions in the propellant mass. Because of this situation, increased use of EP is anticipated for future GEO communication satellites. The results of optimization indicate that the MPT system with 60^0 burning arc half angle provides a reduction of propellant consumption about 21%, and payload of sat would be increased 86%. With increasing of incident power, the transfer time decreases. Comparing with other EP, MPT shows many advantages, such as moderate specific impulse, high efficiency, long lifetime, low plume contamination, simple structure, low weight, and so on. It is more nearly optimum for OT and NSSK applications. Therefore, MPT has a potential prospect of application in the future. For example, it can be used to drag make-up and solar pressure cancellation of low orbit spacecraft, formation flying and precise positioning of small satellite, repositioning and deorbiting of GEO satellite, and main propulsion for interplanetary.

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