Research on Specific Mass of High Power Nuclear Electric Propulsion System with High Temperature Gas-cooled Reactor

IEPC-2015-24／ISTS-2015-b-24

Presented at Joint Conference of 30th International Symposium on Space Technology and Science
34th International Electric Propulsion Conference and 6th Nano-satellite Symposium,
Hyogo-Kobe, Japan
July 4 – 10, 2015

Cheng Zhou [1],Yong Li[2] , Lei Wang [3], Wang Ge[4], Jun Gao [5] *and* Daren Zou. [6]
Beijing Institute of Control Engineering, Beijing, 100190,China

Abstract: High power nuclear electric propulsion (NEP) system offers significant benefits to piloted and robotic solar system exploration missions, due to its advantage of high specific impulse, high power and long-life. Specific mass is the most important parameter of the NEP system, which can effectively reduce the IMLEO of the vehicle, shorten the mission time and increase the payload ratio. In this paper, the specific mass model of high power NEP system is established with the closed Brayton power conversion subsystem. The relationship between the NEP system specific mass with the outlet temperature of the reactor, the radiator inlet temperature, Brayton power conversion system pressure ratio is discussed. The results show that, the radiator inlet temperature and Brayton power conversion system pressure ratio have the biggest impact on NEP specific mass; an increase of the reactor outlet temperature and electric propulsion system efficiency lead to an decrease of NEP specific mass. The specific mass of 15MWe Temperature Gas-cooled Reactor NEP System can be less than 6 kg/kWe, which could meet the requirement of our most deep space missions.

Key Words: Nuclear electric propulsion; Brayton power conversion; Specific mass.

[1]Cheng Zhou, Engineer, zhoucheng0208@163.com.
[2]Yong Li, Professor Engineer,liyong3092@sina.com.
[3]Lei Wang, Engineer,wanglei2275@163.com.
[4]Wang Ge, Engineer, 664945474@qq.com.
[5]Jun Gao, Senior Engineer，Gaojun1189@sina.com.
[6]Daren Zou, Engineer, zoudaren06281@163.com.

Ⅰ. Introduction

The important goal of human is manned Mars mission, in which safety and reliability requirements are much higher than the near-earth space missions. Therefore, Mankind must break through extensive new technologies to achieve the goal, and one technology enhancing for piloted Mars missions is high power nuclear electric propulsion(NEP)[1].

NEP is a propellant-efficient type of low thrust-to-weight space propulsion technology, which employs a nuclear reactor as a thermal source in a closed heat transport system to generate electricity, driving an electric thruster. The electric thruster uses the electrical energy to accelerate a propellant, producing mechanical energy or thrust. NEP has the advantages of high specific impulse, high power, long-life,etc[2]. For manned Mars mission, NEP propulsion system can shorten the duration of transit time. Compared with other space propulsion, NEP is much more tolerant of variations in launch date, stay time, and opportunity, as well as other forms of ballistic propulsion. This same figure of merit, specific impulse, implies low resupply propellant masses, making extremely attractive the idea of a reusable interplanetary space vehicle.

Therefore, NEP has attractive characteristics which enhance mission safety and flexibility for megawatt-class manned Mars mission with lower IMLEO, shorter transit time and higher payload ratio. The key figure of merit for NEP is the NEP system specific mass[3], which is the total propulsion system mass divided by the electrical power available to the thruster, usually measured in units of kilograms per kilowatt-electric[4)]. The lower the specific mass of an NEP system, the higher its performance.

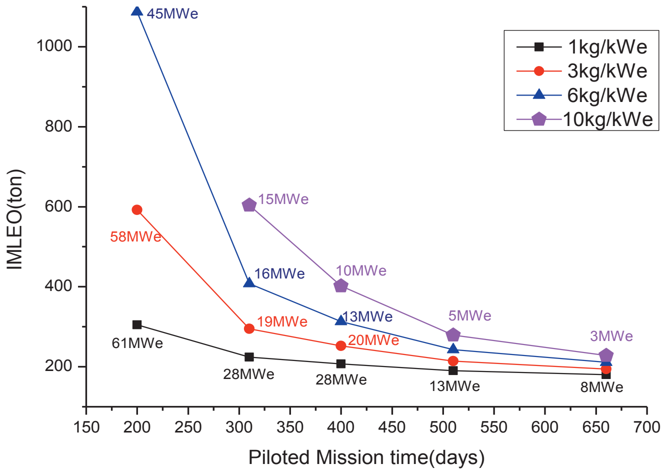

Figure 1. Manned Mars mission IMLEO from Low Earth Orbit (LEO) as a function of specific mass, power, and time.

The parametric study of Earth-Mars transit times is shown in Fig. 1. During our calculation, such parameters are assumed: LEO 800 km, LMO 500 km, 28 day mars surface stay,and payload 95 t (with a lander of 45 t). However, the IMLEO of the entire spaceship will be larger than 1000 t and total time will be larger than 800 days by chemical propulsion for manned mars mission. So, it will result in high cost of the launching mission and long exposing time of pilots in space. As suggested in Fig. 1 that the IMLEO will fall below 313 t and total time can be cut down to 400 days if NEP is employed. What's more, with the reduction of specific mass, the fast manned Mars mission can be realized. For example, if the limitation of IMLEO is set under 350 t and the mission time is about 180 days, the NEP specific mass needs to decrease to 1 kg/kWe. Therefore, the specific mass is a vital parameter, which determines the capacity of manned Mars exploration mission.

In this paper, we establish a model for calculating and analyzing the specific mass in high power NEP system based on the Brayton conversion technology. The parameter of the relationship of outlet temperature of the reactor, the radiator temperature, Brayton power conversion system pressure ratio and the efficiency of electric propulsion system to the specific mass is obtained. The variation rules of these parameters are further analyzed, based on the which, the optimization specific mass is obtained after the optimization calculation.

Ⅱ. Mass modeling of NEP system

The composition of NEP system are Nuclear Reactor Subsystem, Shielding Subsystem, Brayton power conversion Subsystem , Heat Rejection Subsystem , Power Management and Distribution Subsystem and High Power Electric Propulsion Subsystem, as shown in Fig.2. Mass budget definition is summarized in table 1.

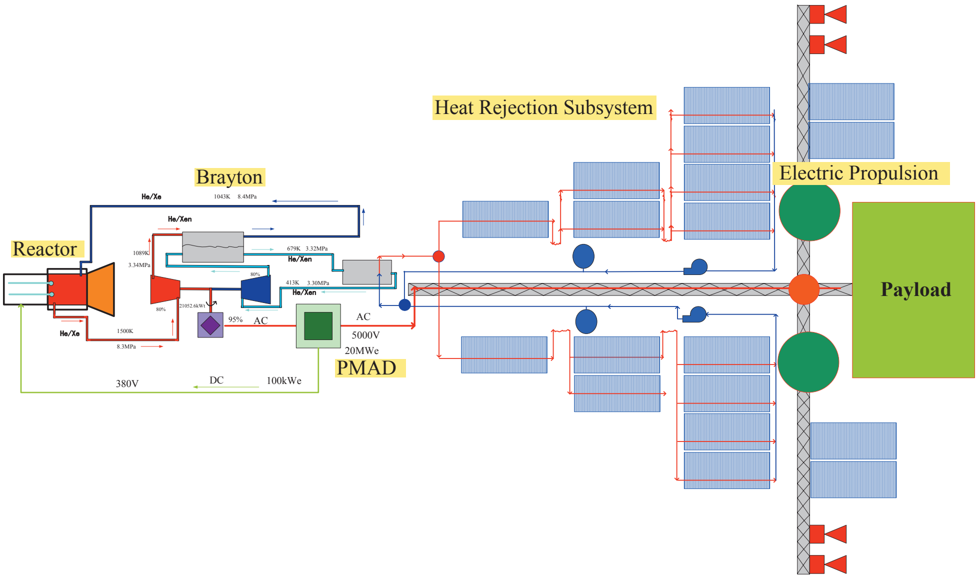

Figure 2. Space Nuclear electric propulsion system schematic(manned mars)

Table 1. Mass budget definition

Mass budget element	Model or expression
Nuclear electric propulsion system(Mw)	$Mw=M_{EP}+M_{NP}$
Nuclear Power(Reactor、Shielding 、CBC、Main Radiator、PMAD)	$M_{NP}=M_{RX}+M_{SH}+M_{CBC}+M_{MRJ}+M_{PMAD}$
Electric propulsion(Tank、Auxiliary Radiator、Thruster)	$M_{EP}=M_{TANK}+M_{EPRJ}+M_{TH}$

A. High-temperature gas cooled reactor Subsystem

The Pellet Bed Reactor (PeBR) Concept utilizes a common reactor type for NEP application. The PeBR is a helium gas cooled, fast spectrum reactor [6]. The fuel is in the form of 15mm diameter pellets. The core is separated in to four 90 degree sectors. Each sector is fully contained and can be operated individually or in concert with one or two other sections. Each of the 90 degree sections is filled with the fuel pellet. The basic parameters of the reactor are as shown in Table 2.

Table 2. Gas-cooled reactor parameters (partly)

Parameter	Unit	Value
Life	year	10
Fuel type	-	TRISO/UC-ZrC
Fuel enrichment	%	93
Pressure	MPa	8
Outlet temperature	K	1500～2000

According to empirical equation[7], the high temperature gas-cooled reactor mass model is as follows:

$$M_{RX}=5.6565\times(\frac{P_e}{\eta_{CBC}})^{0.621} \quad (1)$$

Where, η_{CBC} is the Brayton power conversion efficiency and P_e is the NEP system electric power.

B. Shielding Subsystem

The shadow structure (umbrella structure) is widely used in the shielding part of space nuclear reactor. Shadow shielding layer should be as close to the reactor as possible, for the most significant shielding effect of the shielding layer in unit mass, thus reducing the mass of shieling layer. All the electrical devices and effective payloads should locate behind the shielding layer.

The shield also performs the following functions[8]:

- Serves as structural member between the reactor and spacecraft
- Protect the inner shielding material from physical damage
- Provide structure for drive motors to reactor control elements

For the shielding layer of the reactor power system with the power higher than 100 kWe[8], the hypothesis shown in the following :

- 15 years nominal power
- Shield cone angle 33 degrees
- Payload distance is 80m
- Fast neutron fluence is 900n / cm^2
- Gamma dose is 0.35Mrad

Using the empirically derived formula[9],the shield mass model is as follows：

$$M_{SH} = 26.5 \times (\frac{P_e}{\eta_{CBC}})^{0.461} \tag{2}$$

C. Brayton Power Conversion Subsystem

Only dynamic power conversion system can apply for the MW space nuclear electric propulsion system However, during these dynamic power conversions, only closed Brayton cycle and Rankine cycle can be considered.

In the Brayton power conversion power conversion, single-phase medium (gas) is used to generate electricity through absorbing heat of reactor and making the turbine functioning. The conversion system is composed of a closed-loop gas turbine, an alternator and a compressor. Besides, a low-temperature radiator, a high-temperature heat exchanger and a heat compensator are also necessary[9].

The efficiency of the Brayton power conversion system depends on such parameters as the secondary ideal pressure ratio γ, the cycling temperature ratio τ, the total thermodynamic cycle stress damage coefficient χ, heat regenerator effectiveness ξ, adiabatic factor φ and so on.

$$\eta_{CBC} = \frac{\tau\eta_T[1-(\gamma\chi)^{-\varphi}] - \frac{2(\chi^{\varphi/2}-1)}{\eta_c}}{(1-\xi)[\tau - 1 - \frac{(\chi^{\varphi/2}-1)}{\eta_c}] + \xi\tau\eta_T[1-(\gamma\chi)^{-\varphi}]} \tag{3}$$

Where , $\tau = \frac{T_{out}}{T_{in}}$ $\varphi = \frac{k}{k-1}$, $\xi = \frac{T_{cin} - T_{RJ}}{T_{cout} - T_{RJ}}$ (4)

Where, T_{out} and T_{in} is the outlet and inlet temperature of the reactor, T_{cin} and Tcout is the inlet and outlet temperature of the heat regenerator; T_{RJ} is the average temperature of the radiator. The inlet temperature of the reactor has an energy difference of 467K and 521K with the inlet and outlet temperature of the heat regenerator, respectively.

For the nuclear power system with power more than 1 MWe, taking the ratio of CBC power conversion system mass to the thermal power of reactor as 0.8 Kg/kW_t, the mass of CBC power conversion system is as follows：

$$M_{CBC} = 0.8 \times (\frac{P_e}{\eta_{CBC}}) \tag{5}$$

D. Heat Rejection Subsystem

Heat pipe radiator is a simple radiator discharging thermal load through heat pipe and heat-pipe fins. The heat pipe decorated with C/C synthetic materials as the protective layer is of higher launching power and higher average temperature[9] (more than 750 K), which is the most promising rejection way. The structure size of the radiator can be diminished through decreasing the heat quantity irradiated from the radiator (promoting heat-electricity efficiency), thus lowering down the radiator mass. To investigate the relationship of temperature with the structure size of radiator, the Stephen Boltzmann equation is employed.

$$R = \sigma\varepsilon \mathrm{T}_{RJ}{}^4 \tag{6}$$

Where, R is irradiation power of the radiator, ε is emissivity (taken as unity for black body), σ Boltzmann constant ($5.67\times10^{-8}(\frac{\mathrm{W}}{\mathrm{m^2K^4}})$) and T is the radiator temperature (K)

The equation above suggests that the heat released by the radiator is in direct proportion to the biquadrate of the average temperature in the radiator. Although the radiator mass can be reduced through increasing temperature, the reliability and the lifetime of the system are also decreased, which leads to higher demands of the mechanical properties of the materials. The area of Heat Rejection subsystem is following:

$$S_{RJ} = \frac{P_e}{\eta_{CBC}} \times R \tag{7}$$

So, the mass of Heat Rejection subsystem is calculated as:

$$M_{RJ} = \beta_{RJ} \times S_{RJ} \tag{8}$$

Where, β_{RJ} is the ratio of mass- area for the heat pipe radiator (3 kg/m^2) .

E. **PMAD Subsystem**

The role of the power management unit is to provide proper power output after adjusting and distributing the electricity converted from nuclear energy. The mass modeling is calculated as:

$$M_{PMAD} = \alpha_{PMAD} \times P_e \tag{9}$$

F. High Power Electric Propulsion Subsystem

The high power electric propulsion system mainly includes storage system, power disposing unit, controlling unit, high power electric thruster and radiator, where the summation of the radiator, the thruster and the storage box weights 80% of the total system[10]. The n, k represents electric propulsion efficiency and mass coefficient of the storage box, respectively. The mass modeling of high power electric propulsion system is given by:

$$M_{EP} = M_{TANK} + M_{ERJ} + M_{TH} \tag{10}$$

The mass of propellant is related with electric propulsion efficiency, specific impulse and the orbital parameters. The mass of the tank is calculated as:

$$M_{TANK} = k \bullet M_p \quad M_p = M_i - M_f = \frac{M_i}{1 + (\frac{2\eta_{ep}}{\lambda})(\frac{P_e}{M_i})} \tag{11}$$

Where, the definition of the orbital parameter λ of continuous working NEP system with low thrust is following:

$$\lambda = \int_0^{tf} \gamma^2 dt \tag{12}$$

The unit of λ is m^2/s^3, equivalent with W/kg. For the manned Mars exploration mission, can be simplified as the function of time[11]

$$\lambda\left(t_f\right) \approx a \cdot t_f^b \tag{13}$$

where, a=5.222×10^7, b=-2.9183, t_f denotes the arrival date at Mars.

Taking the ratio α_{RJ} of the mass to the area of heat pipe radiator decorated with C/C synthetic materials as 3kg/m^2, the mass model of electric propulsion radiator can be seen in the expression below,

$$M_{ERJ} = \eta_{PMAD} \times (1 - \eta_{EP}) \times P_e \times \sigma\varepsilon \mathrm{T_{er}}^4 \tag{14}$$

The specific mass of the MW$_e$ AF-MPD thruster is 0.5kg/kW$_e$. Assume the efficiency of PMAD is 95%, the mass of the electric thruster is calculated as:

$$M_{TH} = 0.5 \times \eta_{PMAD} \times P \tag{15}$$

By combing Eqs.(11)-(15), the high power electric propulsion system mass can be expressed as:

$$M_{EP} = k \times \frac{M_i}{1 + (\frac{2\eta_{EP}}{\lambda})(\frac{P_e}{M_i})} + \eta_{PMAD} \times (1 - \eta_{EP}) \times P_e \times \sigma\varepsilon \mathrm{T_{er}}^4 + 0.5 \times \eta_{PMAD} \times P_e \tag{16}$$

Ⅲ. Results and discussion

A. Brayton Power Conversion Efficiency

The Brayton power conversion efficiency is mainly influenced by the secondary ideal pressure ratio γ, cycling temperature ratio τ (depended on the outlet temperature of reactor and the average temperature of radiator)and heat regenerator effectiveness ξ.

In Fig. 3, we present the relationship between the Power conversion efficiency and heat regenerator effectiveness and reactor secondary ideal pressure ratio. The power conversion efficiency can be significantly increased after the installation of heat regenerator. Higher heat regenerator effectiveness can increase the power conversion efficiency remarkably. The pressure ratio for the highest power efficiency decreases gradually if the heat regenerator effectiveness can be increased. In other words, the power conversion efficiency varies with the heat regenerator effectiveness and the pressure ratio, based on the gas-cooling Brayton cycle. For instance, the max η_{CBC} is 36% and the optimization pressure ratio γ is 2.11, if the ξ is taken as 0.95.

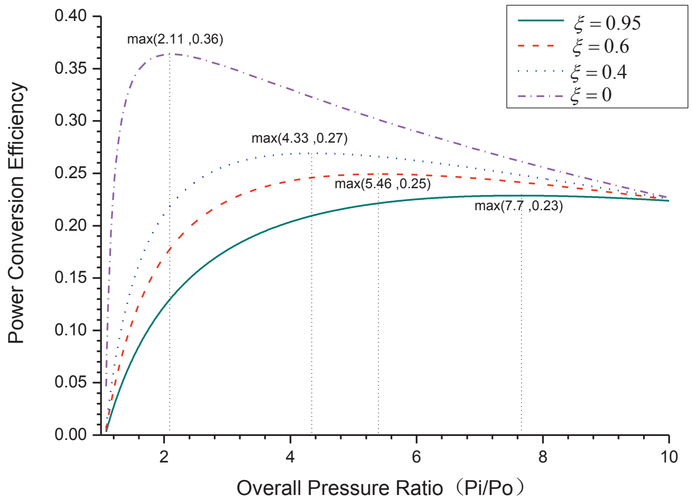

Figure 3.The influence of heat regenerator effectiveness to power conversion efficiency.

In Fig. 4, we present the relationship of conversion efficiency with cycling temperature ratio and the average temperature of the radiator. An obvious decrease from 44% to 14% and from 5.44 to 2.0 occurs in the power conversion efficiency and cycling temperature ratio, respectively when the average temperature of the radiator is increased from 700k to 1000K, with the outlet temperature of the reactor and heat regenerator effectiveness taken as 2000k and 0.95, respectively. In practical application of engineering technology, the cycling temperature ratio is usually in the range from 3.6 to 4.5, and the corresponding Brayton power conversion efficiency is calculated to range from 25% to 35%. Therefore, the cycling temperature ratio of the system can be improved through decreasing the average temperature of radiator, thus improving the power conversion efficiency. However, the decreasing temperature of the radiator may results in the sharply increasing of emission power R, thus leading to the rapidly increasing of area weigh of the radiator.

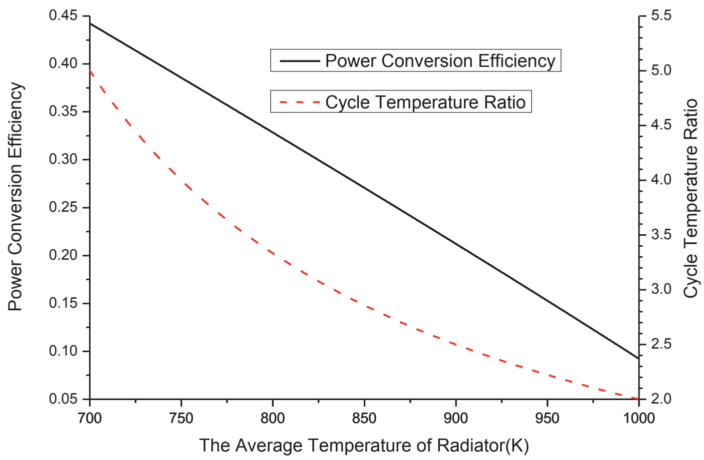

Figure 4.The influence of cycling temperature ratio to power conversion efficiency.

B. NEP Mass Factor

Fig. 5 and Fig. 6 show the relationship between the NEP Subsystem Mass and the Main Radiator with the average temperature. It is observed, the increasing average temperature of the radiator, the mass of major radiator, assistant radiator decreases rapidly while the mass of Brayton power conversion system increases rapidly and the mass of the reactor and shielding subsystem increase slowly.

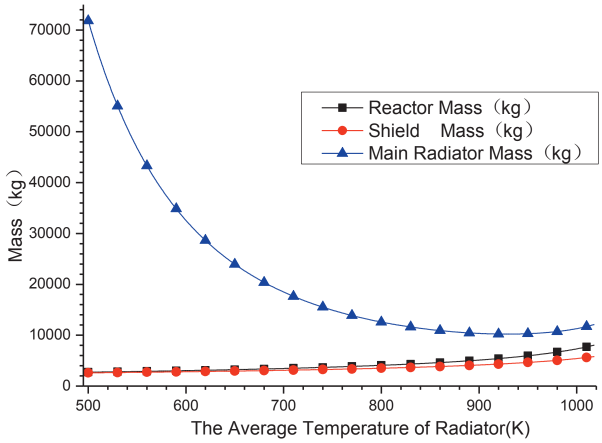

Figure 5.NEP Subsystem Mass as a function of Radiator Average Temperature (1)

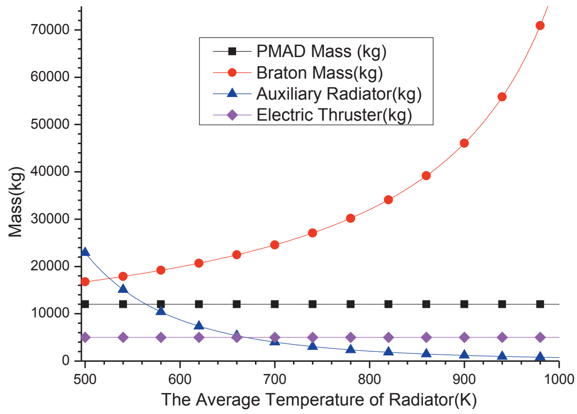

Figure 6.NEP Subsystem Mass as a function of Radiator Average Temperature (2)

Table 3 shows the mass effect factor of all the parts of NEP system with the average temperature of the radiator. The mass effect factor of the major radiator reaches the highest value of 0.54 and the mass effect factor of the reactor reaches the lowest value of 0.021 when the average temperature of the radiator is taken as 500k. When the average temperature of the radiator is taken as 700k, the mass effect factor of the Brayton power conversion system reaches 0.336, acceding that of the radiator (0.269) for the first time. The mass effect factor of the Brayton power conversion system is nearly 0.6 when the average temperature of the radiator is beyond 800k.

Table 3. NEP Mass Effect Factor

Radiator Temperature(K)	NEP Mass Effect Factor(%)						
	Reactor	Shield	PMAD	Brayton	Main Radiator	Thrusters	Auxiliary Radiator
500	0.022	0.021	0.09	0.12	0.54	0.037	0.17
600	0.048	0.046	0.143	0.250	0.358	0.060	0.095
700	0.057	0.055	0.162	0.336	0.269	0.067	0.054
800	0.069	0.067	0.162	0.405	0.202	0.067	0.027
900	0.064	0.059	0.133	0.533	0.144	0.055	0.011
1000	0.083	0.067	0.100	0.584	0.117	0.042	0.007

Through the analysis of the mass factor above, the mass of major radiator influences most on NEP system with radiator temperature below 600K, while the Brayton power conversion system influences most with the radiator temperature beyond 800K. Consequently, neither the extraordinarily high nor low temperature of the radiator is conducive to the decreasing of the total mass. As a result, choosing a proper average temperature of the radiator is necessary for optimizing the NEP mass.

C. NEP Specific Mass

The specific mass of NEP depends on the average temperature of radiator, the outlet temperature of reactor, the power of the reactor, and the efficiency of the electric propulsion system. It is suggested from Fig.7 that the specific mass of NEP system decreases firstly while increases afterwards with increasing average temperature of the radiator, giving birth to a minimum value of the specific mass of NEP. For instance, for the NEP system with the reactor outlet temperature of 1500K, 1800K, and 2000K, the optimization average temperature of the radiator is 741K, 794K and 822K, respectively, and the corresponding optimization specific mass is7.0kg/kWe , 6.0 kg/kWe, and 5.58kg/kWe respectively. It is indicated that the optimization specific mass of NEP system can be reduced through increasing the outlet temperature of the reactor, thus improving the ability of deeper- space exploration of NEP. The mass of NEP should be lower than 6.1kg/kWe. According to such limitation, the radiator average temperature of the radiator ranges 739K~851K, with a small temperature difference of 112K when the outlet temperature of the reactor is taken as 1800. While the radiator average temperature of the radiator ranges 688K~968K, with a temperature difference as high as 280K when the outlet temperature of the reactor is taken as 2000K. It is derived that the increasing of the outlet temperature of the reactor can broaden the range of the radiator average temperature, which is helpful for the design of the heat rejection subsystem.

As shown in Fig.8, the NEP specific mass decreases rapidly and slowly with increasing electric power when the electric power ranges 0~15MWe and 15~40MWe, respectively. The specific mass almost remains invariable when the electric power is beyond 40MWe. Consequently, taking the power in the range of 0~15MWe, it is feasible and effective to reduce the specific mass of the system through increasing the power of the reactor.

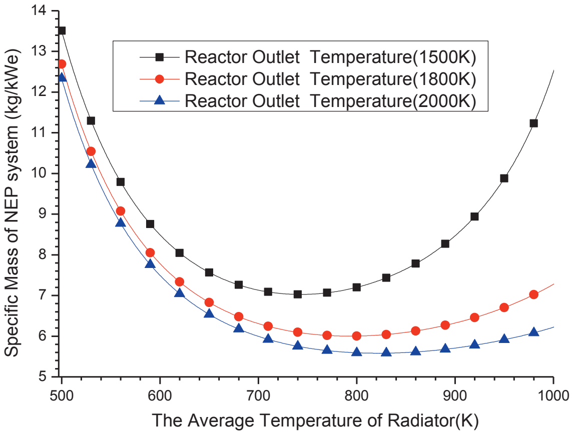

Figure 7.NEP Specific Mass as a function of Reactor outlet Temperature and Radiator average temperature.

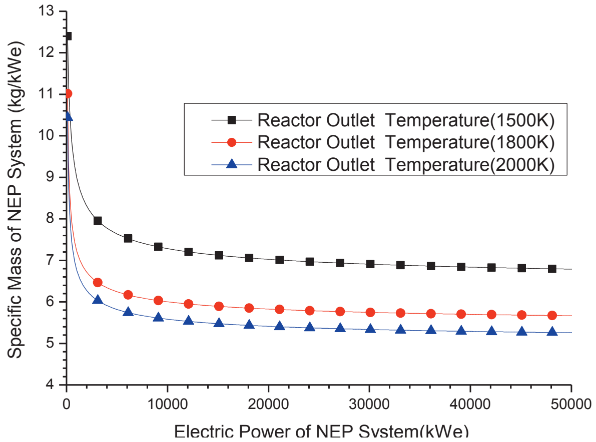

Figure 8. NEP Specific Mass as a function of total Electric Power.

Ⅳ. Conclusion

In this paper, we have established the mass model of high power nuclear electric propulsion system with high temperature Gas-cooled reactor. The variation rules of the specific mass of the system are investigated and the optimized specific mass is obtained .The main conclusions are as follows:

1) The Brayton power conversion efficiency varies with the pressure ratio and an extreme value exists. Higher heat regenerator effectiveness leads to lower optimization value of pressure ratio. The power conversion efficiency decreases significantly with the increasing of the average temperature of the radiator. The power conversion efficiency ranges 25%~35% with the cycling temperature ratio ranging 3.6~4.5.
2) The mass effect factor of all the parts of NEP system varies with the average temperature of the radiator. The mass of major radiator influences most on the mass of NEP system with radiator temperature below 600K , while the mass of the Brayton power conversion system influences most on the mass of NEP system with the radiator temperature beyond 800K. Neither the extraordinarily high nor low temperature of the radiator is conducive to the decreasing of the total mass. Consequently, choosing a proper average temperature of the radiator is necessary for optimizing NEP mass.
3) The NEP specific mass can be reduced through increasing the average temperature of radiator, the outlet temperature of reactor and the power of the reactor. Besides, given a limitation of the specific mass, the increasing of the outlet temperature of the reactor can broaden the range of the radiator average temperature, which is helpful for the heat rejection.
4) According to the calculation of the mass modeling, the outlet temperature of gas-cooling reactor in NEP is 2000K, the Brayton power conversion efficiency is 34%, the average temperature of the radiator is 822K, the optimization specific mass is 5.58 kg/kWe, and the power of the system is 15MWe, respectively, which can meet the demands of a variety of deeper-space exploration mission.

Acknowledgments

This research was supported by the National 863 Foundation "Space nuclear electric power" and the National civil astronautic project "Research on the optimization of mixed-mode propulsion system", all support is gratefully acknowledged.

References

[1] Cliquet, E., Ruault, J.M., Roux, J.P., Cazale, B., Paris, N., "Study of a megawatt level power generation system for exploration missions", Nuclear And Emerging Technologies for Space Conference, The Woodlands, 2012.

[2] Franklin R. Chang Diaz, Mark D. Carter, Timothy W. Glover, Andrew V. Ilin, Christopher S. Olsen, Jared P. Squire, Ron J. Litchford, Nob. Harada, Steven L. Koontz, "Fast and Robust Human Missions to Mars with Advanced Nuclear Electric Power and VASIME Propulsion", Proceedings of Nuclear and Emerging Technologies for Space 2013, Paper 6777, pp8 (2013).

[3] Mason, L., "Evolutionary Development Path for Viable Nuclear Electric Propulsion Systems for Exploration,", oral presentation, 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, San Diego, CA, July 2011.

[4] John H. Scott, Jeffrey A. George, Alfonso G. Tarditi, "Direct Energy Conversion for Low Specific Mass In-Space Power and Propulsion" Proceedings of Nuclear and Emerging Technologies for Space 2013,Albuquerque, NM, February 25-28, 2013.

[5] George, J. A., Hack, K.J., Dudzinski, L.A., Gefert, L.P., and Gilland, J. H., "Piloted Mars Mission Planning: NEP Technology and Power Levels," in Proceedings of 10th Symposium on Space Nuclear Power and Propulsion, edited by M. El-Genk, AIP Conference Proceedings 271, New York, 1993, pp. 493-500.

[6] Juhasz, A. J., "Heat Transfer Analysis of a Closed Brayton Cycle Space Radiator", NASA/TM-2007-21503, 2007.

[7] Scott J. McGinnis, "NUCLEAR POWER SYSTEMS FOR MANNED MISSION TO MARS", United States Navy B.S., United States Naval Academy, 1997.

[8] Scott F. Demuth ,"SP100 Space reactor design",Nuclear Energy, Vol. 42, No. 3, pp. 323-359, 2003.

[9] W. J. Carmack, D.L.Husser, T.C.Mohr, and W.C.Richardson, "Status of Fuels Development and Manufacturing for Space Nuclear Reactors at BWX Technologies", STAIF, February 2004, Albuquerque, NM, 426.

[10] A.V. Illin, L.D. Cassady, T.W. Glover, F.R. Chang Diaz, March 2011. VASIMR Human Mission to Mars. Space Propulsion and Energy Sciences International Forum (SPESIF 2011). College Park, MD. 15–17 March 2011.

[11] Bérend N., "Optimum Design of Power-Limited Propulsion Systems with Application to Fast Earth to Mars transfer", Acta Astronautica 79 (2012) 107–117, doi: 10.1016/j.actaastro.2012.04.042.