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Detail performance for solar thermal propeller with deployable umbrella-shaped keel structure concentrator

Jianfeng Dai[1*], Chunmei Cui[2], Bi Fu[3,4]

[1]State Key Laboratory of Gansu Advanced Non-ferrous Metal Materials, Lanzhou University of Technology, Lanzhou 730050, (CHINA)
[2]Condensed Matter Physics Institute, Lanzhou University of Technology, Lanzhou 730050, (CHINA)
[3]Xi'an Aerospace Precision Electromechanical Institute, Xi'an 710100, (CHINA)
[4]Lanzhou Institute of Physics, China Academy of Space Technology, Lanzhou 730000, (CHINA)
E-mail: Daijf@lut.cn

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*Corresponding author's Name & Address

Jianfeng Dai
State Key Laboratory of Gansu Advanced Non-ferrous Metal Materials, Lanzhou University of Technology, Lanzhou 730050, (CHINA)
E-mail: Daijf@lut.cn

Abstract

A deployable umbrella-shaped keel concentrator has been proposed for the solar thermal propulsion (STP) system, the improved concentrator will make up the inherent defect of traditional inflatable concentrators and rigid fixed concentrators. Taking ammonia as the propellant gas will overcomes the shortcomings of choosing hydrogen and helium. The performance of STP system equipped with this new structure prime concentrator and propellant gas with refractive secondary concentrator has been investigated by the software MATLAB. The results reveal that the thrust and specific impulse could reach to 25N and 3500s, respectively. Indicating this system has significant interesting for selection of optimize parameters and further research of STP in deep layer space operation.

Key Words

Solar thermal propulsion; Umbrella-shaped keel; Specific impulse; Thrust.

INTRODUCTION

Solar thermal propulsion belongs to a special propulsion system[1-3], which makes use of solar energy heat propellant gas directly, and it has a high solar energy utilizing efficiency with a relatively simple structure. And compared with traditional chemical propulsion and electric propulsion, STP system equipped with much more advantages such as follows: (1) Smaller volume and weight: STP system use solar energy heat propellant gas directly that avoid huge storage tank of chemical fuels and power management system. For the same space flight mission, STP system can save much more chemical fuel and increase the payload; (2) Higher utilization rate of solar energy: The total energy utilization rate of STP can reached 60% ~ 70% with simple system, and general electric propulsion which use solar panels to generate electricity to make thrust, the solar energy utilization rate only 20% and lost most of the solar energy lost. (3) STP system equipped with wide range and moderate thrust (0.5N-25N) that suitable for attitude control and orbit transfer[4-7] for micro-and nano-satellites in deep layer space operation.

At present, almost all propellant gas for STP is hydrogen, and the United States and Japan are adopt the secondary concentrate technology to improve the concentrate ratio. In this article, detail performance for STP which equipped with deployable umbrella-shaped keel structure concentrator[8,9] and new propellant gas ammonia with refractive secondary concentrator that has significant interesting for further research of STP.

MATERIAL AND MODEL

Propellant gas-ammonia

Not to mention the permeability of liquid hydrogen, aiming at the ammonia[11-13] itself, the liquefaction technology is simple and the liquid ammonia is take advantage to be stored than hydrogen that can avoid the huge quality of storage tank and complicated manufacturing technology. The major advantage is what almost all ammonia will decomposition into smaller molar mass material hydrogen and nitrogen when the temperature above 1000K, in other words, the specific impulse can still achieve or more than 3000s.

Umbrella-shaped keel structure prime concentrator

In order to improve the concentration efficiency, eliminate the optical aberration and overcoming the shortcomings of traditional inflatable concentrator such as massive existences of superimposed fold, low deployment degree and high optical aberration, as well as the disadvantages low power and huge size of rigid fixed concentrator. In this article, umbrella-shaped keel structure has been introduced into the deployable solar paraboloid concentrator with the equation $y = x^2/32$ is shown in Figure 1. This condenser is not only suitable for STP system[10-12], but also it can be used in space antenna, solar sail and solar thermal power generation system. From the equation above, the focal length of paraboloid concentrator is 8 m. 4.9 m, 30.77 m, 75.39 m and 80 m are corresponding to the opening projection radius of circle, opening perimeter, opening area and parabolic surface area of paraboloid concentrator, respectively. Polyimide film (Kevlar) with thickness of 0.5 mm is selected for reflective film substrate of the concentrator, which proved equipped with all right mechanical properties and chemical stability after frequently used in space engineering. Aluminum film with thickness for 10 μm is the film of reflective which has well film-forming property and high reflectivity in all the range of solar spectrum. Plating silver aluminum composite membrane layer with the thickness of 120 nm above the reflecting film as the reflection increasing film to improve the reflectivity, and plating SiO_x film with 275 nm above silver aluminum composite membrane layer to avoid the film evaporation in the space.

To make sure the concentrator has enough stiffness and strength, adopt SP700 titanium aluminum alloy produced in Japan which equipped with low density, this material can replace Ti-6A1-4V with high strength, good formability and low processing cost, which could attain superplasticity and the elongation can achieve 2000% when the temperature above 755°C. The umbrella-shaped keel structure is composing of 12 parabolic umbrella supports and each umbrella support length is 498 cm, and all the other parameters are shown in TABLE 1.

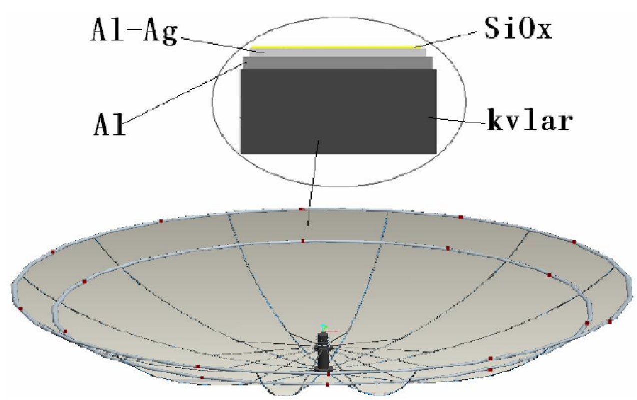

Figure 1 : Structure of umbrella-shaped keel

TABLE 1 : The parameters of umbrella-shaped keel structure prime concentrator

	the U-shaped tube	hollow pipe	each u-shaped tube	hollow cylinder for axial umbrella support	peripheral circle plate racks	Circumference of peripheral circle plate racks
Circumference					30.77 m, 28.26 m	
Diameter		4.2cm		2 cm		
Length	490 cm	10cm	122 cm	500 cm		
Width	2cm		1 cm			1 cm
high	1.5cm					
thickness	1mm	1cm		1 mm	1 mm	2 mm

Herein, the umbrella-shaped keel structure concentrator with an aperture radius of 4.9 m can provide the concentration power of 100 kW, the maximum deformation of umbrella fabric is 0.941 mm, the radius of the spot size is 6.37 cm, and the geometric concentration ratio of umbrella-shaped keel structure concentrator can achieve to 5917, only 1.25% lower than the ratio of the standard parabolic concentrator. The major advantage is that according to the calculate parameters of condenser structure, material and density, the total quality of umbrella-shaped keel condenser is about 30.8 kg and the volume for prelaunch is 0.54 m^3 which is far less than the fixed rigid structure condenser.

PERFORMANCE RESEARCH OF STP

Herein, the fluid dynamics behavior of propellant gas ammonia will be calculated and the relationship diagram among the open area of refractive secondary concentrator, temperature of composite propellant gas, specific impulse and thrust will be drawn with MATLAB software.

Theoretical calculation

In the absorber/thruster[13], the radiation heat transfer equation is based on the-experienced correction formula of stefan-boltzmann law with the equation is:

$$\varepsilon A_r \sigma T_s^4 = \eta_{cl}\eta_{ri}\eta_{c2}\eta_a C_l I_{sal} A_{c2} \quad (1)$$

Heating of gas absorbed should be equal to the heat dissipating capacity of inner chamber wall and the equation can be written by:

$$\dot{m}C_{pm}(T_{cm}-T_i) = hA_h(T_s - T_{cm}) \quad (2)$$

Let transfer area $A_b = 4 \cdot d_b \cdot L_b$ of flow heat for screw propellant gas and the heat transfer coefficient of surface h = kNu/l_c substitution and the equation like:

$$\dot{m}C_{pm}(T_{cm}-T_i) = 4k_m \cdot C_r \cdot N_u \cdot L_h(T_s - T_{cm}) \quad (3)$$

By type (3), the temperature of propellant gas (composite propellant) in absorber/thruster is:

$$T_{cm} = \left(\dot{m}C_{pm}T_i + 4k_m \cdot C_r \cdot N_u \cdot L_h T_s\right) / \left(\dot{m}C_{pm} + 4k_m \cdot C_r \cdot N_u \cdot L_h\right) \quad (4)$$

Ignoring the influence of small nozzle boundary layer condition, supposing the chemical group of propellant gas is divided into frozen equilibrium state and deriving the engineering algorithm of specific impulse, thrust and jet velocity of STP based on the coupled heat transfer theory and solar thermal utilization principle are given by:

$$I_{spm} = [\frac{1}{2}(1+\cos\theta)]\sqrt{2R_0\left(\frac{\gamma_m}{\gamma_m-1}\right)\left(\frac{T_c}{M_m}\right)\left(1-(p_e/p_c)^{\frac{\gamma_m-1}{\gamma_m}}\right)} + \frac{(p_c-p_a)\pi d_c^2}{4\dot{m}}(s) \quad (5)$$

$$F_m = \dot{m}u_e + (p_e - p_a)A_c(N) \quad (6)$$

$$u_{em} = \sqrt{2R_0\left(\frac{\gamma_m}{\gamma_m-1}\right)\left(\frac{T_c}{M_m}\right)\left(1-(p_e/p_c)^{\frac{\gamma_m-1}{\gamma_m}}\right)}(m/s) \quad (7)$$

Where γ_m and M_m corresponding to the specific heat ratio and relative molecular quality of composite propellant gas, respectively; R_0 is the constant of universal gas valued 8.314510$J/(mol\ K)$.

Parameter's selection and calculation

The parameter of the concentrator as follows: (1) Conditions: assumed performance indicate status as the working state (in the nozzle, the gas flow is for whole expansion state), that indicated to $P_e = P_a$; (2) The ideal rotating parabolic condenser has good characteristics of convergent and condensing ratio has a theory maximum of C_{1max} = 11258, so, choose condensing ratio C_1 range from 6000 to 11000 for the performance calculation; (3) Throughput density of radiant energy above the earth's atmosphere is substantially a fixed value $I_{sol} = 1367 \pm 7W/m^2$. But I_{sol} will be reduced under $1000W/m^2$ on the surface of the earth. So choose the scope from 800 to 1300 for the performance indicate calculation; (4) the parameters of absorber/thruster: inside diameter d, outside diameter D, length L, pressure P, nozzle area ratio and structure parameters of STP are shown in TABLE 2.

TABLE 2 : Structure parameters of STP

d(cm)	D(cm)	L(cm)	$P_c(Mp_a)$	A_e/A_c
6	7.6	20	0.2	100

(5) Selection of other parameters: selective absorbing coating HfC with absorption rate η_c = 80% and emission rate ε = 0.51; percentage for reflected light on the surface of secondary condenser η_{cl} = 92% and reflectivity of material η_{il} = 95%; take η_{c2} = 92% for optical efficiency of RSC; Inlet diameter of refraction secondary condenser R_{c2} = 4.45cm. Expansion half angle of nozzle $\theta_{dlv} = 20^0$; (6) In such case, choose the coefficient of thermal conductivity diagram formula λ_m = 0.4961; M_m = 8.51535, γ_m = 1.40226 and C_{pm} = 7085 are representing the relative molecular mass, specific heat ratio and specific heat at constant pressure of composite propellant gas. And performance indicated is shown as figure 2 that taking ammonia as the propellant gas:

From figure 2(a-c) above, we know from 2(a), when condensing ratio of condenser and throughput density of the sun radiant energy are established, the temperature of composite propellant gas in the absorber/thruster will be reduced with the mass flow rate increased, because when the condensing ratio of condenser and throughput density of the sun radiant energy established, that is to say the energy which used to heat the composite propellant gas is established, and with the mass flow rate increased, then each unit of composite propellant gas gain less energy and the temperature of composite propellant gas must be reduced or based on type (4), with the increased mass flow rate the temperature of composite propellant gas reduced, and the temperature of composite propellant gas in the absorber/thruster can achieve 2600K; when the mass flow rate established, the temperature of propellant gas in the absorber/thruster increased with the condensing ratio of condenser and throughput density of the sun radiant energy increased, because when the mass flow rate established, that is to say: the composite propellant gas which need to heat is established and the energy which used to heat the composite propellant gas increased (condensing ratio of condenser and throughput density of the sun radiant energy increased), and the temperature of propellant gas must be increased.

Analysis for figure 2(b), when the condensing ratio of condenser and throughput density of the sun radiant energy are established, the specific impulse of composite propellant gas will be reduced with the mass flow rate increased, because when condensing ratio of condenser and throughput density of the sun radiant energy are established, the temperature of composite propellant gas in the absorber/thruster will be reduced with the mass flow rate increased, with the temperature of composite propellant gas reduced based on formula (5), the specific impulse of composite propellant gas must be reduced, and the specific impulse of composite propellant gas can reach 3900s; when the mass flow rate established, the specific impulse of composite propellant gas increased with the condensing ratio of condenser and throughput density of the sun radiant energy increased, because when the mass flow rate established, the energy which used to heat the composite propellant gas increased (condensing ratio of condenser and throughput density of the sun radiant energy increased), and the specific impulse of composite propellant gas must be increased with the temperature of propellant gas increased.

Analysis for figure 2(c), when the mass flow rate established, the thrust of composite propellant gas increased with the condensing ratio of condenser and throughput density of the sun radiant energy increased, because when the mass flow rate established, much more energy that each unit of propellant gas can absorbed with the increasing condensing ratio of condenser and throughput density of the sun radiant energy, and the thrust of composite propellant gas increased with higher jet velocity and has a broad range from 0.5N to 25N.

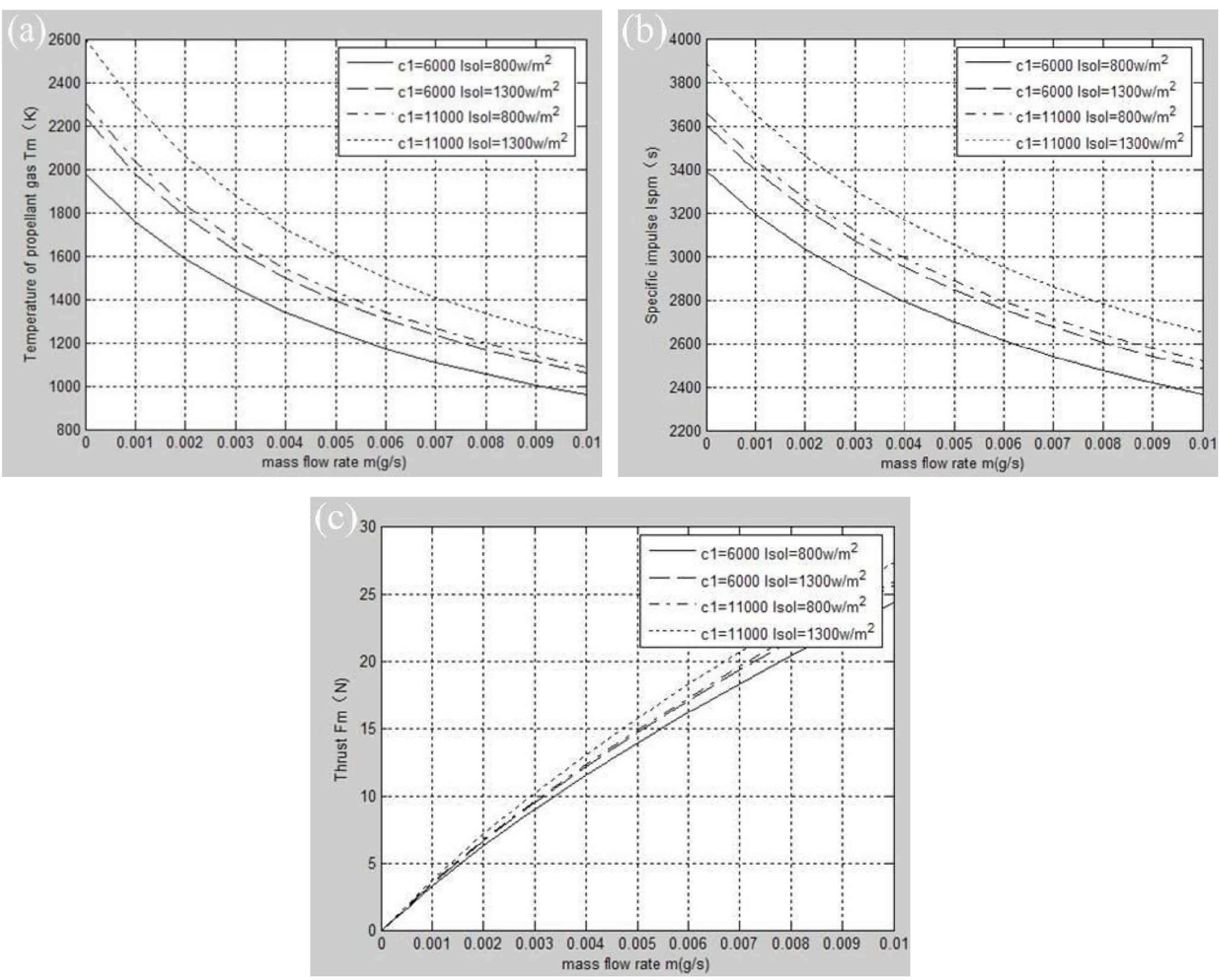

Figure 2 : Performance indicated for ammonia as the propellant gas

The results of analysis

We may draw conclusions based on curves above

(1) A deployable solar paraboloid concentrator adopts the collapsible umbrella-shaped keel structure can avoid the low power, huge size of rigid fixed concentrator, massive existences of superimposed fold, low deployment degree and high optical aberration of traditional inflatable concentrator, this structure of concentrator equipped with high power, specific impulse and thrust.

(2) Let ammonia as propellant gas, when condensing ratio of condenser and throughput density of the sun radiant energy are established, the thrust will be increased and has a broad range with the mass flow rate increased, but the temperature of composite propellant gas in the absorber/thruster and specific impulse are reduced gradually. When the mass flow rate of propellant gas is established, the temperature of composite propellant gas, specific impulse and thrust will be increased with the increasing condensing ratio of condenser and throughput density of the sun radiant energy.

CONCLUSIONS

From the conclusion of researches and analysis results above, let ammonia as the propellant gas with the deployable umbrella-shaped keel structure concentrator, it can produce high specific impulse 3500s, relatively wide range and moderate thrust from 0.5N to 25N, it can reduce the cost and avoid complicated manufacturing technology requirements with simple process and improve the work stability. The temperature of composite propellant gas, mass flow rate, specific impulse and thrust can be determined and coordinated according to the requires of task. So let ammonia as the propellant gas with the deployable umbrella-shaped keel structure concentrator has certain feasibility and scientific value for further study of STP.

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