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Modeling of Iodine Feeding System to Achieve Flow Control under the Coupling of Multiple Conditions

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Abstract: The design of an iodine working medium storage and supply system is one of the key technologies for the electrical propulsion of iodine working medium. Solid iodine sublimates into a gaseous state in the storage tank, and is transported to the thruster through flow control through components such as a proportional valve or throttle tube. However, iodine working medium has corrosive properties and poor thermal conductivity, which can easily cause condensation in the throttle tube and throttle valve, affecting the accuracy of experimental results or blocking the pipeline, leading to the suspension of the experiment. Based on the system level modeling of the iodine working medium electric propulsion storage and supply system, and taking into account the impact of the coupling effects of various conditions such as the physical parameters of iodine vapor, storage tanks, pipelines, outlet conditions, and proportional valves on the outlet mass flow rate of the iodine storage and supply system, the control of the outlet mass flow rate is achieved by adjusting the valve opening of a comparative example, providing a reference for the selection of the size of the throttle tube in future ground experiments or the control of the proportional valve opening.

Keywords: Iodine, Electric propulsion feeding system, System level modeling, One-dimensional simulation.

1. Introduction

Electric propulsion systems typically include three components: a power processing unit, a propellant storage and supply system, and a thruster. The power supply unit provides energy for the entire electric propulsion system, and the storage and supply system mainly includes a working medium storage tank, valves, and pipelines. The thruster heats the working medium through electrical energy or ionizes the propellant working medium in the gaseous state to generate plasma, which is accelerated by an electrostatic field and a magnetic field, causing the plasma to eject at a high speed, thereby forming a thrust force. With the development of aerospace technology, electric propulsion devices are gradually developing towards miniaturization, low-cost, and high-performance. Currently, mainstream electric propulsion devices mainly use xenon as an electric propellant. However, xenon gas has a low reserve in nature and is difficult to exploit, resulting in high prices. At the same time, the purity requirements for xenon gas are very high. The preparation and storage of high-purity xenon gas greatly increases the cost of electric propulsion systems. In order to achieve high-density storage of propellant working fluids, effectively reduce launch loads, and save space on satellites, solid state electric propulsion technology has gradually entered people's vision.

Iodine has been considered as an alternative to xenon for more than a facade [1] [2]. The design of an iodine working medium storage and supply system is one of the key technologies of iodine working medium electric propulsion. Solid iodine is sublimated into the gaseous state in the storage tank, and is transported to the thruster through flow control through components such as a proportional valve or throttle tube. Szabo [3] discussed the potential of iodine propellant in Hall electric thrusters. In 2013, NASA's Marshall Space Flight Center competitively selected a mature project for an iodine flight operational storage and supply system through a technology investment plan. In 2017, NASA's Green Research Center conducted a durability test experiment for an iodine xenon hybrid propulsion system, using xenon as the cathode and iodine as the thruster. The test lasted 1174 hours. However, iodine working fluids have corrosive properties and poor thermal conductivity, which can easily sublimate in the throttle tube and valve, affecting the accuracy of the experimental results or blocking the pipeline, leading to the suspension of the experiment. Therefore, numerical simulation is one of the important means in the design improvement and working characteristics research of the storage and supply system, which can save a lot of time. Simulation research on storage and supply systems can be divided into two types: one is high-dimensional modeling, which focuses on pressure and flow regulating components, and analyzes the impact of component parameters on the system itself, even on system performance; The other is to use low-dimensional modeling to build a relatively complete system level multidisciplinary coupled simulation model, exploring fluid flow characteristics at the system level, coupling relationships between parameters among various components, and other aspects. Currently, the research on electric propulsion storage and supply systems is mostly focused on the former, focusing on a single component of the xenon gas storage and supply system: Dyer et al. [7] conducted research on the flow characteristic model of annular micro flow channel type flow regulating components, comprehensively considering the effects of channel structural parameters, xenon density, temperature, and other factors on the viscosity of xenon gas; Ganapathi et al. [8] modeled the flow characteristics of a porous media type flow control module with a thermal regulation function, and analyzed the uncertainty of the flow. However, all models are built for a module in the xenon electric propulsion storage and supply system, so the reference significance for the iodine working medium electric propulsion storage and supply system with less actual use frequency is limited, and it is very difficult to comprehensively consider the impact on the outlet flow of the iodine storage and supply system under other coupling conditions such as flow and heat transfer.

Therefore, this article uses Dymola to conduct a system level modeling of the iodine working medium electric propulsion storage and supply system, comprehensively considering the impact of the coupling effects of various conditions such as physical parameters of iodine vapor, storage tank, pipeline, outlet conditions, and proportional valve on the mass flow rate at the outlet of the iodine storage and supply system. Firstly, the storage tank is modeled to simulate the process of solid iodine sublimation to generate iodine vapor, and then the generated iodine vapor forms a vapor pressure in the tank cavity, Used as the inlet pressure for calculating the flow rate of iodine vapor during pipeline transportation, and finally read the mass flow rate in the pipeline. Using PI to control the opening of the proportional valve to achieve the target mass flow rate, a system level simulation was completed for the iodine working medium electric propulsion storage and supply system. By adjusting the opening of the comparative example valve, the outlet mass flow rate was controlled, providing a reference for future experiments.

2. Modeling of System

2.1. Physical parameters of iodine

Many of the basic physical properties of iodine that can be queried are data on iodine vapor at about one atmospheric pressure, which is much higher than the working pressure of the propellant storage and supply system. The data for gaseous F2, Cl2, and Br2 may serve as a reference for the physical properties of iodine, but there is also little information about these halogens. As mentioned earlier, for iodine data that cannot be queried, nitrogen is usually used as a reference because it is also a diatomic molecule. The physical parameters of iodine obtained from literature review include saturated vapor pressure, density, viscosity, specific heat capacity, enthalpy, entropy, sublimation rate, etc.

The saturated vapor pressure of iodine can be estimated using Equation 1. It is known that a vapor pressure of about 50 torr (6000 Pa) can be generated at a sublimation temperature of about 100 ℃, allowing iodine vapor to flow through the pipeline and be transported to the thruster.

$$P_{\text{vap}} = 10^{A-\frac{B}{T+C}} \tag{1}$$

Where: A=3.36429, B=1039.159, C=-146.589, and the pressure unit is bar.

The density of iodine vapor is determined by the ideal gas equation of state, with a molecular weight of 253.81 g/mol;

The viscosity of iodine vapor can be determined by Equation 2:

$$\mu = \mu_0 \frac{(T/T_0)^{3/2}}{(1+(T/T_0))} \tag{2}$$

In the formula: $\mu_0 =$ （3.85 ± 0.36）$\times 10^{-5} kg/(m \bullet s)$；

$T_0 =$ （471 ± 41） K

The specific heat capacity, enthalpy, and entropy of iodine vapor are determined by the Shomate equation in NIST:

$$C_P = A + B*T_{1000} + C*T_{1000}^2 + D*T_{1000}^3 + \frac{E}{T_{1000}^2} \tag{3}$$

$$H - H_{298.15} = A*T_{1000} + \frac{B*T_{1000}^2}{2} + \frac{C*T_{1000}^3}{3} + \frac{\mathrm{D}*T_{1000}^4}{4} + \frac{E}{T_{1000}} + F - H \tag{4}$$

$$S = A*\ln(T_{1000}) + B*T_{1000} + \frac{C*T_{1000}^3}{2} + \frac{D*T_{1000}^3}{3} + \frac{E}{2*T_{1000}^2} + G \tag{5}$$

In the formula: $T_{1000} = \frac{T(K)}{1000}$;the units of three physical quantities are: $J/mol*K$,kJ/mol, $J/mol*K$.

The constants in the equation are shown in Table 1:

Table 1. Parameters of Shomate Equation

A	37.79763
B	0.225453
C	-0.912556
D	1.034913
E	-0.083826
F	50.86865
G	305.9199
H	62.42110

The sublimation rate of iodine can be characterized by Equation 6:

$$\frac{dm}{dt} = \alpha A \sqrt{\frac{M}{2\pi RT}} (P_{vap} - P) \tag{6}$$

In the formula:

A———Surface area, m2;

M———Molar mass, g/mol;

R———General gas constant, J/(mol·K);

P———Pressure of surrounding gas, Pa;

T———Ambient gas temperature, K;

P_{vap}———The vapor pressure at the corresponding temperature, Pa

2.2. Pipeline model setting of the storage system

Regardless of the stroke control of the internal spring of the storage tank, the model is simplified as shown in Figure 1. The main elements include a constant volume cavity, the mass source term generated by iodine sublimation, a constant wall temperature pipeline, control valves, and outlet boundaries. Assuming that the system performs sufficient heat tracing, the occurrence of condensation is ignored.

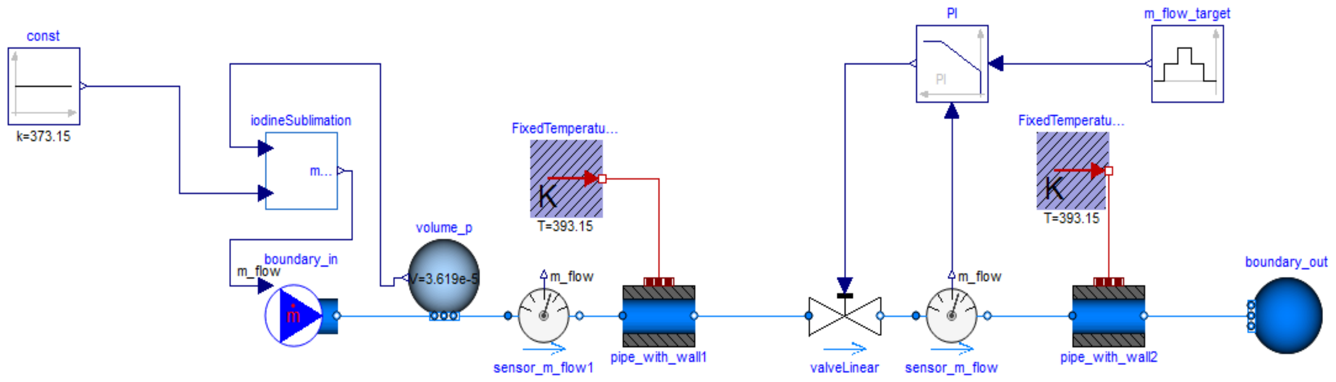


Figure 1. Single pipeline model setup diagram of simulation system

The calculation settings are described as follows:

1) In the dynamic pipeline flow model, one-dimensional NS equations are considered, and the finite volume method and staggered grid scheme are used to deal with partial differential equations. This model can achieve discretization in the flow direction.

2) In the wall model of the wrapped flow channel, two-dimensional unsteady heat conduction along the flow direction and radial direction is considered.

3) The empirical correlation between the fluid and the wall in the pipeline is used to consider convective heat transfer. The Reynolds number Re and the Prandtl number Pr are calculated based on the fluid temperature, physical properties, and flow rate. Then, the appropriate Nusselt number Nu correlation is selected based on the Reynolds number to obtain the convective heat transfer coefficient. In fact, the calculation correlations for laminar flow, transition flow, and turbulence in the model have been unified into a heat transfer coefficient model. This model can not only achieve automatic switching of the correlations for each region, but also carefully smooth the boundaries of each region, ensuring the continuity of the first derivative of Nu, greatly improving the robustness of the model.

4) The first, second, or third type of boundary conditions can be used for pipe walls and the environment as required, and radiation heat transfer can also be considered.

5) In the storage tank, a quality model considering iodine sublimation has been established, and a code that can display the height of solid iodine in real time has been written on the system model interface, achieving visualization in the calculation process.

6) In valve models, linear models are currently used, and the relationship between mass flow and valve opening is linear. "Modeling can also be conducted as required in accordance with GB/T 17213.17-2010/IEC 60534-2-5: 2003 Industrial Process Control Valves - Part 2-5: Calculation Formula for Flow Capacity of Fluid Flowing through Interstage Recovery Multistage Control Valves, taking into account the blocked/non blocked flow of the valve and the relationship between flow coefficient and inlet pressure, fluid density, and expansion coefficient.".

7) The output signal of the flow monitor is used as the input of the PID controller to control the opening of the proportional valve to ensure that the iodine vapor flow to the combustion chamber reaches a preset value.

8) For iodine vapor, the currently used single-phase compressible ideal gas. Data source: Original Data: Computer program for calculation of complex chemical equilibrium compositions and applications Part 1: Analysis Document ID: 19950013764 N (95N20180) File Series: NASA Technical Reports Report Number: NASA-RP-1311 E-8017 NAS 1.61:1311 Authors: Gordon, Sanford (NASA Lewis Research Center) Mcbride, Bonnie J. (NASA Lewis Research Center) Published: Oct 01, 1994.

The cavity is the vapor domain inside the storage tank, which is formed by sublimation of solid iodine and overlies the solid iodine. The temperature and pressure of the iodine vapor affect the sublimation rate of solid iodine. The cavity part is a cylinder, as shown in Figure 2 in the model, and the dimensions are shown in Table 2.

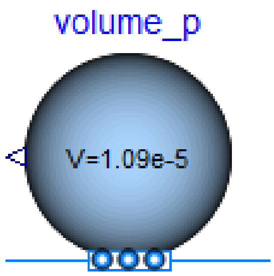


Figure 2. Constant Volume Cavity

Table 2. Cavity Parameters

Radius (mm)	Altitude (mm)
24	6

The mass source term refers to the mass of iodine vapor escaping from the sublimation of iodine solids on a fixed surface per unit time. The sublimation rate is shown in Equation 6, and is shown in Figure 3 in the model. It is related to the pressure, temperature, and surface area of the vapor region. Therefore, two inlets are set in the mass source term, which are respectively the pressure feedback and temperature settings of the cavity region. The output mass flow rate is connected to the cavity, generating vapor pressure in the cavity.

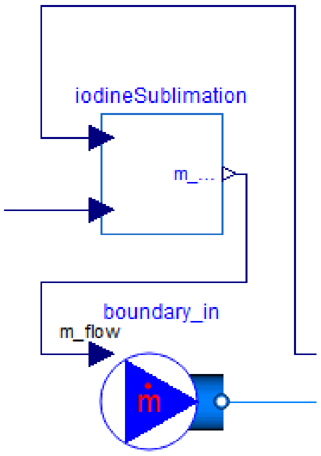


Figure 3. Quality Source Item

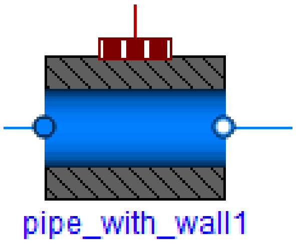


Figure 4. Pipeline

The pipe is composed of stainless steel pipe walls and internal iodine vapor flow channels, as shown in Figure 4. The stainless steel material is 316L, and the relevant parameters of 316L stainless steel are shown in Table 3. The inner diameter of the pipe is 4.6mm, and the outer diameter is 6.35mm. Since the pipeline is attached with Fried Dough Twists type tracing tape and wrapped with insulation material, convection heat transfer can be ignored, and the wall is set as a constant temperature boundary condition, and the pipeline temperature is 120 °C.

Table 3. Parameters of 316L Stainless Steel

Physical property Parameters	Numerical value	Unit
thermal conductivity	8.38266+0.01750316*T^1-3.146906E-6*T^2	W/(m·K)
Constant pressure heat capacity	235.6508+1.300842*T^1-0.001890526*T^2+1.348414E-6*T^3-3.433794E-10*T^4	J/(kg·K)
Surface emissivity	0.5	1
Density	8058.746-0.1963973*T^1-4.830884E-4*T^2+4.114383E-7*T^3-1.337946E-10*T^4	kg/m^3

The valve plays a role in controlling flow, as shown in Figure 5 in the model. According to the experimental data results, the characteristics of the valve can be set. The valve is externally connected to PI control, which is used to simulate the control of the proportional valve over the target flow. A mass flow monitoring module is installed behind the front valve in the channel to collect mass flow parameters in the flow channel. The reality in the model is shown in Figure 6.

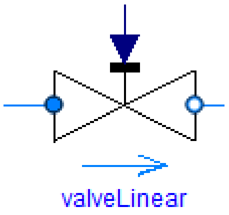


Figure 5. Proportional Control Valve

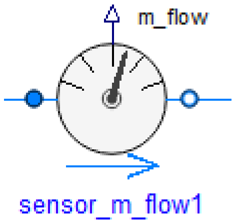


Figure 6. Mass Flow Parameter Collection

A mass flow monitoring module is installed behind the front valve in the channel to collect mass flow parameters in the flow channel. The reality in the model is shown in Figure 6. The outlet boundary is set as a pressure outlet, as shown in Figure 7 in the model. This simulation is aimed at realizing the functions of the storage and supply system and the thruster when they are coupled. When the thruster is working, the back pressure will rise to several hundred Pa, and this simulation will set the back pressure to 100 Pa.

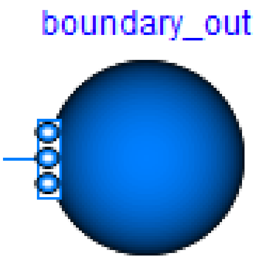


Figure 7. Exit Boundary

3. Simulation Results and The Analysis

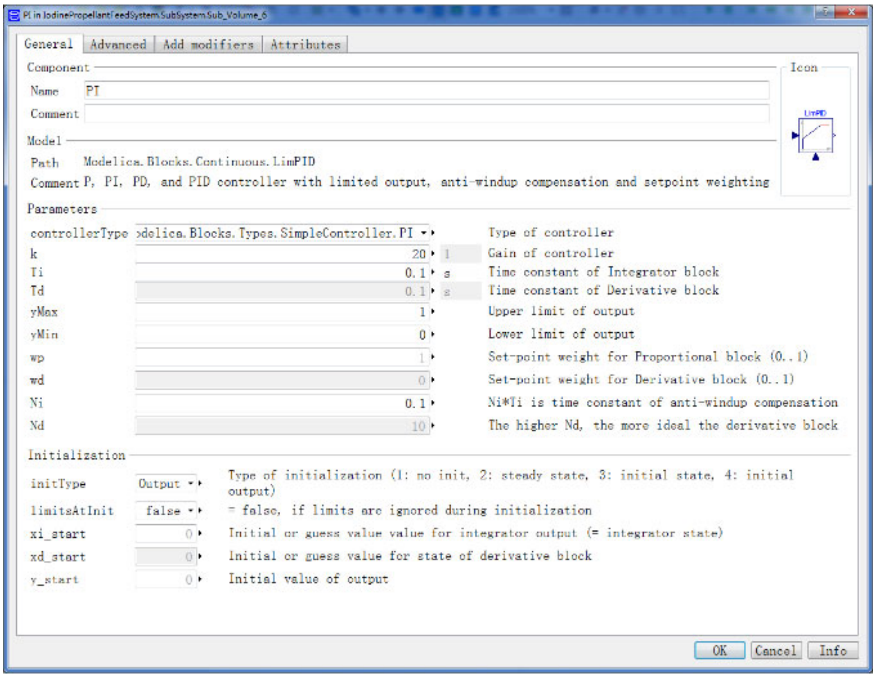
3.1. Parameter setting

The model parameter settings are shown in the table:

Table 4. Model Parameter Settings

Item	Numerical value	Units
The cavity volume	$1.09*10^{-5}$	m^3
Sublimation temperature	373.15	K
Outter diameter of pipe	0.00635	m
Inner diameter of pipe	0.0046	m
Temperature of the Pipe wall	393.15	K
Medium	Iodine	/

PI control settings are shown in Figure 8:



Component

Name PI

Comment

Model

Path Modelica.Blocks.Continuous.LimPID

Comment P, PI, PD, and PID controller with limited output, anti-windup compensation and setpoint weighting

Parameters

controllerType	›delica.Blocks.Types.SimpleController.PI		Type of controller
k	20	1	Gain of controller
Ti	0.1	s	Time constant of Integrator block
Td	0.1	s	Time constant of Derivative block
yMax	1		Upper limit of output
yMin	0		Lower limit of output
wp	1		Set-point weight for Proportional block (0..1)
wd	0		Set-point weight for Derivative block (0..1)
Ni	0.1		Ni*Ti is time constant of anti-windup compensation
Nd	10		The higher Nd, the more ideal the derivative block

Initialization

initType	Output	Type of initialization (1: no init, 2: steady state, 3: initial state, 4: initial output)
limitsAtInit	false	= false, if limits are ignored during initialization
xi_start	0	Initial or guess value value for integrator output (= integrator state)
xd_start	0	Initial or guess value for state of derivative block
y_start	0	Initial value of output

Figure 8. PI Control Settings

3.2. Analysis of simulation results of storage system

Set the target flow rate to 2.0mg/s, and the PI controller will adjust and control the flow rate by adjusting the valve opening to adjust the flow rate in the pipeline to the target flow rate. The simulation calculation results are shown in Figure 9. After PI control, the flow rate can be rapidly increased from 1.8mg/s to 2.0mg/s, so through appropriate parameter selection and settings, the flow rate can be efficiently regulated with the help of a proportional valve.

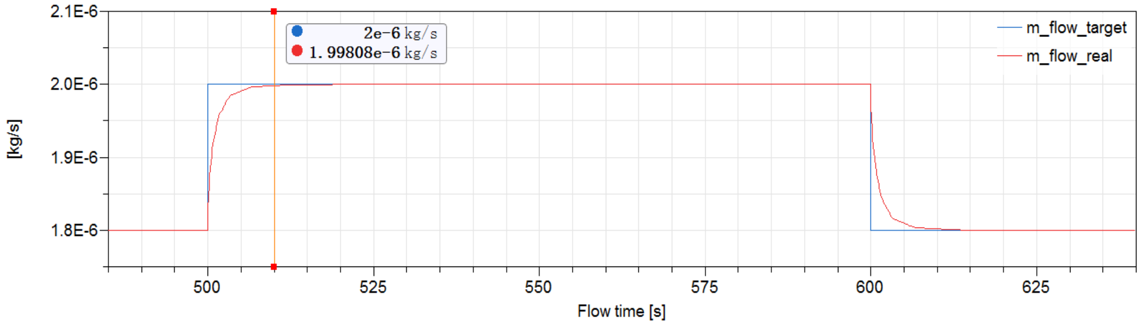
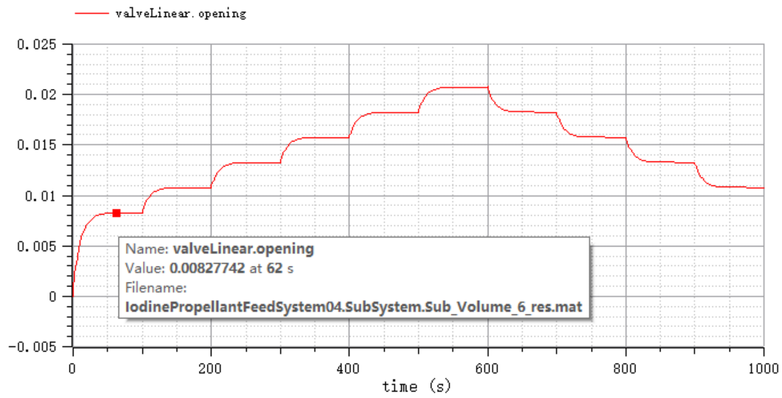
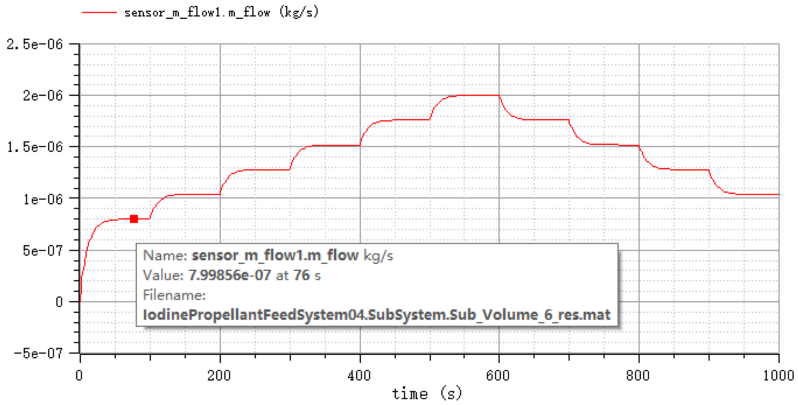


Figure 9. Simulation Results of Flow Regulation

As shown in the figure 10, the relationship between the opening degree of the proportional valve and the corresponding mass flow rate is obtained by controlling the opening degree of the comparative example valve.



(A) Scale valve opening degree



(B) Export mass flow rate

Figure 10. Correspondence between proportional valve opening and outlet mass flow rate

4. Conclusion

Based on a system level modeling of the iodine working medium electric propulsion storage and supply system, and considering the impact of the coupling effects of various conditions such as iodine vapor physical parameters, storage tanks, pipelines, outlet conditions, and proportional valves on the outlet mass flow rate of the iodine storage and supply system, the control of the outlet mass flow rate is achieved by adjusting the valve opening of a comparative example, in order to obtain the corresponding relationship map between the proportional valve opening and the outlet mass flow rate, Provide data support for future ground experiments. Based on the system level modeling of the iodine working medium electric propulsion storage and supply system, the effects of iodine vapor physical parameters, storage tanks, pipelines, outlet conditions, and proportional valves and many other conditions on the outlet mass flow rate of the iodine storage and supply system are considered. By adjusting the opening of the proportional valve, the outlet mass flow rate is controlled. In order to obtain the corresponding relationship map between the opening of the proportional valve and the outlet mass flow rate, Provide data support for future ground experiments.

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