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Substance flow simulation method for manned spacecraft in Matlab/Simulink environment

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ABSTRACT

An Environmental Control and Life Support System (ECLSS) for a large manned spacecraft, such as the International Space Station, is mainly a regenerative ECLSS. Its system is very complex, so it is necessary to conduct on simulation research in order to optimize its design and operation conditions. In this type of simulation optimization work, the substance flow simulation, that is the pressure and flow simulation, is the base of the whole substance and energy simulation. Based on the characteristic analysis of substance flow in multiple subsystems of ECLSS, a typical characteristic system is abstracted from these real physical systems and the corresponding flow models are set up. In addition, two connect methods for flow nets are also presented in order to solve the flow models dynamically in the Matlab/Simulink environment. The simulation results show the feasibility of the above methods.

KEYWORDS

ECLSS; Manned spacecraft; Substance flow; Pressure/flow net; Matlab/simulink simulation.



INTRODUCTION

The ECLSS of manned spacecraft is a typical complex system, especially when a regenerative ECLSS is introduced^[1,2]. Hence it is necessary to conduct some simulation studies on the substance and energy transfer in the ECLSS. By this way, the work performance of system can be evaluated in advance. These simulations can provide detail technical support for system design and qualitative research.

In the ECLSS of manned spacecraft simulation, the simulation of substance flow is the base to analyze the substance transfer and energy utilization. Therefore, the simulation of pressure and flow is very important so as to become the key of simulation and optimization for the ECLSS.

For a large manned spacecraft, such as a space station, a typical characteristic subsystem is abstracted and proposed in this paper based on the analysis of the substance flow characteristics in multiple real physical subsystems of ECLSS. Further, a general substance flow model is established. In addition, two types of connect method for flow network are also presented. The above works ensure the pressure and flow coupling dynamical simulation in the Matlab/Simulink environment. This study can be used in the dynamical simulation of multi-substance flow in the ECLSS in the future.

ANALYSIS OF SUBSTANCE FLOW OF ECLSS

A large manned spacecraft, such as the International Space Station (ISS), mainly is used the complex regenerative ECLSS, so circulation of the substance can be achieved and the supply in orbit can be reduced as much as possible^[3]. However, as shown in Figure 1, because the relationship of internal substance flow is complex, it's necessary to optimize design procedure so that all of the subsystems in the cabin can keep good running conditions.

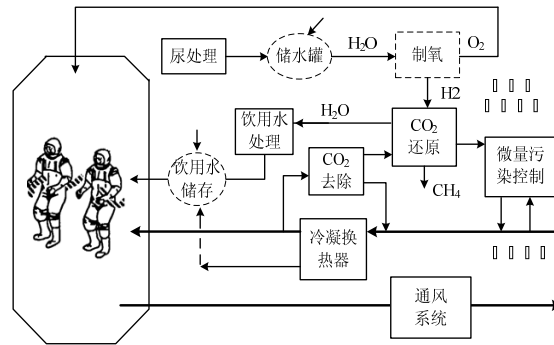


Figure 1 : ECLSS diagram for a large manned spacecraft.

Figure 2 shows a typical four-bed CO₂ removal subsystem^[4], which mainly consists of a power source (a fan), a flow element (a control valve), and a characteristic core devices (four beds and a heat exchanger). Therefore, the structure of a CO₂ removal system can be abstracted as a characteristic structure that has a power source, a flow element and a characteristic core device.

Similarly, the other subsystems, marked with solid line in Figure 1, can also be abstracted as the characteristic structure. In this paper, we use this proposed characteristic structure to deal with the following subsystems, such as the CO₂ reduction subsystem, the CO₂ removal subsystem, the trace contaminant control subsystem, the ventilation and purification subsystem, the urine treatment subsystem and the drinking water treatment, etc. it is named as the characteristic subsystem, as shown in Figure 3.

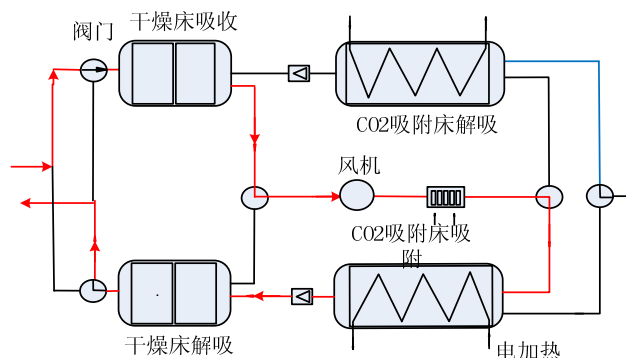


Figure 2 : Relationship between a CO₂ removed system and a cabin.

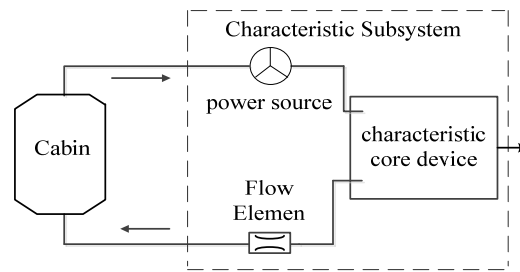


Figure 3 : Connection relationship between a characteristic subsystem of ECLSS and a manned cabin.

SUBSTANCE FLOW MODEL FOR ECLSS

In order to explain the substance flow simulation clearly, the procedure to set up a model for the flow and pressure will be explained in detail. In this section, the procedure will include the connection relationship of devices and the general substance flow simulation method.

As shown in Figure 3, in the typical complex subsystem model of ECLSS in a manned spacecraft, there are some models for pressure elements, such as a cabin and a tank which pressure is calculated by using the flow. There are also some models for flow restriction elements, such as a valve and a flow restriction orifice, which flow is calculated by using the pressure difference between an inlet and an outlet. There are some elements belong to the third category model of pressure change element, such as a characteristic device and a power source. Therefore, the model of elements in ECLSS can be divided into three categories, a pressure element, a flow element and a pressure change element. These three categories can be composed of different physical components^[3,5,6].

Model for pressure element

Pressure element is a dynamic element where pressure for the current point is calculated based on the flow into and out of the node and the mass inside the node. The mass flow rate model of the pressure element is given by:

$$\frac{dm}{dt} = w_{in} - w_{out} \quad (1)$$

where the subscript *in* and *out* represent the inlet and outlet, respectively; *w* represents the mass flow rate, kg/s; *m* represents the mass in the pressure element, kg; *t* represents the time, s.

In the chamber of the pressure element, the air density is $\rho = m/V$, where *V* is the inner volume of the pressure element. The specific internal energy is $u = U/m$. Hence, the pressure of flow element can be calculated by Eq. (2).

$$p = f_1(\rho, u) \quad (2)$$

In the Eq. (2), f_1 is the formula to calculate the physical parameter.

Model for flow element

Flow modules: valve, pump which calculates flow, by given inlet and outlet pressure. The mass flow rate is given by:

$$w = A_{ref} \sqrt{\frac{2\rho(p_{in} - p_{out})}{\xi}} \quad (3)$$

where A_{ref} represents the flowing area of a flow element, m^2 ; ξ represents the coefficient of the resistance.

Model for pressure change element

A pressure change element represents a type of equipment in which there will be pressure loss, the press will change up or down when the working fluid flows through it. The models of a pressure change element are following:

Mass conservation equation:

$$w_{in} = w_{out} \quad (4)$$

Momentum equation:

$$P_{in} - P_{out} = \frac{\xi w_{in} |w_{in}|}{2\rho A_{in}^2} \quad (5)$$

The unknown pressure of inlet or outlet can be calculated by using Eq. (5).

A fan or a pump pressure source element can be considered as the pressure change element. The outlet pressure of a fan as follows:

$$P_{out} - P_{in} = \rho_{in} g f_2(Q) \quad (6)$$

where Q is the volume flow, m^3/h .

The pressure change element can also be characteristic devices, such as the characteristic core device in Figure 3. However, when there is substance transfer, Eq. (5) should be corrected as Eq. (7)~(9):

$$P_{in} - P_{out} = f_3(\Delta p_{ref}, w_{in}, w_{ref}, \rho_{ref}, \rho_{in}) \quad (7)$$

$$w_{in} = w_{out,1} + w_{out,2} \quad (8)$$

$$w_{in,2} = f_4(w_{out,2}, w_{ref}, \rho_{ref}, \rho_{in}, \phi_{in}) \quad (9)$$

where the subscript 'ref' represents reference state; Δp_{ref} represents pressure drop compared to the reference state, Pa; w_{ref} represents reference flow, kg/s; ρ_{ref} represents the reference density, kg/m^3 ; f_3 depends on the specific equipment and is a general formula to calculate the pressure difference between inlet and outlet; $w_{out,1}$ is the outlet mass flow rate of the mainstream air, kg/s; $w_{out,2}$ is the removal mass rate of the micro-component, kg/s; ϕ_{in} is the relative humidity of the inlet air, %; f_4 depends on the specific equipment, is the formula to calculate the removal mass, kg.

It is noted that Eq.(8) and (9) can be used for the atmospheric regeneration subsystem and trace contaminant control subsystem, while there will be a little different to use f_4 for the urine treating subsystem and the potable water subsystem. For the electrolytic oxygen device, we can't use Eq.(8) and (9). But we can use Eq. (3) to treat it as a process of supplying oxygen at a constant pressure. The oxygen can directly release into the cabin.

SIMULATION METHOD FOR FLOW NETWORK IN MATLAB/SIMULINK ENVIRONMENT

In the Matlab/Simulink, the method to simulate the substance flow in a manned spacecraft will face the following problems : (1) The inlet and outlet parameters of steady-state performance formulas used in Matlab/Simulink will easily lead to algebraic loop. This will increase the difficulty to solve these formulas, and even cause solution error^[7,8]. (2) There is a hydraulic coupling relationship between pressure and flow in the flow network simulation. So we can't use the general rigid connection method to solve the steady-state model.

Due to the above problems, two methods for network connection and model solution will be discussed in Matlab/Simulink environment. At the same time, an intelligent simulation method with variable integration step is adopted to realize the substance flow simulation for manned spacecraft in Matlab/ Simulink environment.

Comparison of two connection methods for flow network

Connection methods for flow network

Gas tank and cabin belong to be the pressure element, which has integral part. Value belongs to be the flow element. Besides pipe, characteristic device and power source belong to be the pressure change element. These three elements are used to connect the flow network together in order to ensure one flow value for all the elements in the network and the system stability.

In this paper, we will discuss a general and typical connection mode, that is "cabin+pipeline+fan+pipeline+valve+pipeline", which includes the flow element, the pressure element and the pressure change element. Besides, two network connection methods will be established for the network flow simulation.

Connection method 1

In the connection method 1, the actual flow orifice and length characteristics are considered in detail to reflect the mass flow and the resistance along the way. Based on that simulation concept, a fan can be considered to be an assembly that is composed of a pressure element and a flow element. A pipeline is equal to a pressure element with a pressure change element. A valve is a flow element. A cabin is composed by the flow element (the inlet and outlet orifice) and pressure element. Therefore, for the above typical connection mode, The simulation connection is done by using the connection method 1 in the Matlab/ Simulink.

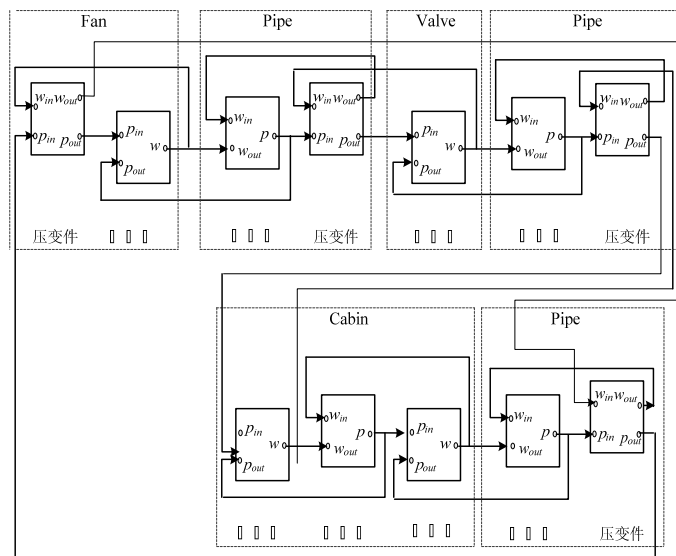


Figure 4 : Connection method 1 in Matlab/Simulink.

In Figure 4, the connection relationship is composed of interval mode of the pressure element and the flow element if the pressure change element is ignored. The connection mode of “pressure and flow” for the whole flow network is made.

Connection method 2

The connection method 1 can match well with the real physical system and obtain the coupling solution. However, there are some disadvantages. There are multiple integral links like Eq. (1) in the system, and they in turn cause huge compute load and bad global robustness. Even worse, it will lead to oscillatory solution in local conditions. Therefore, based on the method 1, the connection method 2 for the flow network is developed in this paper.

In the connection method 2, a fan is simply regarded as a pressure change element, a valve is as a flow element, and a cabin is as a pressure element. A pipeline which has two types, Pipe 1 and Pipe 2, is a pressure change element. For Pipe 1, the outlet pressure can be calculated when the mass flow and the inlet pressure are known. For Pipe 2, the inlet pressure can be calculated when the mass flow and the outlet pressure are known. These two types of pipe are used to adapt different elements in the flow network. In the connection method 2, the flow resistance is concentrated at the outlet or inlet. Compared with the connection method 1, the method 2 reduces the integral parts greatly. Therefore, the solving speed will be improved, and the solution stability and system robustness will also be ensured very well.

The connection relationship of the method 2 in Matlab/Simulink environment is listed in Figure 5. The connection relationship also is composed of an interval mode of the pressure element and the flow element if the pressure change element is ignored.

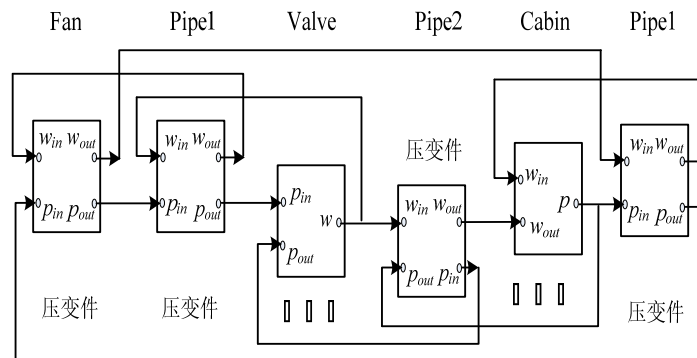


Figure 5 : Model connection of method 2 in Matlab/Simulink.

Comparison of simulation results

In order to test the above connection methods, two simulations for 100s seconds true operating time is done. The valve is turned off at 50s, The flow change and the system robustness of two systems are compared. Figure 6 shows the on /off signal of the valve.

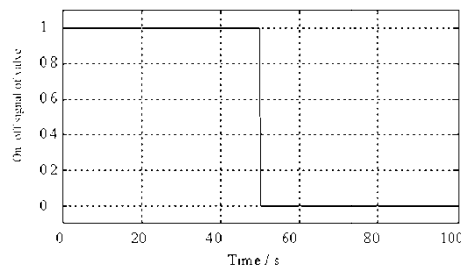


Figure 6 : On /off signal of valve.

Comparison of computing time

The simulation running times of the method 1 and 2 are 13.04s and 7.58s, respectively, for 100s true operating time. Thus, the method 2 can increase the computing speed by 2 times.

Comparison of convergence speed

The curves in Figure 7-8 is the mass flow at the inlet of cabin. It takes about 5s for the method 1 to reach steady state while about 0.2s for the method 2. Thus, the convergence speed for the method 2 is very fast.

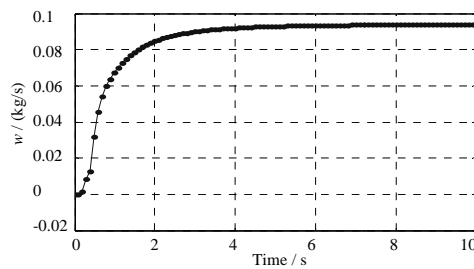


Figure 7 : Cabin inlet mass flow from 0 to 10s in the method 1.

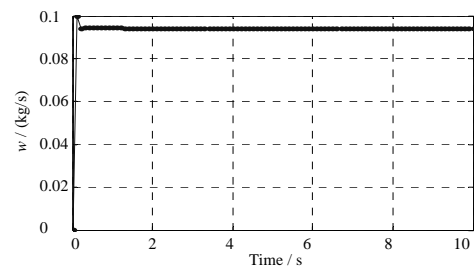


Figure 8 : Cabin inlet mass flow from 0 to 10s in method 2.

Comparison of robustness

The robustness of two methods can be proved by observing the waveforms of mass flow at the inlet of cabin while the valve is closed. The waveform of mass flow is shown in Figure 9 and Figure 10. The system shock is serious and system robustness is poor when the connection method 1 is used. In the other word, the system robustness of the method 2 is better than the method 1.

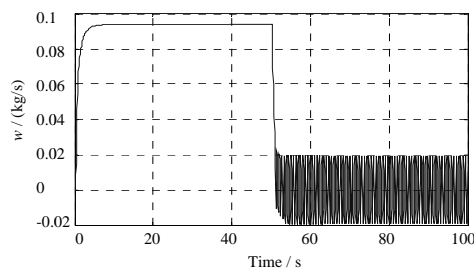


Figure 9 : Mass flow of cabin inlet in the method 1.

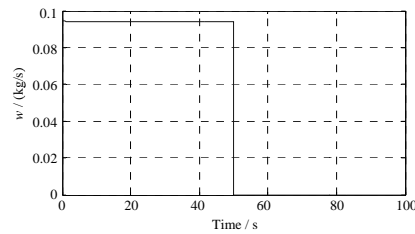


Figure 10 : Mass flow of cabin inlet in the method 2.

The results in Figure 6 to 10 show that the advantages of the method 2 are very obvious. Simulation time is short and the rate of convergence is quick as well as perfect robustness. Therefore, the method 2 is better for carrying out simulation on pressure/flow coupled simulation for a complex system.

Simulation analysis of manned cabin and carbon dioxide removal subsystem

Based on the ECLSS subsystem and cabin connection described in Figure 3, a connection for manned cabin and the carbon dioxide removal assembly is set up in this paper. In the Matlab/Simulink environment, A pressure change element and a pipeline between Pipe 1 and Valve in Figure 5 should be added to represent the characteristic core device, the simulation is made by using the connection method 2.

Simulation conditions

- The volume of manned cabin is 100m^3 ;
- The initial pressure of cabin is 100kPa ;
- There are four astronauts in the cabin, and the produced CO_2 mass flow is 1kg/d for each person.
- The removal capacity of CO_2 removal subsystem can be up to 400L/min . The subsystem adopts four beds molecular sieves with 360min running period.

Figure 11~12 show simulation results for the carbon dioxide partial pressure, P_{CO_2} , when the connection relationship of "astronaut + CO_2 removal subsystem + manned cabin" is adopted.

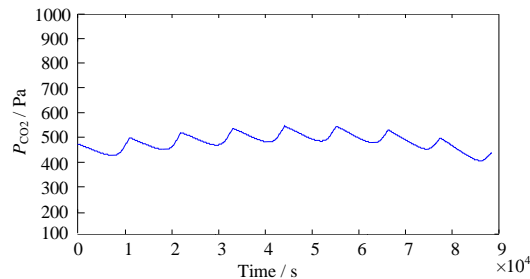


Figure 11 : Curve of CO_2 partial pressure in cabin.

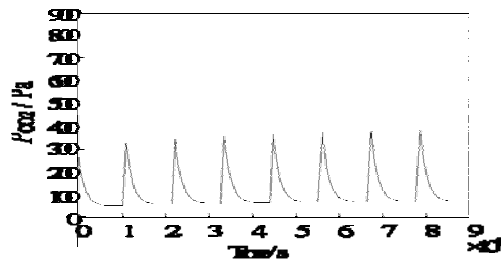


Figure 12 : Curve of CO_2 partial pressure in the outlet of CO_2 removed system.

The simulation results show that concentration of CO_2 in manned spacecraft is steady controlled by the CO_2 removal subsystem. The substance flow is steady without any concussion. Besides, the robustness of the system is also excellent. Hence, the method 2 can describe the pressure and flow process in the simulation system very well.

CONCLUSION

For a large manned spacecraft, such as ISS, a typical characteristic subsystem is abstracted and proposed in this paper based on the analysis of the substance flow feature in multiple real physical subsystems of ECLSS. Further, a general

substance flow model is established. In addition, two network flow connection and simulation methods are also proposed so as to implement dynamic simulation in Matlab/Simulink environment. Both of these two connection methods must obey the following rules: pressure modules can be connected only to flow modules. Flow modules can be connected only to pressure modules. Two valves cannot be connected directly but must have a pressure node between them.

The simulation results show that both of the two proposed methods in this paper can be used to realize the flow network connection as well as dynamic simulation. However, by comparing the two methods, The connect method 2 has some obvious advantages, the system is very stiff and has very fast response. Therefore, it can be concluded that the second connect method is more appropriate for the simulation study of coupled pressure and flow in the ECLSS of manned spacecraft. Further, the pressure and flow coupled simulation study is conducted to study a system including a carbon dioxide removal subsystem and a manned cabin and obtain some results.

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