Modeling and Simulation on Environmental and Thermal Control System of Manned Spacecraft

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Abstract

In order to support crew resides, key air environment parameters of manned spacecraft should be controlled within index range by environmental and thermal control system. In this paper a model of manned spacecraft environmental and thermal control system in Modelica language is developed. Using this simulation model, we analyze air environment parameters varying trend as the crew metabolic level variation. The results show that crew metabolic level could influence air environment parameters dramatically. Furthermore, air environment parameters should be analyzed comprehensively due to important affection of air temperature to oxygen partial pressure, carbon dioxide partial pressure and relative humidity. The work in this paper is helpful to provide a new method for analysis of environmental and thermal control system of manned spacecraft.

Keywords: manned spacecraft, Modelica, MWorks; temperature/humidity control, carbon dioxide removal, oxygen pressure control

1 Introduction

Environmental and thermal control system is a system to guarantee a good life and thermal environment and the key technology to realize manned spaceflight [1].

The current commonly used analysis method is to establish a pressurized cabin simulation model using CFD (computational fluid dynamics) [2-6]. The method is used to analyze the temperature and humidity, partial pressure of oxygen, etc. Using this design method has the following shortcomings:

1) In the program design, the designer is concerned with the system level indicators .CFD software is good at equipment level analysis, not suitable for system level analysis;

2) CFD software is not suitable for system level analysis so that it is difficult to analyze the interrelationship between each parameter of the system;

On the contrary, Modelica is an object-oriented modeling and simulation language. Modelica is good at system level analysis. With Modelica, we can establish mathematical models of each component and an integral model of the entire environmental and thermal control system. The paper has the following objectives:

1) Establish a model of manned spacecraft environmental and thermal control system in Modelica language;

2) Analyze the interrelationship of key parameters of manned spacecraft environmental and thermal control system.

3) Analyze the influence of the change of key parameters on the system.

2 System Descriptions

In this paper, the cabin environment is assumed to be insulated from the outside. Schematic diagram of environmental and thermal control system is shown below.

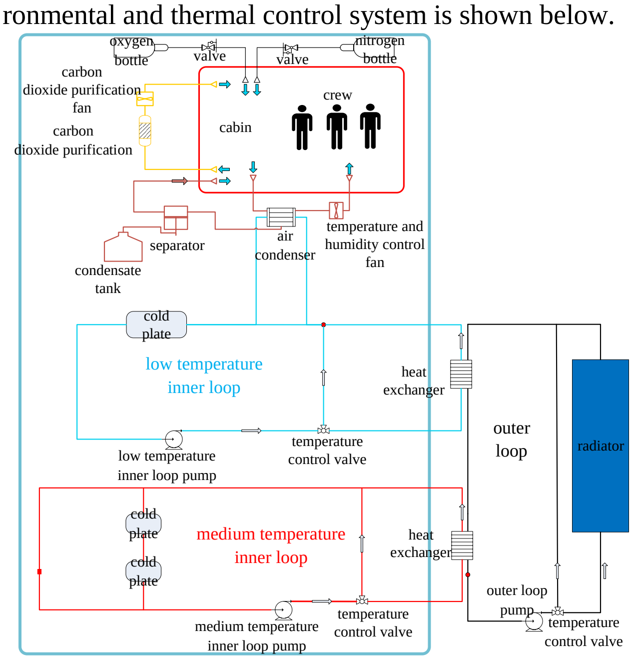

Figure 1 Environment and thermal control system

2.1 Constitute of Environmental and Thermal Control System

Environmental and thermal control system includes:

1) Cabin pressure control system: cabin is equipped with high pressure oxygen bottle. When partial pressure of oxygen bellows the lower limit, oxygen bottle begins to supply oxygen until partial pressure of oxygen reaches the higher limit.

2) Carbon dioxide purification system: cabin is equipped with non-regenerative cabin dioxide purification tank and fan. Fan extracts air from the cabin to purification tank. When carbon dioxide partial pressure reaches the higher limit, a new purification tank will be automatically replaced.

3) Temperature and humidity control system: cabin is equipped with air condenser, moisture separator. Air condenser provides the cold source for the temperature control loop; Fan extracts air from the cabin to air condenser; Water and gas mixture which is collected by the air condenser enters moisture separator to separate. The separated water enters water tank and the separated air returns to the cabin.

4) Low temperature inner loop control system: low temperature inner loop is equipped with pump, heat exchanger and temperature control valve. The speed of pump is a parameter which is set before simulation. Temperature control valve opening is controlled by the PID controller which is set a temperature control point.

5) Medium temperature inner loop control system: medium temperature inner loop is equipped with pump, heat exchanger and temperature control valve.

6) Outer loop control system: heat collected by the low temperature inner loop control system and medium temperature inner loop control system is transferred to the outer loop through heat exchanger. Outer loop collects heat load of the cabin and equipment and exhausts to the space through radiator.

2.2 Metabolic Level of Astronaut

The metabolic level of astronaut changes with the different forms of activities. Referring to the international space station, this paper takes into account four metabolic levels:

1) Sleeping: Metabolic heat production is 80W. The rate of oxygen consumption is 0.0202kg/h. Carbon dioxide output rate is 0.023kg/h;

2) Resting: Metabolic heat production is 100W. The rate of oxygen consumption is 0.0252kg/h. Carbon dioxide output rate is 0.029kg/h;

3) Mild activity: Metabolic heat production is 170W. The rate of oxygen consumption is 0.0432kg/h. Carbon dioxide output rate is 0.049kg/h;

4) Moderate activity: Metabolic heat production is 240W. The rate of oxygen consumption is 0.0606kg/h. Carbon dioxide output rate is 0.069kg/h;

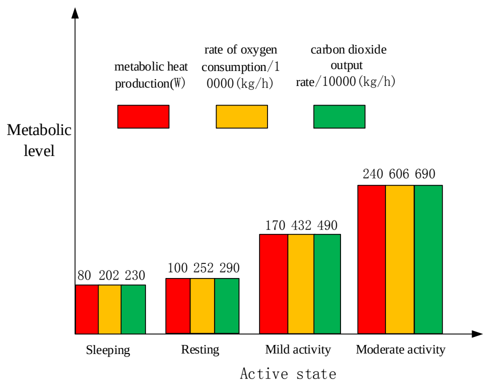

Figure 2 Metabolic level of astronaut at different active state

2.3 Astronaut Schedule

This paper assumes there are three astronauts in the cabin and they are always at the same level of metabolism. Astronaut schedule in a day is arranged as follows: Sleeping is 7 hours. Resting is 4 hours. Moderate activity is 2 hours. Mild activity is 11 hours. Schedule is in accordance with the above order.

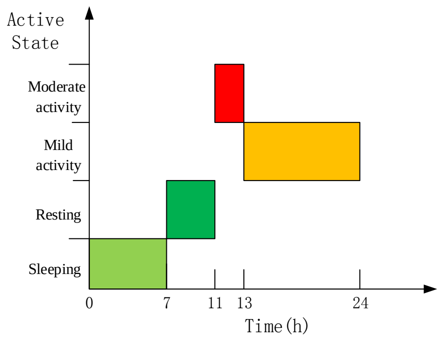

Figure 3 Crew's active state diagram in a day

2.4 Indicator of Air Environment

Indicators of air environment refer to International Space Station [7]. We can see it as follows:

Table 1 The goal of each air environment indicator

Goal	*Request*
temperature	20～26 ℃
relative humidity	30%～70%
partial pressure of oxygen	19000 ～ 22000 Pa
partial pressure of carbon dioxide	≤700 Pa

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3 Models

We use MWorks as a basic platform for modeling and simulating the environmental and thermal control system of manned spacecraft [8].

3.1 Interface Design

Interfaces for physical component models must be physically able to connect components. Environmental and thermal control system involves two areas of heat and fluid so that its interfaces are heat and fluid interfaces which are shown in table 2. There are two basic types of variables for Modelica interfaces, which are flow variables and potential variables. Interfaces connection comply with the general theory of Kirchhoff's law, namely the sum of flow variables is zero and the potential variables are equal when interfaces connect to each other. In order to meet the needs of thermal fluid system modeling, Modelica has added a new interface variable which is stream variable.

Table 2 Interface types and variables in interfaces

Interface type	*Variable*	*Variable type*
fluid interface	pressure	potential variable
	mass flow rate	flow variable
	mass ratio	stream variable
	specific enthalpy	stream variable
thermal interface	temperature	potential variable
	heat flow	flow variable

3.2 Medium Models

Medium models are obtained by expansion and specialization from standard medium of Modelica standard library. Medium models and component models can be decoupled when independent medium models are designed. Medium models are defined as replaceable models. Component models can select medium model by redeclaration. A medium model is a model package which is made up of four parts:

1) Constants, which contain the name of medium and molar mass, etc.

2) Attribute models, which mainly include state equation and other thermodynamic equation.

3) Functions, which calculate property parameters in different states.

4) Types, which apply to the thermodynamic variables.

3.3 Component Models

A component model is a restricted category of Modelica which can include parameters, variables, nested classes, equations and algorithms. A component model is established using a bottom-up approach, inherits base class model, declare subcomponent model and interface and add variables and equations. Component models correspond to the system basic physical components such as pipe, valve, fan, heat exchanger, etc. Component models are fully functional models which can be directly instantiated and used. Main equations of the major components are described as follows:

3.3.1 Cabin

The cabin interacts with the outside world can be abstracted thermal and fluid interfaces. The main equations of a cabin is shown as follows:

1) Mass conservation is calculated by the using the following equation:

$$\frac{dm_j}{dt} = w_{in}x_{in,j} - w_{out}x_{out,j} + w_{lf,j} \tag{1}$$

Where m_j denotes the mass of the J kind ingredient; w_{in} denotes air mass which flow in the cabin; $x_{in,j}$ denotes mass percentage of the J kind ingredient which flow in the cabin; w_{out} denotes air mass which flow out the cabin; $x_{out,j}$ denotes mass percentage of the J kind ingredient which flow out the cabin; $w_{lf,j}$ denotes mass percentage of the J kind ingredient metabolized by Astronaut.

2) Energy passed to the bulkhead is calculated by using the following equation:

$$\frac{dU_{wall}}{dt} = q_{wall} \tag{2}$$

Where U_{wall} denotes internal energy of bulkhead; q_{wall} denotes total heat passed to the bulkhead.

3) Energy passed to air of the cabin is calculated by using the following equation:

$$\frac{dU_{air}}{dt} = w_{in}h_{in} - w_{out}h_{out} + q_{air} \tag{3}$$

Where U_{air} denotes internal energy of air in the cabin; h_{in} denotes enthalpy of air which flow in the cabin; h_{out} denotes enthalpy of air which flow out the cabin; q_{air} denotes total heat added to air.

3.3.2 Crew

The crew interacts with the outside world can be abstracted thermal and fluid interfaces. The main equations of a crew is shown as follows:

1) Metabolism is calculated by the using the following equation:

$$W = \mu(Q_{act} - Q_{bas}) \tag{4}$$

$$Q = Q_{act} + Q_{shiv} \tag{5}$$

Where W denotes mechanical force of every crew; μ denotes mechanical efficiency; Q_{act} denotes metabolic activity of crew; Q_{bas} denotes basal metabolic activity of crew; Q_{shiv} denotes heat generated by muscle tremors.

2) Breathing is calculated by using the following equation:

$$m_{O2} = \frac{Q}{60000 \cdot 247.35 \cdot (0.23 \cdot RQ + 0.77)} \tag{6}$$

$$m_{CO2} = RQ \cdot m_{O2} \cdot \frac{MW_{CO2}}{MW_{O2}} \tag{7}$$

Where RQ denotes respiratory coefficient; MW_{CO2} is molar mass of carbon dioxide; MW_{O2} denotes molar mass of oxygen.

Through inheriting interfaces and adding parameters, variables and equations, we can establish the crew Modelica model.

3.3.3 Carbon Dioxide Purification

The carbon dioxide purification interacts with the outside world can be abstracted thermal and fluid interfaces. The main equations of a carbon dioxide purification is shown as follows:

1) Total amount of carbon dioxide purification control of a purification tank is calculated by using the following equation:

$$M_{CO_2} = x_{load} \cdot m_{LiOH,0} \tag{8}$$

Where x_{load} denotes mass of carbon dioxide purified per kg in the initial state; $m_{LiOH,0}$ denotes mass per purification tank.

2) Carbon dioxide purification rate control is calculated by using the following equation:

$$w_{CO_2} = 0.9185ar\left[1 - \frac{x_{load}}{0.9185a}\right]m_{LiOH,0} \tag{9}$$

Where r denotes chemical reaction rate of carbon dioxide.

3) Water production rate control is calculated by using the following equation:

$$w_{H_2O} = 0.9185ar\left[1 - \frac{x_{load}}{0.9185a}\right]m_{LiOH,0}\frac{MW_{H_2O}}{MW_{CO_2}} \tag{10}$$

Where MW_{H_2O} denotes molecular weight of water; MW_{CO_2} denotes molecular weight of carbon dioxide.

4) Mass conservation is calculated by using the following equation:

$$x_{out,CO_2} = \frac{w_{in,Z}x_{in,CO_2} - w_{CO_2}}{w_{out,Z}} \tag{11}$$

$$x_{out,H_2O} = \frac{w_{in,Z}x_{in,H_2O} + w_{H_2O}}{w_{out,Z}} \tag{12}$$

Where x_{out,CO_2} denotes mass percentage of carbon dioxide in the air which flows out purification tank; x_{out,H_2O} denotes mass percentage of water in the air which flows out purification tank; $w_{in,Z}$ denotes mass flow rate of air which flows in purification tank; $w_{out,Z}$ denotes mass flow rate of air which flows out purification tank; x_{in,CO_2} denotes mass percentage of carbon dioxide in the air which flows in purification tank; x_{in,H_2O} denotes mass percentage of water in the air which flows in purification tank.

5) Momentum conservation is calculated by using the following equation:

$$\Delta p = \Delta p_{ref}\left[\frac{w_{in,Z}}{w_{ref}}\right] \times \left|\frac{w_{in,Z}}{w_{ref}}\right| \times \frac{\rho_{ref}}{\rho_{in,Z}} \tag{13}$$

Where Δp denotes pressure difference of air which flows through purification tank; Δp_{ref} denotes reference pressure difference of air which flows through purification tank; w_{ref} denotes reference mass flow rate of air which flows in purification tank; $\rho_{in,Z}$ denotes density of air which flows in purification tank; ρ_{ref} denotes reference density of air which flows in purification tank.

6) Energy conservation is calculated by using the following equation:

$$\frac{dT_{bed}}{dt} = \frac{w_{in,Z}h_{in,Z} - w_{out,Z}h_{out,Z} + q_{reac}}{M_{bed}Cp_{bed}} \tag{14}$$

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Where T_{bed} denotes temperature of purification tank; $h_{in,Z}$ denotes enthalpy of air which flows in purification tank; $h_{out,Z}$ denotes enthalpy of air which flows out purification tank; q_{reac} denotes heat generated by the chemical reaction; M_{bed} denotes total mass of purification tank; Cp_{bed} denotes specific heat of purification tank.

3.3.4 Air Condenser

The air condenser interacts with the outside world can be abstracted thermal and fluid interfaces. The main equations of an air condenser is shown as follows:

1) Mass conservation of air side is calculated by using the following equation:

$$w_{air,in} = w_{air,out} + w_{drain} \quad (15)$$

Where $w_{air,in}$ denotes mass flow rate of air which flows in air condenser; $w_{air,out}$ denotes mass flow rate of air which flows out air condenser; w_{drain} denotes mass flow rate of gas and liquid mixture which flows in moisture separator.

2) Liquid flow control is calculated by using the following equation:

$$w_{drain,liquid} = \varepsilon_{slurper} x_{slurper,liq} w_{air,in} \quad (16)$$

Where $w_{drain,liquid}$ denotes mass flow rate of liquid which flows in moisture separator; $\varepsilon_{slurper}$ denotes separation efficiency; $x_{slurper,liq}$ denotes mass ratio of liquid in mixture.

3) Heat exchange control is calculated by using the following equation:

$$q_{ex} = e_{hex} min\left(C_{air}, C_{cold}\right)\left(T_{air,in} - T_{cold,in}\right) \quad (17)$$

Where q_{ex} denotes total heat exchange; e_{hex} denotes heat exchange efficiency; C_{air} denotes heat capacity in the gas side; C_{cold} denotes heat capacity in the liquid side; $T_{air,in}$ denotes inlet temperature in the gas side; $T_{cold,in}$ denotes inlet temperature in the liquid side.

3.3.5 Pump

The pump interacts with the outside world can be abstracted thermal and fluid interfaces. The main equations of a pump is shown as follows:

1) Energy is calculated by using the following equation:

$$\frac{dT_{out}}{dt} = \frac{w_{in}\left(h_{in} - h_{out}\right) + q}{Cp_{fluid} \cdot \rho \cdot V + M_{dry} Cp_{dry}} \quad (18)$$

Where T_{out} denotes outlet temperature of working fluid; h_{in} denotes inlet enthalpy of working fluid; h_{out} denotes outlet enthalpy of working fluid; q denotes power delivered to fluid; Cp_{fluid} denotes specific heat capacity of the fluid; ρ denotes density of working fluid; V denotes volume of fluid; M_{dry} denotes mass of solid wall; Cp_{dry} denotes specific heat capacity of solid wall.

2) Hydraulic efficiency is calculated by using the following equation:

$$\varepsilon = \frac{\rho \cdot g \cdot TDH \cdot Q}{W} \quad (19)$$

Where ε denotes hydraulic efficiency of pump; TDH denotes total dynamic head of pump; Q denotes volume flow rate; W denotes braking power.

3.3.6 Fan

The fun interacts with the outside world can be abstracted thermal and fluid interfaces. The main equations of a fun is shown as follows:

1) Energy is calculated by using the following equation:

$$\frac{dT_{out}}{dt} = \frac{w_{in}\left(h_{in} - h_{out}\right) + q}{M_{dry} Cp_{dry}} \quad (20)$$

Where T_{out} denotes outlet temperature of working fluid; h_{in} denotes inlet enthalpy of working fluid; h_{out} denotes outlet enthalpy of working fluid; q denotes power delivered to fluid; M_{dry} denotes mass of solid wall; Cp_{dry} denotes specific heat capacity of solid wall.

2) Hydraulic efficiency is calculated by using the following equation:

$$\varepsilon = \frac{\rho \cdot g \cdot TDH \cdot Q}{W} \quad (21)$$

Where ε denotes hydraulic efficiency of fan; TDH denotes total dynamic head of fan; Q denotes volume flow rate; W denotes braking power.

3.4 Subsystem Models

Through inheriting component models, we establish cabin pressure control system, carbon dioxide purification system, temperature and humidity control system, fluid loop system which includes low temperature inner loop, medium temperature inner loop and outer loop. These subsystem models are shown as follows:

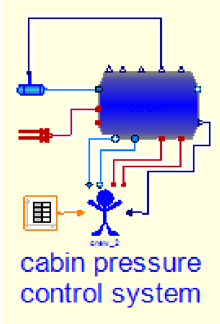

Figure 4 Cabin pressure control system

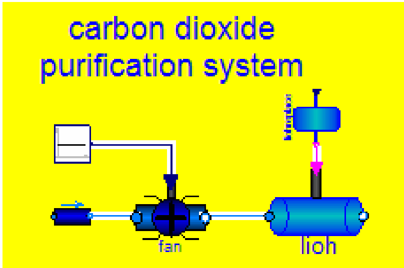

Figure 5 Carbon dioxide purification system

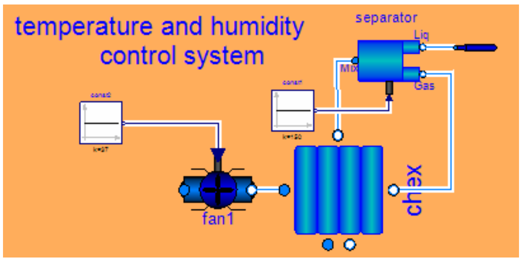

Figure 6 Temperature and humidity control system

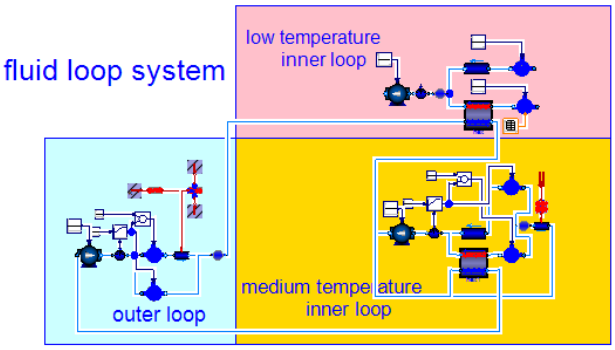

Figure 7 Fluid loop system

3.5 System Model

Through inheriting subsystem models, the model of environmental and thermal control system is established as follows:

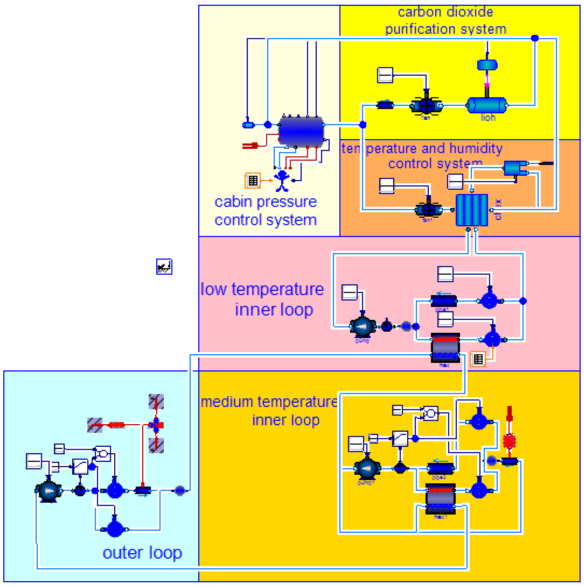

Figure 8 Model of environmental and thermal control system based on Modelica

4 Simulations and Analysis

This paper analyzes the key parameters of the air environment of the cabin in a day. The simulation parameter settings are shown in table 3. The results are shown in figure 9 to figure 16.

Table 3 Simulation parameter settings

Component name	*Parameter name*	*Values*
cabin	air volume in cabin	100 m^3
	cabin inner wall area	600 m^2
carbon dioxide purification	Mass of carbon dioxide purifying agent per box	2kg
carbon dioxide purification fan	speed	150rad/s
air condenser	thermal conductivity	350W/K
separator	speed	150rad/s
temperature and humidity control fan	speed	32rad/s
low temperature inner loop pump	speed	150rad/s
medium temperature inner loop pump	speed	50rad/s

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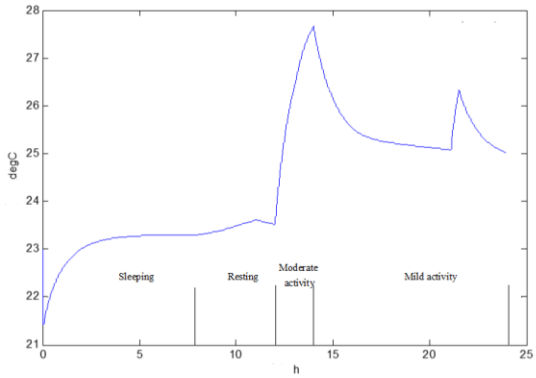

Figure 9 Air temperature

Air temperature in the cabin changes with the variation of crew metabolism (Figure 9). The abscissa is time and its unit is hour. The ordinate is temperature and its unit is centigrade. When crews are sleeping, air temperature is about 21.5 centigrade; From fourth to twelfth hours, air temperature increases slightly; At twelfth hours, when crews are in moderate activity, air temperature increases rapidly and reaches 27.7 centigrade at the highest point, beyond the upper limit of the index; At fourteenth hours, when crews are in mild activity, air temperature decreases rapidly; At twenty-first hours, oxygen partial pressure reaches the lower limit, cabin begins to fill oxygen so that air temperature increases; At twenty-second hours, because the oxygen partial pressure reaches the higher limit, cabin stops filling oxygen so that air temperature decreases.

In summary, during a day, when the crew is in moderate activity, the air temperature is outside the normal range.

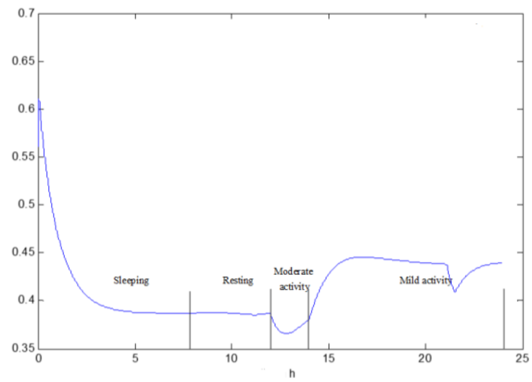

Figure 10 Relative humidity

Relative humidity of air is directly related to metabolic level of crew and air temperature (Figure 10). The abscissa is time and its unit is hour. The ordinate is relative humidity. When crews are sleeping, relative humidity of air remains at around 38%; At fourteenth hours, when crews are in moderate activity, although the crew metabolic wet increases, temperature increases rapidly so that relative humidity of air decreases; At twenty-first hours, because the oxygen partial pressure reaches the lower limit, cabin begins to fill oxygen so that air temperature increases. Relative humidity of air decreases; At twenty-second hours, because the oxygen partial pressure reaches the higher limit, cabin stops to fill oxygen so that air temperature decreases. Relative humidity of air increases.

In summary, air temperature has a greater impact to relative humidity than metabolic level of crew. Relative humidity of air is in the normal range in a day.

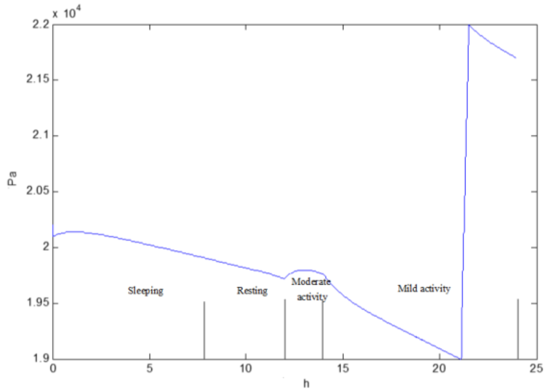

Figure 11 Oxygen partial pressure

The partial pressure of oxygen has a relationship to crew oxygen consumption rate, cycle of supplying gas, air temperature, etc (Figure 11). The abscissa is time and its unit is hour. The ordinate is the partial pressure of oxygen and its unit is Pa. When crews are sleeping and resting, oxygen partial pressure decreases slowly; At twelfth hours, when crews are in moderate activity, although the crew metabolism strengthen and oxygen consumption increases, temperature increases rapidly so that oxygen partial pressure increases; At fourteenth hours, when crews are in mild activity, although crew metabolism decline and oxygen consumption decreases, air temperature decreases rapidly so that oxygen partial pressure decreases; At twenty-first hours, because the oxygen partial pressure reaches the lower limit, cabin begins to fill oxygen so that oxygen partial pressure increases; At twenty-second hours, because the oxygen partial pressure reaches the higher limit, cabin stops to fill oxygen so that oxygen partial pressure decreases.

In summary, oxygen partial pressure is in the normal range in a day.

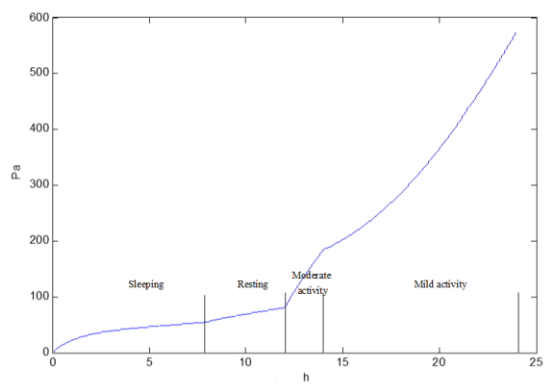

Figure 12 Carbon dioxide partial pressure

Carbon dioxide partial pressure changes with the change of crew metabolism (Figure 12). The abscissa is time and its unit is hour. The ordinate is the partial pressure of oxygen and its unit is Pa. We suppose the initial carbon dioxide partial pressure is 0 .When crews are sleeping or resting, carbon dioxide partial pressure increases; At twelfth hours, when crews are in moderate activity, crew metabolism strengthen and more carbon dioxide is generated, carbon dioxide partial pressure increases fast; At fourteenth hours, when crews are in mild activity, crew metabolism decline and less carbon dioxide is generated, carbon dioxide partial pressure increases slowly.

In summary, carbon dioxide partial pressure is in the normal range in a day.

In the case of the above model parameters, the air temperature beyond the normal range in a day. The air temperature is controlled by the condensing dryer, and the fluid flow into the condensing dryer is controlled by the temperature and humidity control fan. In the case of other parameters unchanged, we increase the temperature and humidity control fan speed to 40 rad/s and observe the change of air environmental parameters.

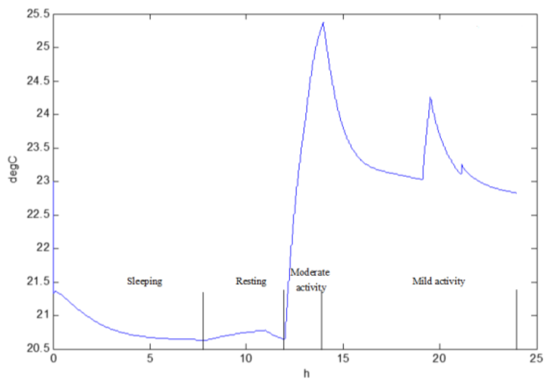

Figure 13 Air temperature at 40 rad/s of fan speed

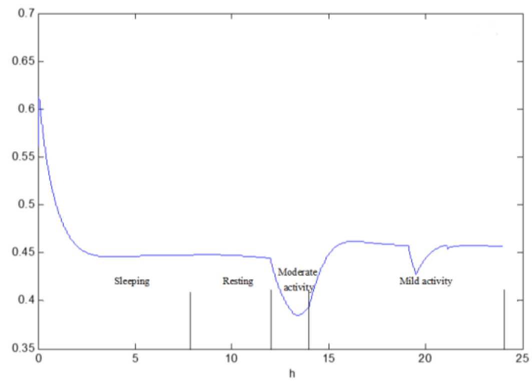

Figure 14 Relative humidity at 40 rad/s of fan speed

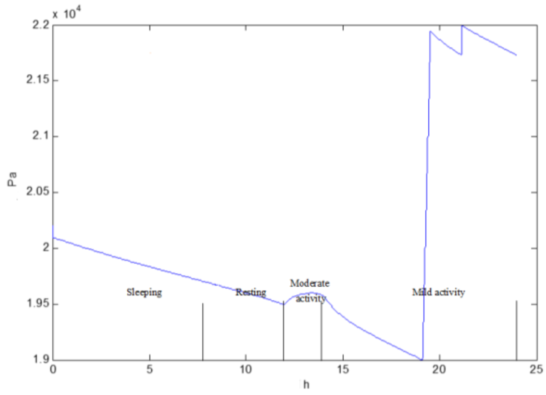

Figure 15 Oxygen partial pressure at 40 rad/s of fan speed

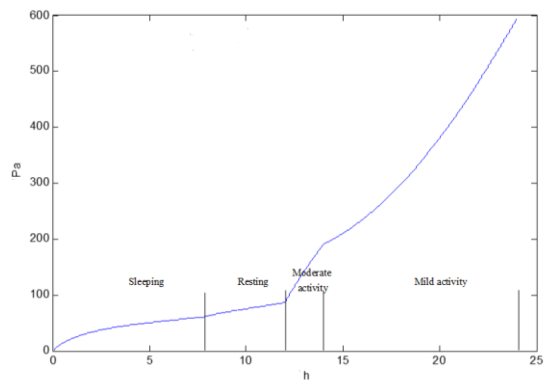

Figure 16 Carbon dioxide partial pressure at 40 rad/s of fan speed

In summary, in a day, air temperature, air relative humidity, oxygen and carbon dioxide partial pressure are in the range of indicators.

5 Conclusions

In this paper a model of manned spacecraft environmental and thermal control system in Modelica language is developed based on the professional knowledge. Using this simulation model, air environment parameters varying trend as the crew metabolic level variation has been analyzed. Draw the conclusion as follows:

1) Crew metabolic level could influence air environment parameters dramatically.

2) Air environment parameters should be analyzed comprehensively due to important affection of air temperature to oxygen partial pressure, carbon dioxide partial pressure and relative humidity.

3) The simulation of the environmental and thermal control system can be carried out by modifying the key parameters of the components, which greatly reduces the workload of the test and the working time of the engineer.

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