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Temperature and Humidity Control Strategy for Spacecraft Cabin based on Humidity Priority

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Abstract. Air parameters control in most manned spacecraft is a kind of "temperature priority control" scheme as there is no regeneration heat exchanger or heater in its Temperature and Humidity Control Subsystem (THCS). The merits of this THCS are simple structure, high reliability, while its disadvantage is humidity could not be controlled well all the time. So a control strategy of "humidity priority control" is put forward to overcome the disadvantage, and its realization method is also given. The simulation results showed that the control strategy could not only keep the temperature and humidity effectively, but also ensure the heat comfort.

Keywords: Control strategy; thermal-humidity coupling; optimal predicted control

1. Introduction

Temperature-humidity parameters in spacecraft cabin can affect both the health of cosmonaut and the performance of equipment. The spacecrafts at present, such as airship, international space station and so on, commonly control the temperature and humidity in the cabin using a condensator due to the restriction of energy and mass, which is a kind of "temperature priority, and humidity passivity". This control system is a kind of double input and single output system, which combines temperature and humidity, often results in an unreasonable temperature and humidity control, and part dew, that impacts on the comfort of cosmonauts and the reliability of equipments, or even causes microorganism pollution, electrochemistry corrosion, wiring short circuit and so on. The atmosphere in the cabin is nonlinear and coupled, so it's necessary to analysis the mechanism of thermal-humidity coupling, and to advance a corresponding control strategy, then to realize the optimized control of temperature and humidity in spacecraft cabin.

2. Temperature And Humidity Control System In Spacecraft

Fig. 1 shows a temperature and humidity control system of an international space station [1]. It consists of fan group, condensation heat exchanger (CHE), temperature control cell value (TCCV) etc. The filtrated air enters the T&H control system driven by fan group, then the controller regulates the opening degree of TCCV based on the difference between designed and actual T. The flux distribution between the CHE and bypass leg is determined by the opening degree of TCCV. The air in the CHE is cooled and dehumidified, and then returns the cabin after mixed with the air from bypass leg.

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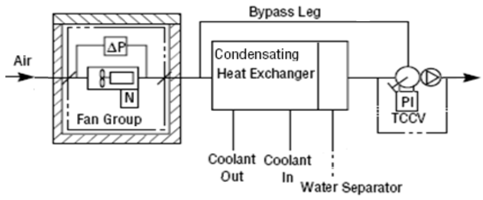

Figure 1. T&H control system

3. The Optimal Predict and Control Strategy for Spacecraft Cabin

The great change of humidity in the cabin is mainly caused by the change of human activity in different periods. The metabolizable energy in space is 118W when sleeping while 256W when doing activities. It's obvious that different activities would cause different thermal and humidity. The thermal load Q and humidity load D can hardly be determined accurately as a result of the uncertainty of Q and D 's variability. However, if the value of Q and D can be dynamic predicted on line based on the observation data, then the value of T and relative humidity(RH) can be predicted, moreover, the optimal flux in CHE is obtained through the mathematic model in combination with the objective function and boundary condition, thereby, the optimal control of temperature and humidity comes true [3~4].

3.1 Optimal coefficient of flux in CHE

Define the coefficient of flux in CHE as follows:

Xs = flux in CHE ÷ total flux in fan group

Xs can be devided into 16 levels: 0, 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%, 60%, 70%, 80%, 90%, 100%.

3.2 Scheme of optimal predict and control for temperature and humidity

Fig. 2 shows the scheme of optimal predicts and control for temperature and humidity.

The optimal predict and control for temperature and humidity can be realized through the following steps:

1) Set up a process model, and then implement the identification of parameters;

2) Predict different coefficients of flux in CHE via the corresponding T and RH trend aftertime within the controlled time step.

3) Fix the optimal coefficient Xs through objective function and boundary condition;

4) Deal with the air in the cabin with a constant flux Xs.

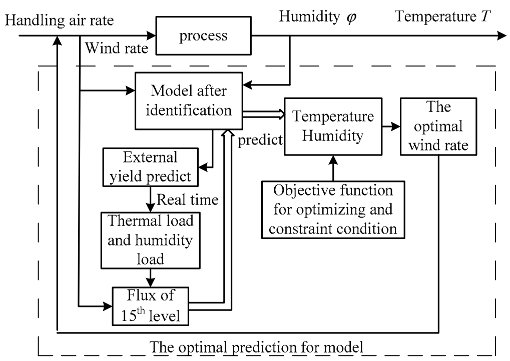

Figure 2. Optimal predict and control for temperature and humidity

3.3 Optimal predict and control model for temperature and humidity in the cabin

The model of temperature and humidity variety handling by CHE can be written as follows [5-8]:

$$M_C \frac{dT}{d\tau} = q_{load} - q_{CHX} - M_R \cdot T + M_{ROut}$$

$$M \cdot \frac{dw}{d\tau} = w_{load}(\tau) - w_{CHX}(\tau)$$
$$q_{CHX} = 1010\dot{m} \cdot E(T - 6)$$
$$T_{0h} = T - E \times (T - 6)$$
$$w_{CHX} = \dot{m} \cdot \varepsilon \cdot (w_{in} - w_{out,sat}) \geq 0$$
$$w_{out,sat} = \frac{0.62198 P_{qb}(T_{oh})}{P - P_{qb}(T_{oh})}$$

3.4 The implement of optimal predict and control for temperature and humidity in cabin

Firstly, identification of model parameters without control.

Given the exact external yield thermal load and humidity load, identify the parameters of thermal model with least square method without control, compute as follows:

1) With both controller and condenser non-operating, identify the parameters of objects using least square method, and set up the temperature and humidity model.

2) The controller non-operating while the condenser operating, fix the characteristic parameters.

Secondly, online estimation of parameters for steady temperature and humidity load.

With the measured historical T and RH, fix the thermal load (produced thermal minus removed thermal) and the humidity load (produced humidity minus removed thermal) in short term steady state as the input of predict model, and then estimate the temperature and humidity aftertime.

Thirdly, optimal predict and control based on the identification model.

If the predicted time step is $\tau_{predict} = 3 \times \Delta\tau$, then the time sequence is n=-1,0,1,2,3, known the measured value of temperature and humidity at n=-1,0, we can predict the value of temperature and humidity at n=1,2,3 and with a given flux of 15th level from the short term temperature load and humidity load, finally, we can fix the optimal flux Xs from the objective function and constraint condition. As it shown in figure 2.

3.5 Objective function for optimizing thermal inductance

The periodic variations of humidity in the cabin are usually caused by the periodic activities of cosmonauts. The commonly used thermal amenity analysis such as TS index for environment evaluate can't commendably reflect the thermal inductance index, therefore, it's necessary to advance a new thermal inductance and thermal amenity equation, and express it as a function of temperature and humidity in the cabin, which is the same with optimal control of temperature hand humidity in spacecraft cabin and be used as a objective function.

The best technique for cosmonauts' thermal inductance is experimental investigation, considering the investigation status and the hardness to do experimental investigation, this paper introduced a simulation study based on the human metabolism model. This study results in an expression among temperature, humidity and human thermal inductance, viz. optimizing objective function:

TSENS=0.1258×T_cabin+1.1782×φ_cabin-3.1895,

Constraint condition: T_air∈[18，22]，φ∈[0.25，0.8].

From the objective function, we can find the optimal value for optimal predict and control, and then get the optimal flux Xs.

Thermal inductance grade scale: + 5 very hot; + 4 quite hot; + 3 hot; + 2 warm; + 1 slightly hot; 0 comfort; 1 slightly cold; 2 cool; 3 cold; 4 quite cold; 5 very cold.

4. Simulation Results

Assume that the cabin is 1.4m in diameter, 7.3m long, its volume is 111m3. The thermal entering the cabin consists of metabolized thermal of three person and part of the thermal produced by equipment(most of the thermal produced by equipment is removed by cold plate).

4.1 Models for thermal load and humidity load

The thermal removed by CHE in spacecraft include the thermal produced by human metabolism, electronic equipment, luminous energy and so on.

1) Human metabolism: Based on the middling metabolism, reference the metabolism specified in NASA-STD- 3000 293 Rev. A [9].

2) Thermal produced by electronic equipment: Estimate the period of spacecraft in sunlight area and shade area respectively based on orbit height and the angle between orbit plane and the line of earth and sun. Besides human metabolism, other peak heat dissipating (heat produced by electronic equipment, luminous energy etc.) is about 2.5kW, which commonly occurs in sunlight area; however, when it occurs in shade area, the value reduce 15%, namely 2.13W. We get the simulation results according to this energy consume cycle.

4.2 The simulated thermal-humidity environment in spacecraft

The predict and control is based on experiment data, which comes from the simulated experiment. The simulation is carried out using European Space Agency(ESA)'s software EcosimPro, which has taken on powerful function on thermal control and simulation for environment control and life protection, and has been used to help designing the thermal and environment control system in 'Columbus' space station. We chose its temperature- humidity control system model, the cabin environment system model, cosmonaut thermal inductance model(the thermal resistance of dress is 1 clo)[10], in combination with the secondly developed optimal predict and control system for temperature and humidity, carried through simulated study. In addition, the experiment data for simulation is independent from the predict and control model, thus this study is reliable.

4.3 Simulation of optimal predict and control for thermal-humidity

The metabolize rate is shown in fig.3 when three people working. Thermal inductance is the objective function for optimal predict and control, and the time step is 5min. Simulation results is shown in fig.3-9. From the simulation results, we know that the shorter the period of optimal control, the more accurate the estimation of thermal and humidity load is, and the better the effect of optimal predict is. However, if the period of optimal control is too short, it may results in a worse system performance as the predict loop is shorter than control loop, and can't achieve an ideal effect. Thus it's necessary to find a best control period between the veracity of thermal/humidity estimation and the character of system control. From the simulated analysis, we fix a period of 5 min.

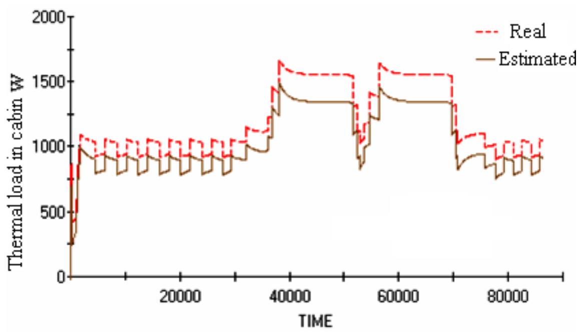

Figure 3. Estimation of thermal load in cabin

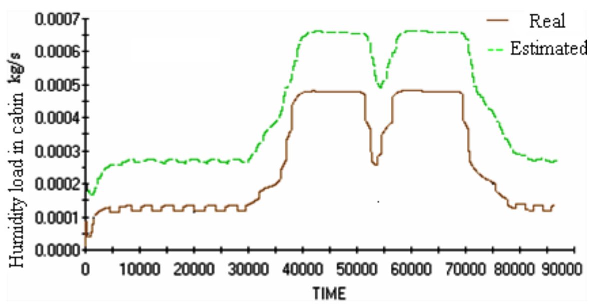

Figure 4. Estimation of humidity load in cabin

The optimal predict and control has the following virtues:

It can control the absolute humidity forwardly based on the variety of humidity in cabin and cosmonaut's activities, and ensure a comfort temperature, then realize humidity Priority;

It can improve the thermal amenity effectively, and reduce the thermal inductive of cosmonaut to 0.4, as is shown in fig.8.

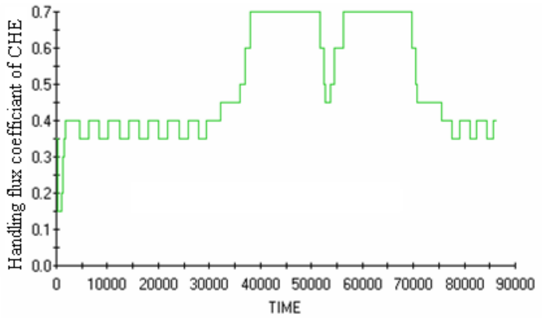

Figure 5. Coefficient of processing flux in CHE

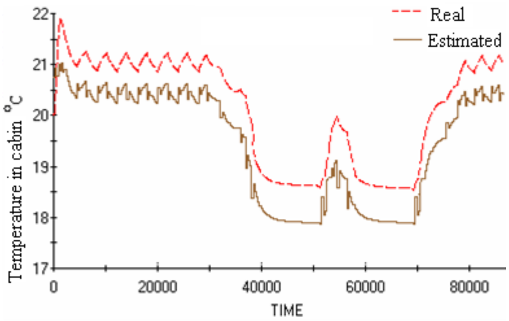

Figure 6. Temperature prediction in cabin

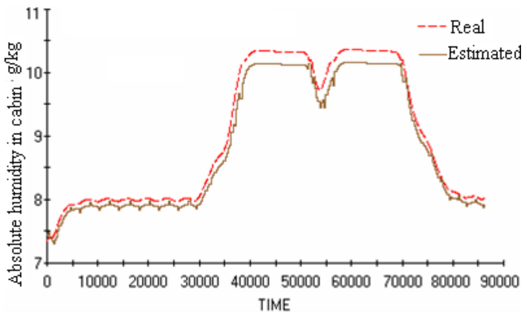

Figure 7. Absolute humidity prediction in cabin

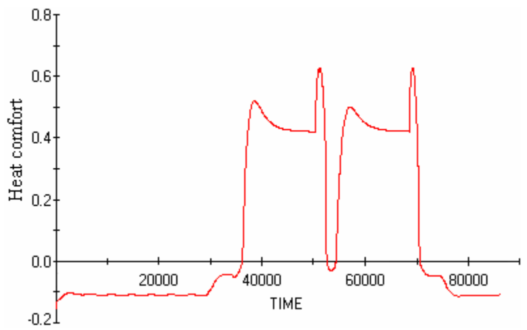

Figure 8. Heat comfort curve of cosmonauts produced by EcosimPro

What's more, the optimal predict and control method advanced in this paper can also be used in batch processing systems adopted by our 'Shenzhou' airship. According to the predicted results, we can guide the cosmonauts to operate the temperature and humidity control system based on the temperature and humidity in the cabin.

5. Conclusion

Air parameters control in most manned spacecraft is a kind of “temperature priority control” scheme, which has no regeneration heat exchanger or electric heater, and therefore it’s simple in structure and with the merit of high reliability, however, it can’t satisfy the requirement of dehumidify sometimes. In this paper, a control strategy of humidity control prior is put forward to satisfy the requirement of cooling and dehumidify as well as to ensure the heat comfort of cosmonauts. This kind of temperature and humidity optimal control strategy is effective for the manned cabin in our country, still more, it can give guidance to cosmonauts and realize optimal control according to the predict technique.

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