Simulation on Thermal Control System of the Extravehicular Spacesuit

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Abstract. The extravehicular (EVA) spacesuit is the life support system for astronauts in the extravehicular activity and help the astronauts perform the assembling of large space vehicle and maintenance. The thermal control system is one of the most important functions for extravehicular spacesuit, and it's directly related to the thermal protection structure and active temperature control, especially to the human body heat load. In this study, a human-suit thermal control model was built and the effect of human heat load, outside thermal environment and their composition effect to the thermal control system was analyzed. The extravehicular spacesuit prototyping system was used to validate the model. The results show as the follows.(1) It's reasonable to set 3 percent of the chiller flow as the lowest gear of thermal control system which can maintain the inside suit thermal comfort during low temperature and low metabolism situation. (2) The thermal control system's response will be faster if the temperature gear is higher. (3) It is not significantly affected to the temperature response of cooling input if the human metabolism rate is below 500W. (4) Thermal control model's validation and evaluation by dry thermal manikin is receivable. Overall, the human-suit thermal control model can be used to improve the design of extravehicular spacesuit's thermal protection system.

Keywords: spacesuit, thermal control, human body heat load.

1 Introduction

The extravehicular (EVA) spacesuit is basic protection and support system for astronauts' extravehicular working performance and is the core equipment system for the construction and maintenance of the large space facility. Thermal protection and vacuum pressure protection are the core functions of the EVA spacesuit. After nearly half a century of technological development, spacesuit thermal control system has become the active / passive integrated, ventilation / liquid-cooled mixed and liquid

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cooling dominated form [1-2], but there is still much room for improvement of the comfort and economy of the thermal control system [3-5]. For the thermal comfort evaluation of the EVA spacesuit, Yifen Qiu et al has done simulating calculation for the 'space environment - spacesuit – human' system. However, they simply put the spacesuit into two parts, EVA spacesuit and liquid-cooled suit, lacking more specific analysis on the internal structure of the spacesuit. SINDA, the U.S. spacesuit portable life support system simulation software, uses 41 notes' human thermal model and the spacesuit model to combine the spacesuit' thermal control device model and human heat transfer model, and then through computer simulation methods, it guides the costume design[6-7]. However, the current structure division of spacesuit of the software is relatively simple [8-9]. In order to meet the overall thermal design requirements and applications of the EVA spacesuit thermal control system, this paper did system-level simulation analysis and experimental research on the spacesuit's all levels of thermal control and dynamic thermal response of mutual restraint.

2 The Composition of the Spacesuit Thermal Control System and Thermal Model

From outside to inside, all levels of the EVA spacesuit's protective structures are vacuum shield insulation layer, pressure suit layer, comfortable layer, ventilation layer, liquid-cooled suit layer and underwear layer (Figure 1). While temperature, heat flux and other physical parameters exhibit distributed features in the actual process, considering that the inside of EVA spacesuit system is closed ventilation system, the temperature is largely homogenized, so this paper tries to build dynamics model and analyze the system using lumped parameter method. That is each layer considered as a lumped node, and each node representing all the physical properties and structural properties, thermal parameters of the certain layer, without considering the temperature distribution differences on each spatial location.

According to the general design and testability considerations, this paper takes the vacuum shield insulation layer, pressure suit layer and comfortable layer as a total

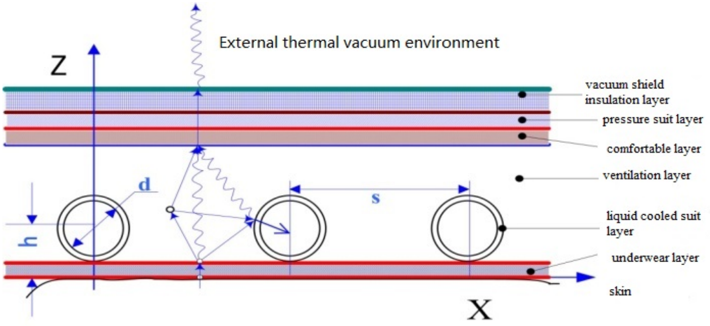

Fig. 1. The composition of the spacesuit thermal control system and thermal model

protective layer, so the thermal control system can be simplified into three layers which are protection layer, ventilation layer and liquid-cooled layer (considering the underwear and human skin together as thermal load model). The heat balance equations of all levels are as follows.

2.1 Thermal Equation of State of the Outer Protective Layer

The temperature variation of the thermal protective layer depends on the heat capacity and the heat flux which is accepted, reflected by the protective layer and penetrates through it. The thermal equation of state is as formula (1).

$$c_{sp}M_{sp}\frac{dT_{sp}}{dt} = Q_r - Q_e + Q_{leak} \tag{1}$$

C_{sp} represents the integrated heat capacity of the EVA spacesuit outer protective layer, and the unit is kJ/kgK; M_{sp} is the total mass of outer protective layer, in kg; T_{sp} is the average temperature, in ℃. Q_e is the external heat flux absorbed by the outer surface, in W; Q_r is the neat flux the outer surface radiates to the external space, in W, and its value as the formula (2).

$$Q_r = A_{sp}\ \varepsilon\ \sigma\ T_a^4 \tag{2}$$

A_{sp} is the superficial area of the outer surface of EVA spacesuit, and the unit is m^2; T_a is the surface temperature of the outer protective layer, in K; ε is the material emissivity of the outer layer; σ is the Boltzmann constant. Q_{leak} is the leakage bustling flow of the EVA spacesuit, in W; its value is as follows.

$$Q_{leak} = k_{eq}(T_g - T_a) \tag{3}$$

k_{eq} is the equivalent heat transfer coefficient of thermal protective layer, and the unit is W/m2℃; T_g is the average gas temperature of the EVA spacesuit ventilation layer, in K.

According to the formula (1), (2) &(3), and assuming that the system temperature change having the same overall trends, we can get the temperature conversion relations of the outer casing, as the formula (4).

$$c_{sp}M_{sp}\frac{dT_o}{dt} = -Q_e + A_{sp}\varepsilon\sigma {T_o}^4 + k_{eq}(T_g - T_o) \tag{4}$$

2.2 Heat Balance Equation of the Ventilation Layer Gas

Airflow of the ventilation layer is mainly through water sublimation / heat exchanger for heat exchange; part of the heat get into the fluid path system through the heat exchange with the liquid-cooled suit, and the thermal load mainly comes from the life support system equipment and parts of the body heat production, as formula (5) shows.

$$C_gV_g\rho_g\frac{dT_g}{dt} = Q_{plss} + Q_{mg} - Q_{lg} - Q_{leak} - Q_{gs} \tag{5}$$

C_g is the specific heat capacity of the ventilated gas in kJ/kg℃; V_g is the internal volume of the spacesuit, in m^3; ρ_g is the internal gas density, in kg/ m3; T_g of the average temperature of the ventilation layer gas, in ℃; Q_{plss} is the heat production rate of the built-in life support system (excluding the part liquid-cooled pumps taken), in W; Q_{lg} is the heat exchanging rate between the ventilation layer and liquid-cooled layer, in W; Q_{leak} is heat leakage rate of the system (leakage of heat per unit time), in W; Q_{mg} is the heat exchanging rate between the ventilation air and the bod, in W; its value is as follows.

$$Q_{mg} = hA_m\ (T_w - T_g) \tag{6}$$

h is the heat exchanging coefficient and the unit is W/m2℃; Am is the surface area of the human body, in m2; TW is the average temperature of the liquid-cooled ventilation layer interface, in ℃; Q_{gs} is the cooling rate of the cold water source of the water sublimator to the gas (the heat taken from the air road per unit time), in W, and its value is as follows.

$$Q_{gs} = cgm_g\Delta T_{sp} = cgm_g\ (T_{go} - T_{gs}) \tag{7}$$

m_g is the ventilation gas flow rate, and the unit is kg/s; C_g is the specific heat of the ventilation gas, in kJ/kg℃; T_{go} is the inlet temperature of the ventilation air, in ℃; T_{gs} is the outlet air temperature of the water sublimator, in ℃.

Combining the formula (5), (6) and (7), we get the heat balance equation of the ventilation layer gas.

$$C_g V_g \rho_g \frac{dT_g}{dt} = Q_{plss} + hA_m(T_w - T_g) - k_{eq}A_{sp}(T_g - T_a) - C_g M_g(T_{go} - T_{gs}) - Q_{lg} \tag{8}$$

2.3 Liquid Thermal Power Equation of the Liquid Circuit

The heat exchange between the fluid within the fluid circuit and the external part includes those from the human body, the ventilation layer, the fluid path inside the device heat rate and the internal device of the fluid path. Finally, the heat from the fluid path is discharged into the space by cold source / heat exchanger, without considering the radiative heat exchange between the wall of the tubes in liquid cooling suit and the inner wall of the pressure suit (due to the relatively small temperature difference). The liquid thermal power equation of the liquid circuit is as follows.

$$C_w M_w \frac{dT_{wa}}{dt} = Q_{ml} + Q_p + Q_{lg} - Q_{ls} \tag{9}$$

C_w is the specific heat of water, in kJ/kg℃; M_w is the total mass of the liquid fluid loop, in kg; Twa is the average water temperature of the liquid cooling suit, in ℃; Q_p is the heat generation rate of the liquid cooling circuit, in W; Q_{ml} is the heat exchange rate of liquid cooling system with the human body, in W, which is as follows.

$$Q_{ml} = K_w(T_s - T_i) \tag{10}$$

Q_{lg} is the heat exchange rate between the liquid-cooled layer and the ventilation layer, ignoring the thermal resistance of the liquid cooling tubes, and the unit is W. Its value is as follows.

$$Q_{lg} = h_x \pi dL(T_w - T_{wa}) \tag{11}$$

h_x is the natural convection heat exchange coefficient for the ventilation layer and the liquid-cooled tube, in W/m2℃; d is the diameter of the liquid-cooled tube, in m; L is the total length of the liquid-cooled pipeline, in m. Q_{ls} is the heat exchange rate of the liquid-cooled suit via the sublimation's cold source, in W, and its value is as follows.

$$Q_{ls} = C_w M_w (T_o - T_{ws}) \tag{12}$$

T_o represents the outlet temperature of the liquid-cooled suit, in ℃; T_{ws} is the outlet water temperature of the sublimation, in ℃.

Combining (9) - (12), we get formula (13).

$$C_w M_w \frac{dT_{wa}}{dt} = K_w(T_s - T_i) - C_w M_w (T_o - T_{ws}) + Q_p + h_x \pi dL(T_w - T_{wa}) \tag{13}$$

In summary, the EVA spacesuit thermal control system can be described synthetically by formula (4), (8) and (13).

3 Parameters Affecting the Life Support System

In the EVA spacesuit life support system, adjustment device of the cold source and valve controller are key links of the thermal control. The following analysis shows the relevant characteristics in the above formulas.

3.1 Water Sublimator

Water sublimator is simultaneously a cold source and heat exchanger of the system, as well as the main pathway to control the heat exchange of the active temperature control system with the external space. Analysis and testing show that the outlet gas temperature and outlet water temperature is stable on the whole for the water sublimation device with full cooling capacity and efficiency. This paper regards T_{gs} and T_{ws} in the formula (7) and (11) as constants (little change were found of the value in testing).

3.2 Temperature Adjustment Device

As shows in figure 2, the active temperature control system, the shunt flow ratio inflowing the water sublimation can be regulated by setting the thermostatic valve at different stalls; the ratio is denoted as k_n (n corresponds to the 0,1,2,3,4,5 stall separately). Relationship of the temperatures is as follows.

$$T_o - T_i = \frac{k_n(T_i - T_{ls})}{1 - k_n} \tag{14}$$

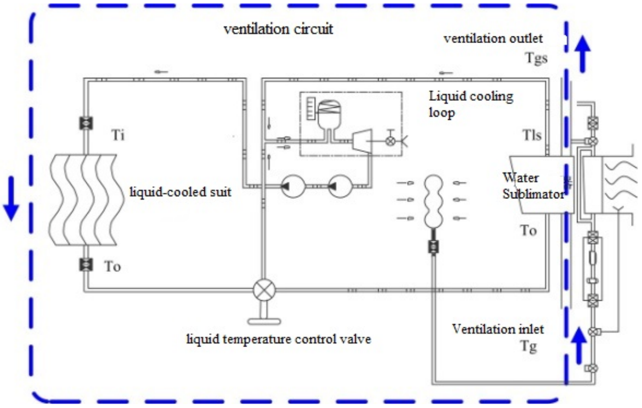

Fig. 2. Active temperature control system schematics

In the formula (13), T_{wa} can be represented by the average temperature at the outlet and inlet.

$$T_{wa} = \frac{T_i + T_o}{2} \tag{15}$$

So, the liquid thermal power equation of the liquid circuit-formula (13) - is further expressed as (16).

$$\frac{C_w M_w}{(1-K_n)} \frac{dT_i}{dt} = K_w(T_s - T_i) + Q_p + Q_{lg} - \frac{C_w M_w}{1-K_n} K_n (T_o - T_i) \tag{16}$$

For the ventilation circuit, the ventilating air flow is fixed and non-adjustable; the temperature relationship can be expressed as (17).

$$T_{go} - T_{gs} = 2(T_g - T_{gs}) \tag{17}$$

Q_{plss}, the built-in heat production rate of life support system, generally consists of fans, pumps and its controllers, sensors and its conditioning circuit, and purification device. Under working condition, in addition to the purification device producing reaction heat, the rest devices produce fixed heat according to their device power; we set it as Q_d. LiOH is widely used to absorb CO_2 and the reaction equation is as follows.

$$2LiOH + CO_2 = Li_2CO_3 + H_2O$$

This reaction is an exothermic reaction, producing heat and water vapor. The reaction heat is 158 J/mol; the clean tank heat balance equation can be expressed as (18).

$$c_g \rho_g V_p \frac{dT_g}{dt} = c_g M_g \left(T_{go} - T_g\right) + Q_m \ \beta F \rho^{0}_{co_2} \tag{18}$$

Vp is the gas volume of the purification tank; Qm is the heat from human body; β is the apparatus for the purification of the void coefficient and F is a parameter associated with the purification contact area in the purification apparatus. ρ^{0}_{co2} is the outlet concentration of CO2 gas of the purification tank.

The above analysis shows that the reaction heat of the purification apparatus is related to the human metabolic state. Summarily, the heat balance equation of the ventilation layer is as follows.

$$c_g \rho_g V_p \frac{dT_g}{dt} = Q_m + Q_d + hA_m(T_w - T_g) - k_{eq}(T_g - T_a) - 2C_g M_g(T_g - T_{go}) - h_x \pi \, dL(T_w - T_{wa}) \tag{19}$$

Other life support control devices include power equipment, such as pumps, fans and their controllers, sensors and their conditioning circuits. Their impact on the power cycle is considered in the traffic flow, and their heat effect is considered with other devices separately. Ventilation circuit is the main channel for heat dissipation of the protection devices; the reaction heat of fans and purification device are directly into the ventilation circuit; other electrical and electronic equipment exchange heat mainly through the ventilation cycle in the backpack. Heat from the pump are directly included in the liquid loop load. As closed to the cold source of the water sublimation, part of the life support system equipment can directly heat, but since it is a very small part of the overall, it is not considered when analyzing the whole system.

4 Dynamics Model of the Thermal Control System

Human heat regulation model is necessary for the simulation of human-uniform-environment whole system. Dual-node model by Gagge is prior in the process of parameters collection in human heat regulation model. Both dynamic model of the thermal control system and simulation model applied the same dummies experiment. This section introduces the simulation model by combining the equation of (4), (16), (19) and the structure of spacesuit thermal control system and flow parameters. CO_2 injection was applied in simulation of heat condition in human metabolism.

4.1 Model of Warm Body Mummy

Dynamic characteristics of extravehicular spacesuit are closely related with its response to heat fluctuation. Equations above and human heat regulation model provide the feasibility for analysis of human-uniform-environment characterization. This paper focuses on the spacesuit heat control feature and the corresponding authentication method investigation. The investigation of heat feature experiments was conducted by simulation heat load and mummy experiments. Mummy heat load model, including heat section, liquid cooling section and ventilation section, was summarized by the following equation.

$$C_m M_m \frac{dT}{dt} = Q_m - Q_{ml} - Q_{mg} \tag{20}$$

Where C_m, M_m and Q_m are specific heat capacity, total mass and simulation metabolism heat of mummies, respectively. Heat load equation can be rewritten with equation (6) and (10).

$$C_m M_m \frac{dT}{dt} = Q_m - K_w(T_s - T_i) - hA_m(T_w - T_g) \tag{21}$$

4.2 Heat Control System Parameters

Several parameters are related to the above model. A ccording to the test, extravehicular spacesuit solar absorption spectrum α_s=0.2, emissivityε=0.85, typical ventilation flow is 150-170 L/min, liquid ventilation is about 50 L, circle flow is 100-120 kg/h, total mass of circle flow is 2.5-3 kg, temperature of ventilation outlet is 6-8 ℃.

5 Result and Analysis of System Feature and Simulation

This section mainly discusses the sensitivity of heat control system response to environment, heat load, and control variables. Matlab 7 was applied to simulation different environment in simulation.

5.1 Low Temperature Simulation

Cryogenic condition is the process of spacesuit transforming from airlock to cryogenic condition. According to the preparation of spacesuit in transition process and temperature condition in airlock, initial temperature in and out of spacesuit was set as 20℃, and the stalls of temperature controller was set as 0 stage (K_n=0.1, i.e. Cooling flow was 10% of the total cooling flow), initial metabolism of warm body mummy was 100 W, fans and pumps in life support system and purification device reaction heat was 17 W, which was corresponding to the 100 W metabolism. Figure 3 was the inlet temperature Ti of the cooling liquid, average temperature of ventilation Tg and temperature of the out surface were compared with the experiment result, external heat temperature was set as 100 K.

The simulation results reveal that the temperature of spacesuit out surface drops rapidly due to the external dark environment. Besides, the significant temperature difference promotes the heat leak, and hence, the temperature of internal of spacesuit and mummy drops. Under the condition given above, the temperature of internal of spacesuit and mummy drops 5 ℃ in 30 min, which can feel by people obviously. Apparently, the temperature then cannot support the comfortable environment.

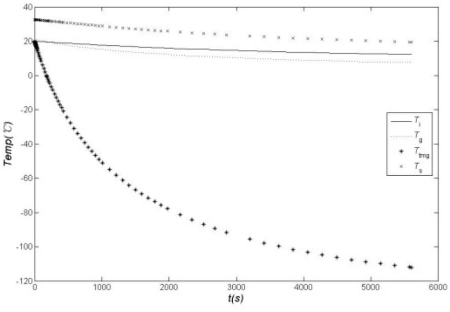

Fig. 3. Metabolism 100 W feature at the range from 100 K to homoeothermy

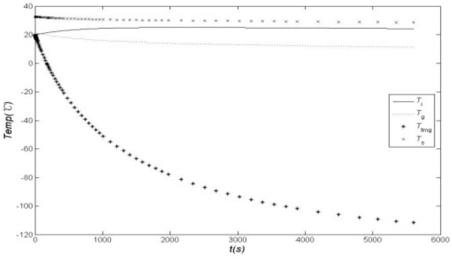

Fig. 4. Temperature of in/out spacesuit behavior under the condition of 100 W metabolism

Heat radiation including the heat leaking from the insulation layer (external heat exchange behavior refers to the heat radiation under cold background) and liquid cooling system. Depress the liquid cooling system heat radiation is a feasible method to achieve comfortable heat balance. Liquid flow can be controlled by valve so that the heat radiation is depressed. Figure 4 reveals the simulation result under the condition of 3% total circle flow. It can be seen that the temperature in the spacesuit can be sustained and the cooling flow decreases 7%. Therefore, basic heat balance can be supported by decreasing liquid cooling flow, and the heat exchange then decreases about 100 W.

Actually, under the given condition (kn= 0.1), comfortable environment can be achieved by increasing body metabolism. Figure 5 reveal the simulation result of 200 W metabolism. Internal temperature by then can be sustained (air temperature stable, warm body mummy temperature increases, and the liquid cooling temperature at inlet increases). Obviously, under the 100 W metabolism condition, heat leak was less than 100 W, which was agree with the method of decreasing liquid cooling flow.

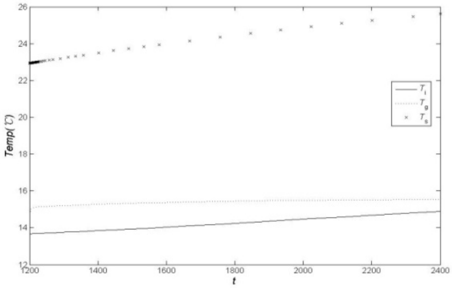

Fig. 5. Simulation result of temperature behavior under 200 W metabolism

Figure 6 reveal that the internal temperature behavior when metabolism increased to 400 W (k_n= 0.1). Figure 7 is the simulation result of internal temperature under the low temperature metabolism (k_n= 0.1). Simulation metabolism varies from 100 W (20 min)-200 W (20 min)-400 W (80 min) - 250 W (30 min), and internal temperature changes accordingly.

Above simulation results reveals that liquid flow set as 3% is reasonable, and internal temperature and comfortable environment can be achieved under this condition.

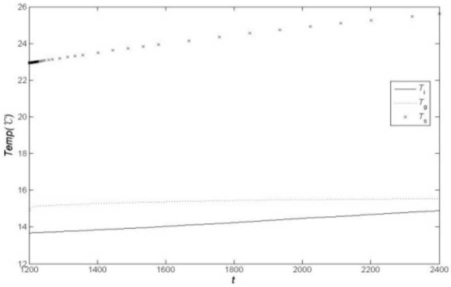

Fig. 6. Simulation result of temperature behavior under 400 W metabolism

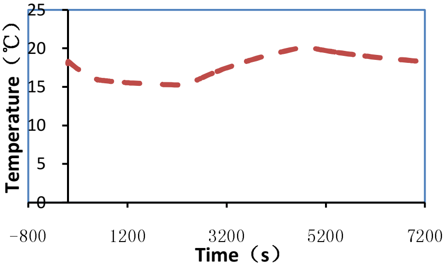

Fig. 7. Simulation result of internal temperature under the low temperature metabolism

5.2 Average Out Heat Flow Heat Simulation

As introduced in above heat balance experiment result, spacesuit under the condition of external heat radiation, heat leak is about 30 W, which is the most close to the orbit extravehicular condition. Figure 8 shows the temperature behavior with 400 W simulation metabolism under different flow condition. It can be seen that temperature controller switches to 1 stage (k_n= 0.2), internal temperature can be controlled well. The simulation results also shows that when the controller switches to higher stage, heat control system respond more rapidly. This is mainly attributed to the heat inertia of liquid circle. The bigger the liquid flow mass is, the more heat exchange is. The liquid cooling response time is about 3~8 min, air temperature in ventilation circle changes more rapidly due to the low heat capacity.

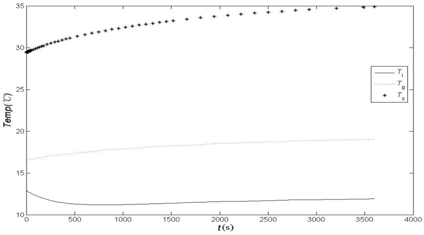

Fig. 8. 400 W metabolism of 1 stage (kn=0.2) under average temperature condition

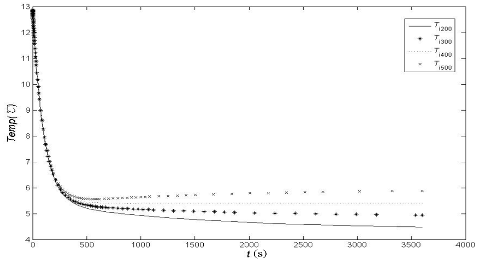

Fig. 9. Effect of different metabolism on liquid inlet temperature when flow parameter kn=0.6

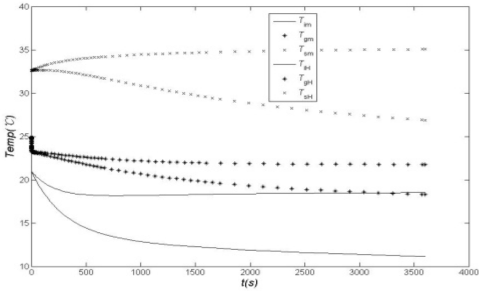

Fig. 10. Comparison of simulation heat exchange parameter and mummy heat radiation control

Figure 9 shows different simulation metabolism effect on spacesuit under the same flow (k_n= 0.6). The results reveal that different metabolism affect inlet temperature little when the metabolism bellows 500 W. It because that under the same flow, cooling source heat radiation almost reaches stability (when k_n= 0.5 and metabolism reaches 500 W, temperature controls stable). When metabolism changes, astronaut needs to adjust controller valve frequently so that comfortable heat environment can be obtained.

Figure 10 compares the experiment heat exchange parameter (Kwr≈25) and warm body mummy heat radiation parameter (Kwr≈15). It can be seen that the inlet liquid temperature dropped about 11 ℃ when the warm body mummy reached heat balance, and its average temperature was increasing by then. However, human body can reaches heat balance at a higher liquid inlet temperature (about 19 ℃). Therefore, comparing with real condition, experiment on dry manikin to simulate the spacesuit heat control system is conservative. For more delicate design, more closed to real condition result can be obtained by further investigation in the following two aspects: (1) develop more advanced mummy with more close to human to be test on; (2) find out the relationship between dry manikin and human heat response experiment.

6 Conclusion

This paper carried out warm body mummy test and external temperature heat control by applying the spacesuit prototype thermal control system under vacuum condition. The results show simulation analysis is highly agreed with experiment data, which possess high engineering value in system solution design and analysis.

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