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Results of Research Tests of Robot of Anthropomorphous Type Thermal Control System

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Abstract: This study presents results of heat-vacuum testing of an anthropomorphic robot. The data analysis obtained during the tests allows us to determine the main characteristics of means for ensuring a thermal mode. Possibility of continuous work under extreme operating conditions for a long period of time 1.5 h is demonstrated. Testing conditions in various modes are described as well as the robot placement on rigging in a camera. The system of a stand vacuum pumping is described. The method of external heat fluxes simulation and equipment used for this purpose are presented in detail. Thermal sensors and heaters layout is given. Temperature values at the beginning and ending of modes are presented. Graphs of temperature changes in the RAT construction are shown in various modes. Pictures of the robot in the thermo-pressure chamber are presented before and during testing.

Key words: Robot of anthropomorphous type, thermal control system, thermal-vacuum tests, space, multilayer insulation, thermo-pressure chamber, heat flux simulators

INTRODUCTION

The space is an unsuitable environment for human work and existence. Lack of pressure and atmosphere, extremely low temperatures do not allow carrying out any work or research outside space stations without special equipment. Nowadays designing and creating of all possible devices are being made to perform such kind of work. The Robot of Anthropomorphous Type (RAT) is an example of such a "tool". RAT is designed as close as possible to a human body which is supposed to ensure its highly efficient work which humans had to carry out outside a space station. Using of robots for simulating operations on space objects will allow expanding the list of such operations and the range of using these objects (Kryuchkov *et al*., 2013; Saprykin *et al*., 2016). For these purposes robot systems are designed and made: RAT simulating system, RAT control system (Kutlubaev *et al*., 2016) and the RAT Thermal Control System (TCS) (Krochak *et al*., 2016). Before designing the thermal control system, the RAT thermal simulation, where the finite element method was used was carried out taking into account specific features of thermal calculations in outer space (Krochak *et al*., 2016).

Restrictions at operation: RAT is a mechanism which also has a number of restrictions for service conditions under which it will work (outer space, planet surface, etc.). One of the main restrictions for RAT functioning is a narrow range of temperatures it can work. This condition imposes a number of requirements when modeling similar devices for maintaining them in a working zone of temperatures determined.

Major factors which determine the temperature of the RAT are "coldness" and "emissivity" of a surrounding space. In the absence of internal thermal emissions, the RAT will approach to 4°K (residual temperature of the big bang relic radiation in surrounding space) within several hours from initial temperature +20°C ("normal conditions"). Estimated robot autonomy does not provide its connection with a satellite and receiving thermal fluxes from there. Therefore, compensation of heat leaving into surrounding space and keeping permissible temperature ranges for construction elements can be provided only at the expense of internal thermal emission of construction elements and covering of the construction with Multilayer Insulation (MLI) (AWS, 1991).

RAT operation will take place under unfavorable conditions (outer space) with a wide range of temperatures (shadow, the sun). Working limit of temperatures for RAT (from -40 to +80°C) is determined by electronics which is installed in it (Soragi, 2004).

Typically, the temperature limits for critical elements can be assigned basing on the thermal resistance criterion defined as an ability of an item or material to withstand the effect of high or low temperatures without damaging or degrading structural and functional properties. Requirements to permissible temperature limits for RAT critical structural elements are given in Table 1.

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Table 1: Thermal criteria for RAT structural elements

	Temperature limits for effective work (°C)		Limits of resistance to heating/cooling (°C)	
Components	Max.	Min.	Max.	Min.
Motor (winding)	+125	-30	-	-
Scan-camera (housing)	+50		-	-
Laser rangefinder	+50 Environment	-10	+75 Environment, storage	-25
Electronic control unit *1)	+60 Mounting surface	-30	+70 Non-operating mode	
Heater	+200	-75	-	-

Environ., ambient temperature; Mounting surface: temperature of a mounting surface under the control unit; On the example of an electronic control unit for the mechanism of rocket engines orientation of spacecraft correction and orientation system

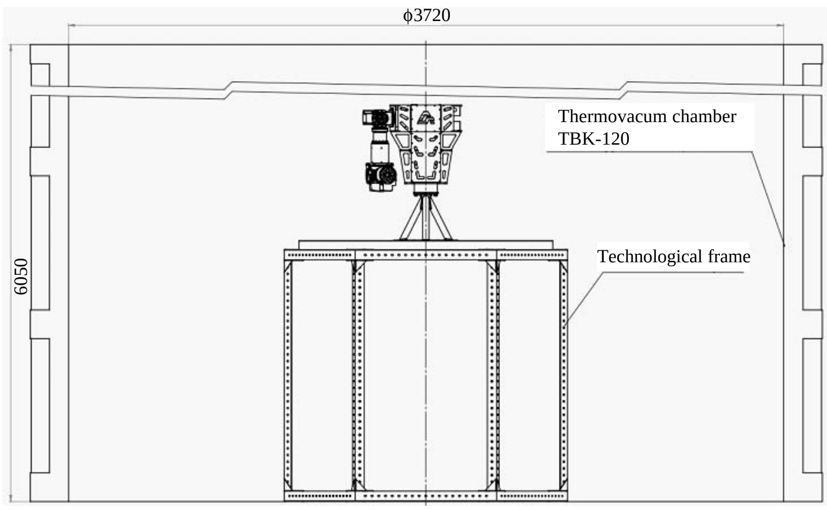

Fig. 1: RAT layout in the thermo-pressure chamber TPC-120

The set of tasks solved by rat: At all stages of orbital functioning, RAT's work is ensured under the following boundary thermal conditions:

- RAT is installed on a spacecraft landing surface whose temperature is maintained by external means within a predetermined range
- RAT can be located for a long time both under conditions of constant solar radiation with a maximum midsection ("overheat" mode) and in a long shadow, i.e., in the complete absence of a solar radiation flux ("overcool" mode)

In the "overheat" mode, continuous exposure of maximum external heat flows on the RAT external surfaces where the values of optical characteristics for thermostatic coatings are taken with regard to possible degradation at the end of active life is combined with maximum internal heat loads corresponding to a long continuous operation. "Overheat" takes into account the solar heat flow, heat released to the electric motors. For this mode the power supplied to the electric motors and the optical coating for holding the RAT in the operating temperature range is selected.

In the "overcool" mode the thermal mode is considered when RAT is not in operation, it is completely shaded (external heat fluxes are absent) and when heat regulators operate to maintain the lower limits of the permissible temperature range, according to a given control algorithm. You can also use the power supplied to the electric motors instead of heaters.

"Overcool" is the Earth shadow, the absence of a solar flux where ambient temperature is Tenv = -269°C. For this mode the power supplied to electric motors is selected to keep the RAT in the operating temperature range.

MATERIALS AND METHODS

Preparation for heat-vacuum tests

Location of testing: The preparation and carrying out of the tests were conducted at the site of the heat-vacuum testing department in a thermo-pressure chamber TPC-120, located in the industrial premises of JSC "ISS" named after Reshetenev, Zheleznogorsk. RAT layout in the thermo-pressure chamber TPC-120 is presented in Fig. 1. List of testing facilities:

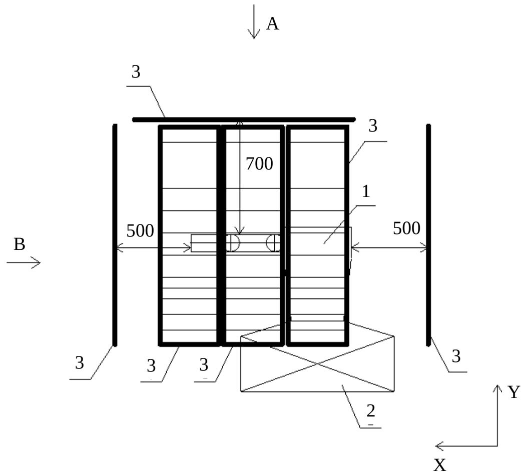

Fig. 2: HFS layout, where; 1) The object of testing; 2) Thermo-stationary support stand and 3) Background heat flux simulator

- Thermo-Pressure Chamber (TPC), the pressure in the chamber is not more than 1×10-4 mm Hg. The coefficient of solar absorbance by camera screens is not <0.9
- Vacuum Pumping System (VPS)
- TPC nitrogen system; the temperature of chamber internal nitrogen screens is minus (170±10)°C, emissivity of chamber nitrogen screens is not <0.9 at 20°C
- Heat Flux Simulators (HFS) (infrared panels), the error in measuring the consumed power of HFS panels is not more than ±5%
- System for measuring temperature parameters
- System for HFS and heating elements power control, the error in measuring the consumed power by TCS electric heaters is not more than ±2%

Figure 2-4 show the layout of infrared thermal panels which are EHF (sun) simulators. Infrared thermal panels are Heat Flow Simulators (HFS), simulating external heat fluxes from the Sun which interact with the external layer of multilayer insulation of a housing module and radiation surfaces of the RAT Model thermal control system. All HFS lamps were equipped with reflectors and emitters. Four HFS panels could control two lamps per channel.

The thermo-pressure chamber has 2 cascades of vacuum pumps. The first cascade contains forevacuum mechanical pumps which provide air evacuation to a level of 10^{-2} mm Hg. The second cascade contains molecular pumps providing high vacuum. Also, there are nitrogen

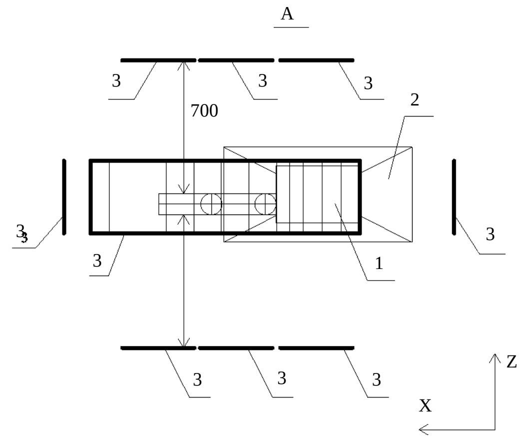

Fig. 3: HFS layout, type A (top), where; 1) The object of testing; 2) Thermo-stationary support stand and 3) Background heat flux simulator

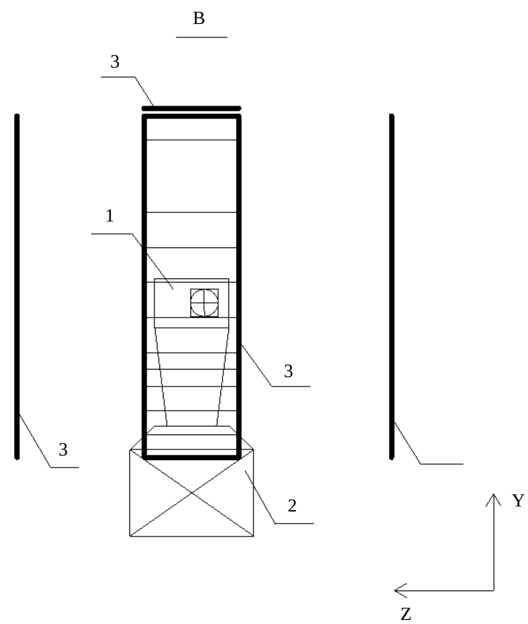

Fig. 4: HFS layout, type B, where; 1) The object of testing; 2) Thermo-stationary support stand and 3) Background heat flux simulator

traps for air evacuation, “freezing” the remnants of air molecules. However, the main consumption of nitrogen falls on cooling down nitrogen screens simulating the “emissivity” and “coldness” of outer space.

Temperatures of nitrogen screens during this time reached stationary values in the negative area (170±10)°C. Before testing, thermocouples and electric heaters are installed on a test object. Their layout is demonstrated in Fig. 5.

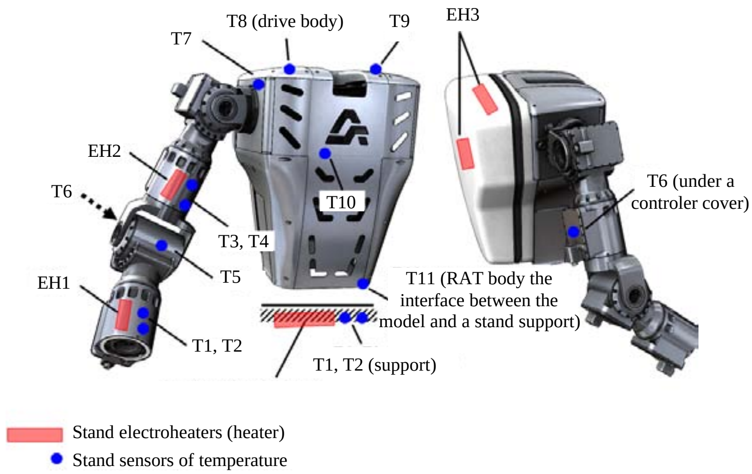

Fig. 5: Temperature sensors and heaters layout on RAT Model during research tests

RESULTS AND DISCUSSION

Research tests: The main aim of thermal testing of any object and its TCS is temperature measuring in characteristic zones and in points (of a temperature thermal field) of a tested object in various boundary conditions, processing of results and comparison of temperature values received experimentally to permissible limits (criteria); developing of measures to address situations of non-compliance with the criteria and requirements for TCS and with exceeding permissible limits by separate temperature values, forecasting for supplementary research modes or concluding on the completeness of tests and achievement of its goals (Table 2).

Chronology of heat-vacuum tests: In the course of carrying out the HVT of RAT Model simulator, the following modes were implemented. Brief description of each mode:

"Overcool 1": External fluxes-off. Simulator thermal emission -(23.5 W). Mounting interface was maintained at -20°C. Indications of hardware and EH capacities for the modeending are provided.

"Overcool 2": External fluxes-off. Simulator thermal emission -(0 W). Mounting interface was maintained at minus 20°C. Indications of hardware and EH capacities for the mode ending are provided.

"Overcool 3": External fluxes-off. Simulator thermal emission -(0 W). Mounting interface was maintained at 0°C. Indications of hardware and EH capacities for the mode ending are provided.

Table 2: Research modes

Modes	Mode beginning	Mode ending
1 "Overcool 1"	15.12.16 18:00	15.12.16 21:40
2 "Overcool 2"	15.12.16 22:00	16.12.16 00:30
3 "Overcool 3"	16.12.16 02:40	16.12.16 06:40
4 "Overcool 4"	16.12.16 07:30	16.12.16 10:30
5 "Overheat 1"	16.12.16 12:30	16.12.16 17:10
6 "Overheat 2"	16.12.16 17:15	16.12.16 19:36
7 "Overheat 3"	16.12.16 20:25	16.12.16 23:00

"Overcool 4": External fluxes-off. Simulator thermal emission -(28.2 W). Mounting interface was maintained at 0°C. Indications of hardware and EH capacities for the mode ending are provided.

"Overheat 1": External fluxes are supplied from the maximum midsection of a tested object at S_0 = 1440 W/m^2 for equivalent simulator coefficients (E = 0.3; As = 0.15; the coefficient for thermal-pressure chamber nitrogen screens f = 0.7). Thermal dissipation of the simulator -(0 W). Mounting interface was maintained at 50°C. Indications of hardware and EH capacities for the mode ending are provided.

"Overheat 2": External fluxes coincide with those in "overheat 1" mode. Thermal dissipation of the simulator with discreteness of 3.5 minutes increased iteratively: 22.2; 25.0; 25.9; 28; 32.6; 40.9 W. Then, within 95 min the simulator made monotonous movements at maximum (40.9 W) heat dissipation with an average angular velocity of all drives at 33.4 angular degrees/sec. Mounting interface was maintained at 50°C. Indications of hardware and EH capacities for the mode ending are provided.

"Overheat 3": External fluxes coincide with those in "overheat 1" and "overheat 2" modes. By means of EH, predicted established simulator temperatures (85-90°)

were reached as though simulator controllers had not failed in the "overheat 2" mode and it continued working at the level of 40.9 W. Mounting interface was maintained at 50°C. Indications of hardware and EH capacities for the mode ending are provided.

"Cooling 1": External fluxes coincide with those in "overheat 1", "overheat 2" and "overheat 3" modes. Upon reaching steady-state temperatures in the "overheat 3", EH were disconnected and the rate of the tested object cooling during external thermal flux simulation was fixed. Mounting interface was maintained at 50°C. Temperature of nitrogen screens is -180°C.

"Cooling 2": External fluxes-off. Temperature of nitrogen screens is -5°C for the mode beginning and +5°C for the mode ending. By means of EH simulator temperatures of the same level as in the "overheat 3" mode were reached. Mounting interface was maintained at 50°C. EH capacities are provided. The next steps are "atmosphere letting" into the thermo-pressure chamber and its opening P.S. After outer space factors impact no visible surface defects were detected.

Description of carrying out heat-vacuum tests modes: Carrying out "Overcool" modes. Initially, whilst carrying out tests, so-called "Overcool" modes were executed, when problems of minimum levels simulation of external thermal loads were solved. Respectively, during all four carried-out modes: "Overcool 1", ..., "Overcool 4" EHF simulation was not performed. During nitrogen screens cooling, TCS heaters control was performed in such a way so as to ensure that all temperatures of the the RAT Model were maintained not lower than -20°C.

Thus, in the course of these modes, the power of 23.5 W is confirmed, sufficient to maintain the temperatures of the RAT Model not lower than -20°C. Distributions of steady-state temperature values for the model at two different power levels of the RAT Model thermal control system heaters and at two different power levels of additional heaters installed on the radiation surfaces and on the housing module are obtained.

Carrying out "Overheat" and additional modes. After that, 3 "overheat" modes were carried out. In the second part of research tests of the RAT Model thermal control system, the tasks for maximum levels of external thermal loads simulation were being solved. In all these modes the temperature for the RAT Model stand support was maintained at +50°C.

External streams were supplied from the maximum midsection of a tested object at S_0 = 1440 W/m^2 for equivalent coefficients of radiation surfaces coatings of the RAT Model thermal control system (E = 0.3; A_s = 0.15; the coefficient of visibility for thermal-pressure chamber nitrogen screens f = 0.7). Below demonstrates a picture fragment of an "overheat" mode with a chamber closed and the HFS running. In the right side of the picture you can see the HFS lamp glow brightly and the light reflect off the radiation surfaces and the outer layer of multilayer insulation covering the torso block (Fig. 6).

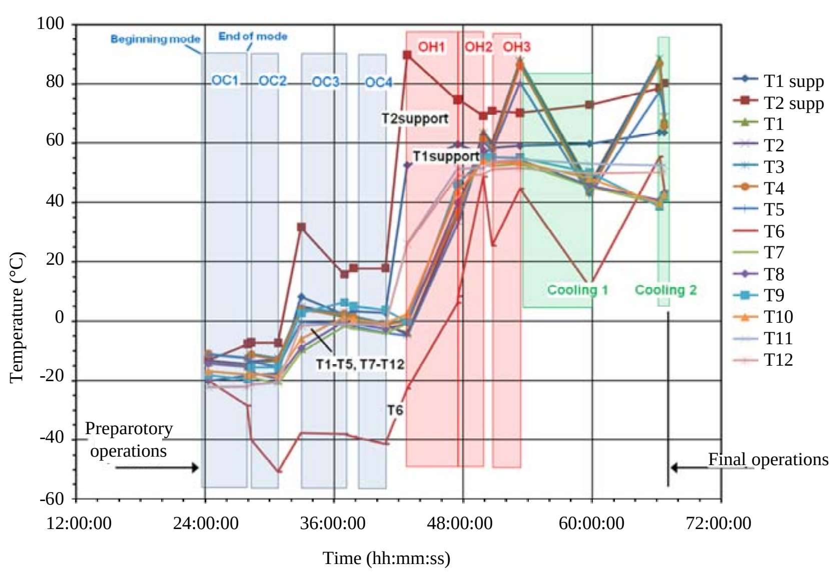

Fig. 6: Temperature change (mode beginning/ending) at carrying out research tests of the RAT Model TCS

Table 3: Summary results of the RAT Model research tests TCS (TPC-120 stand, JSC ISS)

Index of temperature sensor (T)	T position (heater)	Testing mode (OC-"Overcool", OH-"Overheat", "cooling")																	
		OC1 H1-H3 = 0, RAT = 5×4.7 W		OC2		OC3		OC4		OH1		OH2		OH3		Cooling 1		Cooling 2	
		Data (dd.mm.yy)																	
		15.12.16		15-16.12.17		16.12.16		15.12.16		15.12.16		15.12.16		15.12.16		16-17.12.17		17.12.16	
		Time (hh:mm)																	
		Beg.	End	Beg.	End	Beg.	End	Beg.	End	Beg.	End	Beg.	End	Beg.	End	Beg.	End	Beg.	End
		18:00	21:40	22:00	0:30	2:40	6:40	7:30	10:30	12:30	17:10	17:15	19:40	20:25	23:00	23:00	5:30	12:00	12:25
		Time of test (hh:mm)																	
		24:17	27:57	28:17	30:47	32:57	36:57	37:47	40:47	42:47	47:27	47:32	49:53	50:42	53:17	53:17	59:45	66:15	66:42
		Temperature (°C)																	
T1supp	Support	-20.1	-18.3	-18.0	-17.6	8.3	2.4	3.4	3.0	52.7	59.6	59.7	56.6	58.6	59.2	59.2	59.9	63.7	63.7
T2supp	Support	-13.1	-7.7	-7.2	-7.3	31.7	15.8	17.9	17.3	89.8	74.4	74.8	69.2	70.9	70.2	70.2	72.9	78.6	80.3
T1	Forearm (EH1)	-13.9	-15.2	-14.2	-13.3	4.5	1.3	0.2	-1.7	-3.7	36.1	36.2	63.9	60.3	88.0	88.0	46.3	88.3	68.1
T2	Forearm (EH 1)	-13.2	-14.5	-13.6	-12.8	5.0	1.9	0.8	-1.1	-4.5	35.6	35.6	63.5	59.7	87.5	87.5	45.6	88.6	68.7
T3	Shoulder (EH 2)	-10.9	-12.2	-11.0	-12.4	4.5	2.9	1.8	-0.6	0.6	36.9	36.9	61.8	58.9	87.8	87.8	44.1	88.5	66.7
T4	Shoulder (EH 2)	-11.0	-12.4	-11.2	-12.9	3.8	2.4	1.3	-1.2	0.1	36.3	36.4	61.3	58.2	86.4	86.4	43.4	86.9	65.8
T5	Elbow	-11.2	-12.5	-13.7	-15.4	-0.3	-0.7	-1.7	-3.9	-4.9	32.8	32.8	60.3	57.4	80.5	80.5	42.5	77.3	70.1
T6	Controller	-20.1	-28.5	-39.9	-50.8	-37.8	-38.0	-39.0	-41.4	-22.8	6.2	8.3	48.6	25.5	44.6	44.6	11.7	55.5	43.9

Table 4: Summary results of research tests of the RAT Model TCS (TPC-120 stand, JSC ISS)

Index of temperature sensor (T)	T position (heater)	Testing mode (OC-"Overcool", OH-"Overheat", "cooling")																	
		OC1 H1-H3 = 0, RAT = 5×4.7 W		OC2		OC3		OC4		OH1		OH2		OH3		Cooling 1		Cooling 2	
		Data (dd.mm.yy)																	
		15.12.16		15-16.12.17		16.12.16		15.12.16		15.12.16		15.12.16		15.12.16		16-17.12.17		17.12.16	
		Time (hh:mm)																	
		Beg.	End	Beg.	End	Beg.	End	Beg.	End	Beg.	End	Beg.	End	Beg.	End	Beg.	End	Beg.	End
		18:00	21:40	22:00	0:30	2:40	6:40	7:30	10:30	12:30	17:10	17:15	19:40	20:25	23:00	23:00	5:30	12:00	12:25
		Time of test (hh:mm)																	
		24:17	27:57	28:17	30:47	32:57	36:57	37:47	40:47	42:47	47:27	47:32	49:53	50:42	53:17	53:17	59:45	66:15	66:42
		Temperature (°C)																	
T7	Body	-16.7	-17.9	-18.8	-21.0	-10.3	-1.7	-2.5	-4.1	-0.7	39.6	39.6	55.1	52.4	53.1	53.1	45.3	39.5	42.1
T8	Drive	-14.3	-15.3	-17.1	-19.4	-9.0	-0.1	-0.9	-2.6	-0.6	39.9	40.0	57.7	53.4	54.4	54.4	45.8	40.7	43.3
T9	Body (H3)	-18.2	-19.6	-15.6	-15.5	2.8	6.3	5.1	3.8	0	46.3	46.3	55.0	55.4	55.3	55.3	50.3	38.6	41.8
T10	Body ("breast")	-16.9	-18.0	-17.8	-18.4	-6.0	1.3	0.6	-0.7	2.4	43.6	43.6	54.2	53.5	53.7	53.7	48.1	39.7	42.6
T11	Body (support zone)	-22.3	-22.1	-21.3	-20.7	-1.4	-1.0	-0.7	-1.3	26.2	51.5	51.4	51.6	53.8	54.6	54.6	53.1	52.5	52.6
T12	Body (support zone)	-22.2	-22.1	-21.3	-20.7	-1.5	-1.0	-0.8	-1.3	25.9	49.2	49.1	49.4	51.4	51.7	51.7	49.8	50.2	50.4

Results of tests: Upon completion of tests the obtained data were analyzed and systematized. Results of tests are recorded in Table 3 and 4.

According to research tests results of the RAT Model thermal control system, the required amount of data was obtained to create means for ensuring a thermal mode of this model. The data analysis makes it possible to determine the main characteristics of means for ensuring the thermal mode:

- The power of electric heaters is not <15 W per each half-arm of the simulator "arm", the power of electric heaters of the simulator "body" is not <10 W
- Thermal MLI resistance of the simulato "body" is not <5 T_0/W, MLI coating is not <95% of the simulator "body" area
- Characteristics of thermal control coating of the simulator "arm": the coefficient of solar radiation absorption is A_s = 0.14-0.16, emissivity degree is E = 0.3-0.4 whereas the cold black space visibility coefficient is not <0.7

CONCLUSION

Research tests of the RAT Model thermal control system are carried out in a required volume with positive results:

- During all modes of research tests the RAT Model thermal control system maintained all RAT components temperature in a range from -20 to +80°C in compliance with requirements
- The RAT Model power consumption in a “ready” mode did not exceed 100 W in compliance with requirements

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