DEVELOPMENT OF CRYOGENIC HEAT PIPE DIODES FOR GERMANIUM GAMMA-SPECTROMETER THERMAL CONTROL SYSTEM

*A. Paschin, I. Prokopenko, B. Rybkin
**A. Chernenko, V. Kostenko, I. Mitrofanov

*Scientific-technical Center “Teploenergotechnika”, Protvino, Moscow region
**Space Research Institute, Moscow

Abstract

The Precision Gamma Spectrometer instrument included to the scientific payload of the project "MAPC-96" was intended for investigation of gamma radiation during the cruise to Mars and at a orbital around the planet. Temperature of the spectrometer detectors in an operational mode should not exceed 120K. At passage of the Martian perigee it is difficult to achieve this temperature because of heating radiators by an external heat flow as high as 550 W/m2. At the same time it was necessary to provide for detectors annealing at temperature 373K given the restricted power capabilities of space craft. To meet these requirements each germanium detector was coupled with the radiator by means of two cryogenic heat pipe diodes (HPDs), which allowed efficiently to transfer heat to the radiator during a majority of orbit and had large thermal resistance to reverse heat flow, when the radiator temperature exceeds temperature of detectors. In this article we share our experience of creation of HPD with nitrogen and oxygen as working fluids, present their characteristics in forward and reverse heat flow direction, and demonstrate the capability the design to preserve the performance after long-term storage.

KEYWORDS

Detector, cryogenic heat pipe diode, nitrogen, oxygen, forward and reverse heat flows, thermal conductivity

INTRODUCTION

The germanium detectors have high energy resolution at cryogenic temperatures. It is known, that temperature of their operation should not exceed 120K [1]. During the transit flight to Mars this requirement is easily met by means of a two-stage passive cooler-radiator. Orbital stage requires more complex thermal control methods, able to deal with a considerable heat flow from Martian surface being absorbed by the radiator during an approximately 70-minuts long pericenter phase depicted in. The heat load leads to significant increase of radiator's temperature as presented in fig. 1.

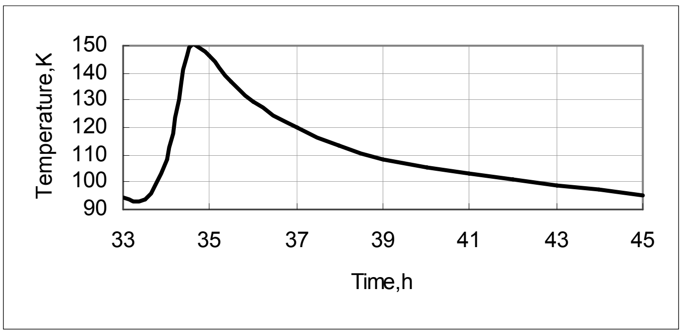

Fig.1. Radiator temperature during pericenter simulation

To keep detectors working it was required, that during the pericenter passage the temperature of detectors should increase no more than by 25K. For this purpose we involved HPD. Each detector incorporated with the radiator by means of two HPDs working in parallel. From the operation conditions by forward heat flow direction (from the detector to the radiator) it was required, that the thermal conductivity of each HPD should be not greater than 1 W/K, and the heat-transfer limit of about 4 W at temperature 90-100 K. The greater value of a transferred heat flow was not allowed because annealing mode of detectors at temperature of 373K was planed. For this procedure the power of no more than 8 W per detector was allocated owing to restricted onboard resources of energy. HPDs should fast dry up, gain high thermal resistance and hinder with heat transfer on the radiator.

DESIGN

The overall dimensions of cryogenic heat pipe-diodes were determined by the operating conditions and the design of assembly "detector-radiator". The scheme of the HPD is shown in Fig.2. In all, two detectors and, therefore, four identical HPDs were used.

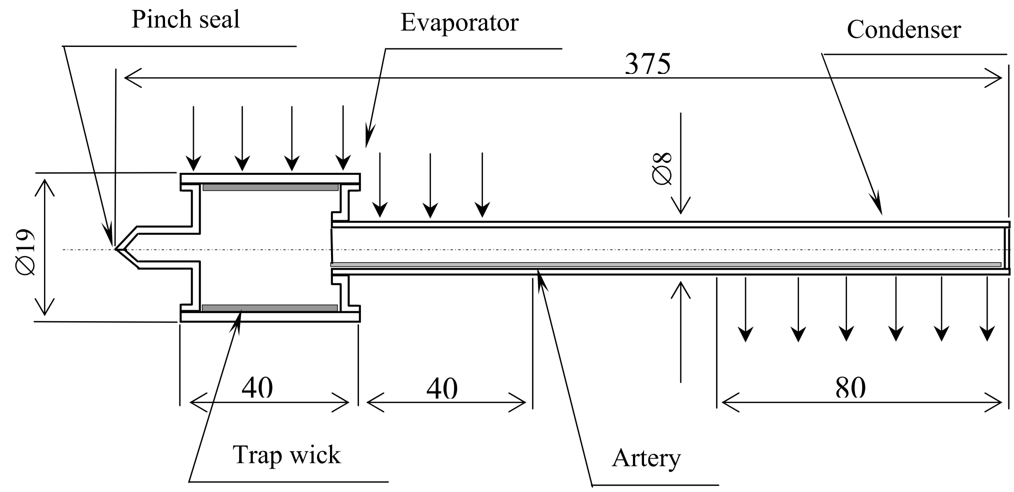

Fig.2. Layout drawing of the heat pipe diode

Many cases of application of cryogenic HPD in a space technology have been described in literature [2,3,4], where various methods of implementing diode-effect: variants of capillary structures, heat-carriers etc were used. Based on theoretical investigation and experimental improvement the authors have made choice on a construction of HPD with a liquid trap implementing the diode functionality and with artery-thread wick in container of a heat pipe. The experience has shown that liquids trap is the most reliable and effective a method of implementing the diode functionality. The artery wick with thread grooves created by the developers, has small volume for a liquid phase and low thermal resistance, that is important for a cryogenic range of temperatures where heat-carriers are not very efficient.

For the considered problem the operation temperatures were limited within 90-120 K. For this range, there exists a limited choice of heat-carriers: nitrogen, oxygen, argon and monoxide of carbon. Nitrogen and argon are neutral substances while oxygen and monoxide of carbon can potentially enter produce a radiation-chemical response. We decided to use nitrogen as a main working fluid. Utilization of oxygen was also considered as it has the broadest interval of operation temperatures and best parameters on thermal complex.

The geometry of HPD is shown on Fig.2. A material of container of a heat pipe and trap is a stainless steel. A material of a grid forming artery and wick holding a working liquid in a trap in diode mode is nickel grid with an effective radius of pore equal to 20 microns. External diameters of a heat pipe and trap 8 and 19 mm, respectively. The transposition a pair is carried out on the steam channel a diameter of 6 mm. A hydraulic diameter of artery is 0,5 mm. Length of the liquid trap is 40 mm, zone of evaporation of a heat pipe is 40 mm long. Thus, general length of a heater zone (evaporator) of HPD equals to 80 mm. Length of a cooling zone (condenser) is also 80 mm. In the design of HPD implemented for MARS-96 project, nitrogen was used as a working liquid. Later, for another application developed within an INTAS project we manufactured similar HPDs, charged by oxygen, which on many parameters is the more perspective heat-carrier, than nitrogen.

For want of reversion of a heat flow a working liquid, being condensed in a liquid trap not have hydraulic connection with a wick of a heat pipe, the gradually is accumulated in it. The duration of this transient depends on a potency of a reverse stream and rate of its increase. As a rule, the evaporation-condensation cycle in some minutes is interrupted, the conductivity HPD sharply decreases on 2-3 order and begins to come nearer to conductivity of container. For deduction of a liquid phase of a working fluid in a trap the gofer nickel grid wick was used, is uniform located on an internal cylindrical surface. Volume of a wick was determined from a condition guaranteed accommodation of all liquid phase of a working fluid for upper significance of operation temperature 120 K in conditions as full-scale (g = 0), and ground improvement (g = 1). Capillary structures the traps and heat pipe had a hydraulic outcome.

CALCULATION

The development of HPD based on theoretical investigation that took into account such important performance parameters as strength of a construction and its components, heat transfer ability, thermal resistance and conductivity. The equations for an evaluation of heat transfer ability (1), thermal resistance and conductivity (2) of HPD, were based on published materials [5,6] and experience of our own development as indicated below. Heat transfer ability was evaluated under the theory of capillary limits for return of a liquid, as other factors (restriction on a sound limit, on ablation of a liquid, crisis of boiling) are of secondary importance.

$$Q_{max} = \frac{0{,}125\sigma_l L\cos\Theta(1/d_0 - 1/d_v)}{\nu_l(4l_{ef}/(\pi\cdot d_{ar}^4) + l_{efr}S_r/(l_c F_r d_r^2)) + \nu_v l_{ef}/(F_v d_v^2)} \tag{1}$$

The indicated formula (1) is not exact, as it does not take into account influence of excess of a working liquid and other effects, on the other hand, it is rather reliable for design application.

$$\sigma = 1/R_\Sigma, \qquad R_\Sigma = R_e + R_c\ ,$$
$$R_e = \ln(d_n/(d_0+2h_r))/(l_e(\pi-\varphi_b)\lambda_m) + h_r\sqrt{\sin\Theta tg(\alpha_r/2)/\lambda_l\lambda_m}/(l_e(\pi-\varphi_b)d_0),$$
$$R_c = \ln(d_n/(d_0+2h_r))/2\pi l_c\lambda_m + h_r\sqrt{\sin\Theta tg(\alpha_r/2)/\lambda_l\lambda_m}/l_c\pi d_0 \tag{2}$$

In the improvement process of the a construction special attention was given to optimization between an amount of a charged working fluid (nitrogen), start temperature of HPD, prevention of blocking of the condenser by a liquid phase for lower layer of operation temperature 90 K, and strength and rigidity of the HPD during its operation and storage. The operating conditions required start of heat pipes at the temperature of 120 K, i.e. in immediate proximity from a critical point of nitrogen (126,2K). There is a high value of density of a pair at indicated temperature. The optimum charge (for this temperature) can reduce in significant surplus of working fluid and blocking of condenser part at lowering of temperature up to 90K. For a successful resolution of this problem the initial ratio between steam and liquid volumes in HPD was changed by installation of special insertions in the steam channel of a pipe. As the result, HPDs demonstrated stable started from temperature 120-121 K, but it was necessary take into account that at 90 K approximately 40 % of length of the condenser is blocked by excess of the working liquid. It is especially important for the full-scale operating conditions (g = 0). To check performance of HPD under these conditions we conducted thermal tests with length of a heat removal zone of 40 mm (50 % from full-scale length of a heat rejection). Positive result was obtained. Other singularity of charge mass optimization became necessity of obtaining strength and tightness of HPDs required withstanding internal pressure of gas of the order 10-12 MPa in conditions of a long storage in room temperature.

TECHNOLOGY

Cryogenic HPD, intended for use in a long space mission, should have sufficient durability, high reliability and stability of working performance during all mission life. It can be achieved through the necessary level of development, and creation of appropriate technology. The most important technological problems solved in the course of creation of the HPDs are indicated below:

The original equipment for contact welding edge of a wick forming artery, with container of a heat pipe is developed.

The special tool for deriving a thread on an interior surface of a container is created.

The technique of purification of the working liquids up to cleanness 99,99% was developed.

The technique of charging of working liquids to within 0,02 was developed.

The technological processes for a pressure test of container, monitoring tightness of the equipped items, on radiographic monitoring, on modes of welding were implemented.

Thorough monitoring complemented each fabrication stage of HPD.

THERMO-VACUUM TESTS

HPDs were tested as in an autonomous mode and in the full thermal assembly of the device. In autonomous tests heat transfer-ability and thermal performances of HPD were determined for forward and reverse mode of a heat flow. The full assembly was tested in SRI (RAS) with maximum simulation of external conditions and real modes of operation. Both simulators and actual germanium detectors were used. Separately in SRI the full complex of mechanical tests for confirmation of strength of a construction for possible mechanical loads was conducted.

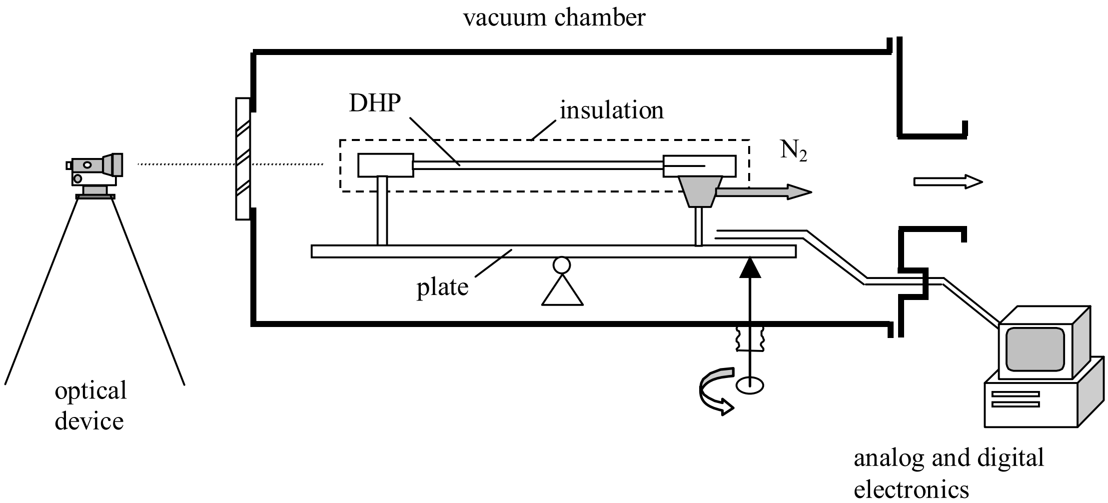

Fig.3. The experimental set-up

All thermal tests were conducted in thermal-vacuum chamber equipped with cryogenic screens, high-vacuum equipment, systems with high thermal resistance for fixing the items being tested, complexes of the instrumentation for data processing. For imitation of full-scale operation conditions, the HPDs were installed in a nearly horizontal position. The vacuum for the purpose want of the tests was maintained supported at the level 10^{-3} Pa. As temperature sensors cooper-copel thermocouple and thermoresistors were used. On Fig.3 the scheme of the test bed for autonomous tests of HPD is shown. The HPDs were placed on a rotary platform. The position of the HPD was inspected with the help of measuring device with an error no more than 0,2 mm before and after tests, and for closed chamber with the help of electronic level. All assembly was isolated by not less than 30 layers of MLI. The electrical power to heat input and output zones was applied by means resistor heaters. Temperature of the assembly was measured by cooper-copel thermocouples selected from a homogeneous set with a minimum scatter of the parameters. A temperature variation during the tests was registered with intervals from 1 up to 5 minutes with the help of multichannel ADC. The heat input zone, including the liquid trap, was incorporated within the detector simulator. Thermal capacity of the simulator was sometimes less, than that of real detector. This was allowed to decrease the duration of the tests without loss of sensitivity.

The test procedure involved the following milestones. After reaching the required vacuum the flow of liquid nitrogen through the heat exchanger was switched on, the zone of condensation of HPD was removed on a level of temperature 180 K and was fixed on it in limits ± 3K. The process of start-up

HPD (dynamic mode) from a supercritical condition and transition to the usual for a heat pipe isothermal mode was registered. After registration of the stationary condition the heater was switched on. In 30 minutes temperature of the heat removal zone increased up to 150 K, then the flow of liquid nitrogen was renewed (mode of a return stream). While HPD were conducting heat in normal operational mode we determined the heat transfer performance (the maximum transmission power). Transmitted power, both in a dynamic mode, and in reverse mode was determined through analysis of temperature variation rate of the items with known thermal capacity (simulator of the detector with connected zone of evaporation) using formula (3).

$$Q_i = [1{,}6*10^{-5}((T_{ai}+T_{ai+1})/2)^3-9{,}64*10^{-3}((T_{ai}+T_{ai+1})/2)^2+2{,}248(T_{ai}+T_{ai+1})/2-70{,}9](T_{ai+1}-T_{ai})/(\tau_{i+1}-\tau_i) \quad (3)$$

The term in brackets in the formula (3) represents approximate expression of a thermal capacity joined to the zone of evaporation. Correspondingly, conductivity of HPD was determined using formula (4).

$$\sigma_i = Q_i/((T_{ci}+T_{ci+1})/2-(T_{ai}+T_{ai+1})/2) \quad (4)$$

The above mentioned technique of tests represents only general scheme, which was repeatedly adjusted, changed and supplemented in the course of improvement of HPD.

EXPERIMENTAL DATA

The considered materials were accumulated over the period of four years. In particular, we present performance data for the stages of manufacturing and final improvement of HPD, for tests of full thermal assembly in SRI, for manufacturing oxygen HPDs, and also after two (nitrogen and oxygen) and four (nitrogen) years of storage of HPDs. Control samples of HPDs were made on spent technology, but were not including in structure of flight equipment.

A distinctive feature of the cryogenic heat pipes functionality was the necessity for their operation in non-stationary modes under high gradients of temperature between a source and sink of heat. This was especially important for start-up of HPD from supercritical conditions. During autonomous improvement of HPD the dynamics of cooling of the thermal accumulator (control mass attached to the evaporation zone) for simultaneous fixing of temperature of the heat sink at a level as 180 K was investigated, as was shown above, and for higher temperature down to 120K. The thermal conductivity nitrogen HPDs in a start-up mode proved to be weakly dependent on temperatures of a heat source and sink. In the temperature range most interesting for simulation (T_c = 150 … 125 K) the conductivity grows with lowering of temperature on the average of 0,03 - 0,06 W/K. With further cooling a sharp increase associated with the final filling of the wick structure and formation of a stable working cycle of a heat pipe begins.

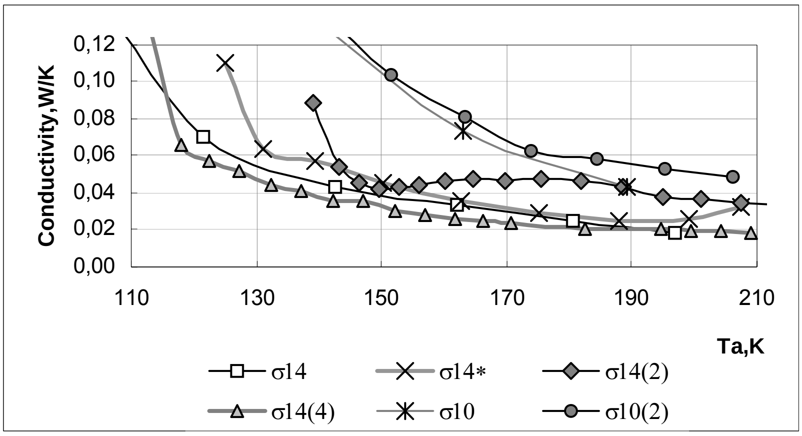

Fig.4. Thermal conductivity of HPD (supercritical startup)

In Fig.4 are shown to dependence of conductivity on temperature of a heat input zone (T_a): at the time of manufacturing at the sink temperature T_c = 90K (σ14); T_c = 120K (σ14*), two years after manufacturing σ14(2) and after four years of a storage σ14(4) for nitrogen HPD #14. The conductivity of oxygen HPD #10 at the time of manufacturing and after two years of storage is also shown. It is possible to note, that the conductivity of the oxygen HPD is approximately twice as high, than that of the nitrogen HPD and the moment of its startup is observed at higher temperature. The power transmitted partially drained, unisothermal HPDs make significance from 1 up to 3 W. In accordance with cooling the transmitted power drops, as HPDs come to a stationary condition, for want of which the transferable potency is determined only by level external heat to assembly.

The reverse mode of heat flow is divided into two stages: the transient regime, for which HPD changes its properties, and a purely diode mode. For transient regime, when the temperature of a condenser zone begins to exceed the temperature of the evaporation zone, HPD continues to function for some time (usually for a few minutes) in a mode of a drained heat pipe, and only after all working liquid is accumulated in the trap the diode mode develops. In Fig.5 a typical evolution of the source T_a and the sink T_c (HPD #14) temperatures for reverse mode is presented for the time of fabrication and after four years of storage. In the latter case the diagram of the process is saturated at the temperature of T_c = 145 $^{+5}$ K. It is easy to see, that the dynamics of reverse mode practically did not change after four years.

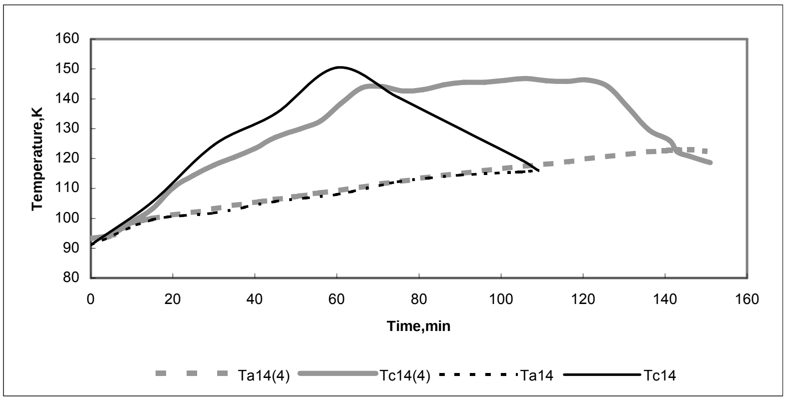

Fig.5. The reverse heat flow mode of nitrogen HPD

The significance of conductivity of nitrogen (#14) and oxygen (#10) HPDs in the developed diode mode is shown in Fig.6.

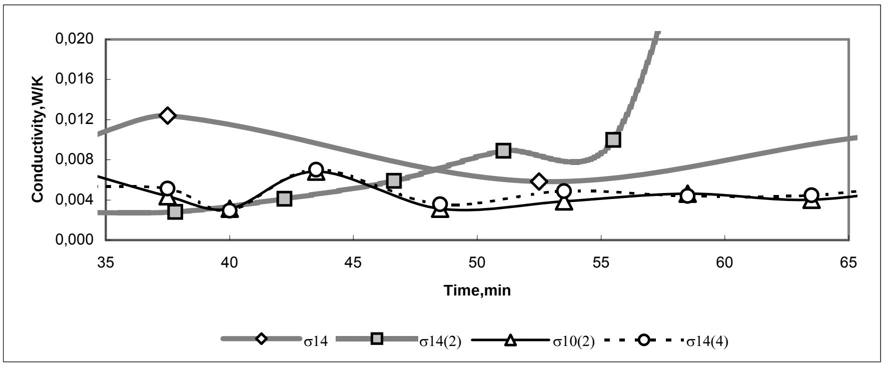

Fig.6. Thermal conductivity by reverse mode

Significant scatter conductivity between 0,003 and 0,012 W/K is caused by influence of external heat to the assembly for preliminary tests. The following tests were performed in a chamber enclosed by a continuous black nitrogen screen, in the other cases less effective imitation of deep space was used. For of simulation of thermal regimes it is possible to assume that the HPD conductivity in reverse mode is about 0,005 W/K.

Theoretical conductivity of nitrogen and oxygen HPDs in usual operational mode in the entire temperature lies in the range of 1,3-1,5 W/K. Experimentally obtained value of conductivity lies within the limits of 1,1-1,4 W/K. The difference might be to explained by influence of excess the working liquid in the condenser zone and difficulty of taking into account the magnitude of contact thermal resistance in heat input and output zones. Generally, the derived diode ratio K_d for the HPDs under investigation is not less than 100, which is typical for this type of diodes. The maximum heat flow for nitrogen HPD did not exceed 3 W, while that for the oxygen HPD - 4W, for operation temperatures in the range of 90-100 K.

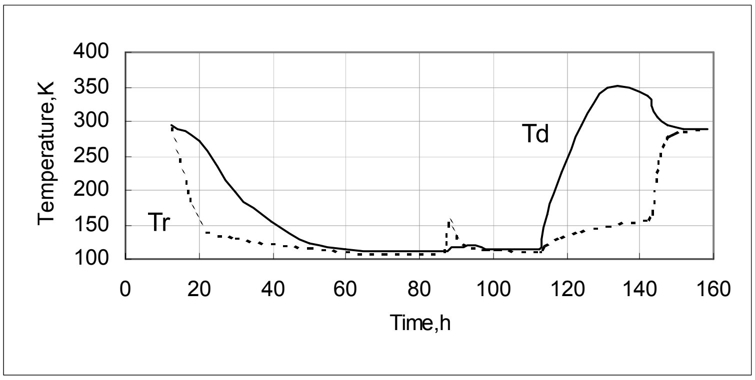

Fig.7. Assembly temperature plots: detector (Td) and radiator (Tr)

The basic results of the tests of the thermal assembly are presented in Fig.7. The data obtained in the conditions closely resembling the real flight, demonstrate that the HPDs performances were adequate in all modes of operation [7]. The temperature of the detectors while the DHPs operated in reverse mode never exceeded 119K. Simulation of the mode detector annealing was also successful.

CONCLUSIONS

1. Cryogenic HPDs with nitrogen as the heat-carrier were developed which were capable to operate at temperatures below 120-121 K. The HPDs had a range of conductivity from 1,4 W/K for forward mode of a heat flow down to 0,003 W/K for reverse mode of heat flow. HPDs had undergone all cycle of improvement and tests and completely satisfied all requirements of the project “MARS-96”.
2. Oxygen HPD with overall dimensions identical to the nitrogen HPD, and having broader range of operation temperatures and higher transmitting performances for forward mode of a heat flow were designed and manufactured.
3. The possibility of a storage and reproduction of thermal tests results after four years of storage from the moment of manufacturing was demonstrated for the nitrogen HPDs. Similar confirmation was obtained after two years for the oxygen HPDs.

Acknowledgment

The present work was executed under the contract with SRI (RAS) in a part of creation nitrogen HPD for the project "MARS-96" and under project INTAS 96-2269 in part of creation oxygen HPD.

Nomenclature

Q_{max} – maximum heat transfer rate, σ_l – liquid surface tension, σ - thermal conductivity, L – latent heat of evaporation, θ - liquid / vapor contact angle, ν_l and ν_v – kinematic viscosities of liquid and vapor, λ_l and λ_m – thermal conductivity of liquid and material of HPD body, R – thermal resistance, T – temperature, τ - time, d_0 – diameter of the artery holes in heat input zone, d_v – diameter of vapor channel, l_{ef} – effective length of heat pipe, d_{ar} – hydraulic diameter of the artery, l_{efr} – effective length of the threaded groove, l_e and l_c – length of the evaporation and condensation zones, d_n – outer diameter of the heat pipe body, d_r – hydraulic diameter of the threaded groove, h_r – thread height, α_r – thread profile angle, φ_b – half-opening angle of the segmental artery wick, S_r – thread step, F_v and F_r – cross-sectional area of the vapor channel and threaded groove.

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