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NEW APROACH TO THE PASSIVE THERMAL CONTROL SYSTEM WITH LOW-TEMPERATURE "AL-NH_3" HEAT PIPES: QUALIFICATION TESTING RESULTS AND FLIGHT PERFORMANCE ON MICROSATELLITE BIRD

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ANNOTATION

An important question of exploitation of near-Earth space environment investigation satellites is the support of a thermal regime of satellite as a whole and devices in particular. Guarantee of their reliable working in space depends on thermocontrol system (TCS) operation that is confirmed by qualification working-off ground tests both with heat pipes separately and when they are a part of satellite TCS. The program of qualification tests and its realization is considered in this paper. The typical modelling object is an ammonia aluminium grooved heat pipe (shell diameter of 12 mm, 30 grooves) developed for DLR's BIRD small satellite program. Qualification tests consist of thermal steady-state and non-stationary performance tests, long life tests, environmental tests and others reviewed in the paper. Tests of determination of thermal resistance, maximum heat transfer rate, influence of tilt on maximum heat transfer rate are related to determination of thermal technical characteristics of heat pipes. Start-up tests, in which an ability of heat pipe to continue the function normally after certain power surge is determined, tests on definition of priming time, in which the priming time of heat pipe capillary structure after its full drainage by method of direct discharging and continuing the power supply is defined, are related to non-stationary tests. During the long life tests an ability of heat pipe to function for a long time is checked and quantity of noncondensable gas generated is defined. Test program was realized on test facilities of the National Technical University of Ukraine "Kyiv Polytechnic Institute" (Kyiv, Ukraine) and Institute of Structural Mechanics (Berlin, Germany). The analysis of heat pipe operation during qualification test and flight performance of BIRD satellite is shortly reviewed on the base of telemetric information.

INTRODUCTION

Heat pipes efficiency for space thermal engineering is widely recognized and illustrated [1, 2] and numerous up-to-date literature. Among majority of heat transfer tasks the heat pipe employment for high precision optical devices thermal control is interesting and challenging. The main heat pipe functions are associated with a) heat transfer tasks in the wide temperature range 90…300 K; b) heat redistribution inside/outside of system; c) providing of isothermality of device mounting place (seats); d) regulation of temperature in selected device or group of devices without electrical power consumption.

Most heat pipe applications in space thermal technology are associated with large space structure (such as geostationary satellites) where they execute the heat transfer between radiation panels, periodically illuminated by sun light [3]. Exploitation of the heat pipes in microsatellite design is very limited due to the problems of their implementation inside very compact satellite structure, the lack of theoretical and experimental baseground of their usefulness, sometimes, due to possibility to solve the thermal tasks by traditional thermal control means but enlarging the mass and power consumption. Therefore novelty of this work is to describe the positive features of heat pipe application in microsatellites thermal control, qualification testing (which is inalienable part of practical implementation) and to analyze the thermal performance of the whole system during its space exploitation.

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The description of BIRD project, originated by German Aerospace Center in Berlin (DLR) and micro satellite features are reviewed in [4]. The spacecraft bus design is based on the circular sun synchronous orbit 573 km and the payload requirements to observe required areas of Earth. The concept of the satellite bus meets the requirements with the satellite dimensions of about 550 x 610 x 620 mm3 and a total mass of approximently 94 kg (Fig. 1) in order to lauch it as piggy-back payload.

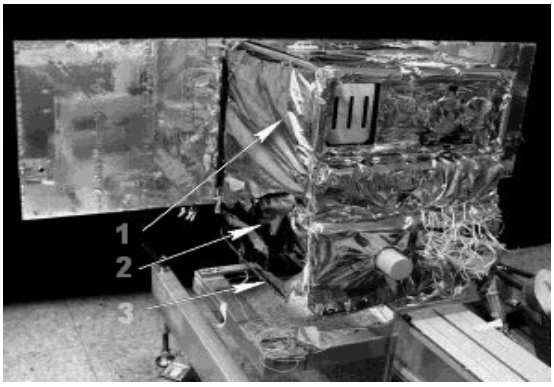

Fig.1 BIRD satellite during thermal vacuum test on facilities of Institute of Structural Mechanics, Berlin, Germany. Courtesy of DLR

Satellite structure was based on segment hierarchy. Payload instruments are located in payload segment 1 (Fig.1). The scientific payload is a novel multi-spectral sensor system, consisting of two new developed, cooled infrared sensor arrays operating at 8.5…9.3 μm and 3.4…4.2 μm wavelength, working at temperature level of -193 and -168 oC, correspondently, and Wide Angle Optoelectronic Stereo Scanner (WAOSS), operating at the temperature of 20 oC. Electronic and housekeeping segments (2) are combined together and are the base for main radiator plane (3).

Heat pipe assignment in thermal design of BIRD microsatellite program [4] is presented as the illustration of heat pipe implementation in design of Payload mounting plate with sizes of 0.5 x 0.5 m for group of payload optical devices. They require dimension stability of optical systems inside the temperature range of –20…+50 oC and should be supported inside of this temperature range without mechanical distortion of optical axes. Therefore thermal control system concept is based on the following thermal features: heat pipe effective heat conductance is essentially less than solid material heat conductivity (a), ability of heat transfer in both directions (b), montage flexibility of thermal line, connecting two main heat generated compartments without stress, caused by temperature variation.

THERMAL CONTROL SYSTEM CONCEPT AND HARDWARE

BIRD TCS was planned to be passive by using merely the dissipated heat of all components of the spacecraft housekeeping systems and payloads to support the whole system on required temperature level by sizing the radiative surfaces. The structure of the satellite is an essential part of the TCS.

The TCS for the Infrered (IR) Payload Complex has been designed as an autonomous one, because the thermal requirements to the IR channels differ greatly from the requirements to other payload and bus system. Two Stirling Coolers are used for the cooling of the IR-sensors; their operating heat losses are radiated to free space via a separate complex of heat storage, heat transfer system and their own radiators.

The BIRD TCS is based on usage of the follwing thermal control elements:

- MLI cover for protection of inner satellite content against external light disturbances, coming from the Sun and the Earth;
- sized radiators (main and additional) with selective optical coating to illuminate the heat generated by equipment on appropriate temperature level;
- two heat pipes, which thermally connect the service segment and the payload segment in order to solve the problem of heat transfer between two thermally insulated units.

Proposed thermal design is based on the following basis. Among up-to-date tendencies to minimize the thermal deformation of assembly of two segments (payload and housekeeping) the use of interface elements with low temperature expansion coefficient is required. Typically such materials have low conductivity that leads to the high thermal resistance between payload segment (PS) and and service segment (SS) $R_{PS\text{-}SS}$ = 10…20 K/W that produces large temperature difference between them. Heat pipes with much smaller thermal resistance and montage flexibility allows minimizing the temperature difference between segments to value less than 10 oC (fig.2), providing

flexible mechanical connection between them.

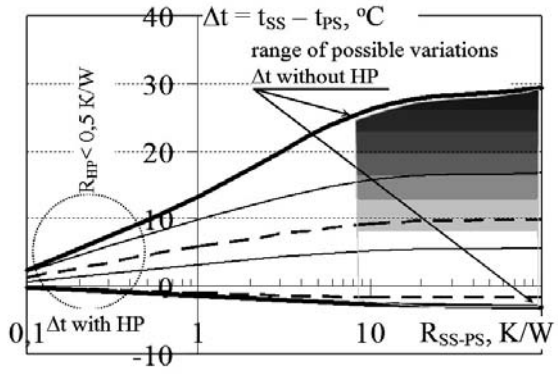

Fig.2 Predicted temperature difference between satellite segments as function of thermal resistance

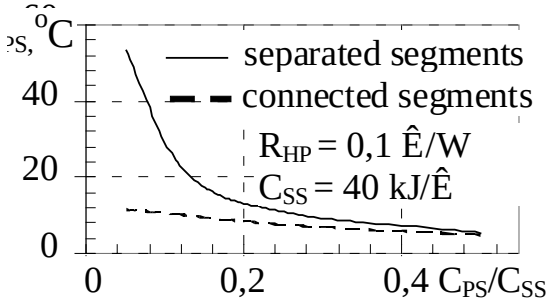

Fig.3 Predicted temperature variation of payload satellite segment (ΔtPS) as the function of its thermal capacity in the case of periodical power generation of payload instruments and constant power generation of devices in service segment

Another reason of heat pipe application is assosiated with the possibility to increase the thermal capacity of the satellite main radiator by thermally connecting segments one to another. At higher thermal mass the impact of periodically acting inner power generation and external heat fluxs on main radiator produces less temperature variation in comparison with segments having separated radiation surfaces (fig.3).

The technical requirements to parallelism of optical axes of payload optical instruments (fig.4) and to geometric location of focal planes have initiated the selection of payload baseplate design as the assembly of two carbon fiber layer (7) aramid honeycomb structures (3, 6) with embedded between them 3 mm layer of Carbon-Fibre-Carbon (2), having low coefficient of thermal expansion and thermal conductivity of 155 W/mK.

It fulfils the functions of heat transfer line between payload instruments (seats, 4, 5) and heat pipe flanges (1), which are attached to opposite sides of payload platform. Further the heat energy is transported by heat pipes to the main radiator, located in service segment area.

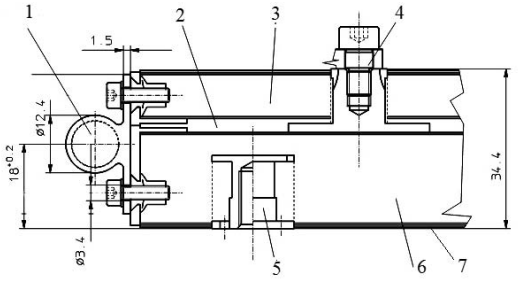

Fig.4 Unit of heat pipe thermal junction with payload carbon fiber platform with carbon fiber honeycomb structure. Courtesy of DLR

Heat transfer can be realised in both directions that prevents overcooling of payload instruments in non-operating mode. Such approach enlarges thermal mass of main radiator, which smoothes the change of the radiator temperature due to variation of external heat fluxes (solar, Earth Albedo and Earth IR), including shadow phase and due to power generation of payload.

FOR THERMAL TASKS SOLUTION HEAT PIPES QUALIFICATION AND ACCEPTANCE TESTS

In BIRD Project the heat pipe type with the following parameters has been selected. Heat pipe shell is the round extruded profile made of aluminium alloy with one integral flange. Flanged zones correspond only to evaporation zone (325 x 30 x 1.2 mm) and condensation zone (285 x 30 x 1.2 mm). Other characteristics are presented in table 1 and 2. Two heat pipes are used in satellite design.

The programs of the acceptance and qualification tests are elaborated mainly according to ESA requirements [5]. The heat pipe test programs elaborated by authors for VEGA Project (1984-86), Phobos Project (1986-87), and Mars – 96 have been applied as well. The following main tests have been foreseen: (a) inspection and physical measurements; (b) proof

pressure test - leak test; (c) performance testing; (d) burst test; (e) random vibration; (f) storage simulation test; (g) thermal cycles/shock test; (h) aging test (long life test).

Table 1. Main parameters of heat pipes for BIRD Project

Shell diameter, m	0.0122
Wall thickness, m	0.001
Length of evaporator, m	0.325
Length of transport zone, m	0.344
Length of condenser, m	0.285
Effective length	0.649
Bending radius	0.048
Shell protection	polishing
Capillary structure:	axial grooves
- groove depth, mm:	1
- width in opening, mm	0.5
- width in bottom, mm	0.45
Quantity of axial grooves	30
Vapour core diameter, m	0.008
Heat carrier	ammonia
Exploitation temperature, °C	-50...+50
Thermal resistance, K/W	less than 0.07
Transported heat, W·m	not less than 60
Rated heat transfer, W	60
Long-life tests, hours	32000
Flange material	aluminium alloy
Mass, kg	less than 0.23

Among performance tests are the following:

- definition of thermal resistance of heat pipes
- definition of maximum heat transfer ability
- definition of temperature distribution along the heat pipe length
- definition of priming time of heat pipe after the full dry-out of an evaporation zone
- definition of heat pipe capability to start-up with 80% of maximum heat transport capacity at various vapour temperatures.

In these tests the thermal technical characteristics of heat pipes in the wide range of input heat fluxes (from 5 to 170 W) and constant vapor temperature (tv) have been checked. Vapor temperature was supported stable at the levels: -50°C, -20°C, 0°C, +20°C, +30°C, +50°C independently of input heat power. At the vapor temperatures –50°C and -20°C the tests were carried out in a vacuum chamber with a nitrogen cooler. For tv = 0…+50°C the tests have been conducted in air medium with force liquid cooling of condenser zone.

Figure 5 illustrate the heat pipe generalised performance within exploitation temperature range, namely shows the thermal resistance variation R_{hp} as function of vapor temperature at power of 90 W (FM-01 – FM-04, QM-05, QM-08 – marks of heat pipes). With rising of temperature the resistance is slightly decreased that deals with reducing of noncondensable gas influence and intensification of heat exchange processes. For heat pipes of one manufacture series experimental dependencies R_{hp} = f(Q) have the similar behaviour, and the dispersion of Rhp for the same value of power transferred is no more than 0.01 K/W. Such behaviour and the values dispersion are observed at the boundary temperatures –50ºC and +50ºC as well.

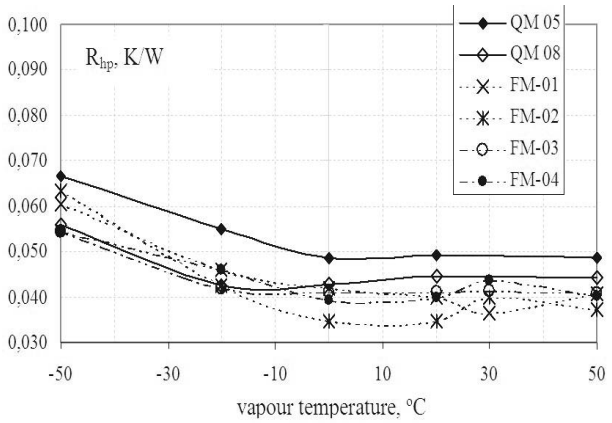

Fig.5 Thermal resistance of heat pipes Rhp as function of saturation vapor temperature at transferred power of 90 W

Definition of maximum heat transport rate of HP (Qmax) is realised by two techniques recommended in [5] and [6]. Function $Q_{max} \cdot L_{eff}$ (W·m) = $-2{,}95 \cdot 10^{-3} \cdot T_v^2 + 1{,}873 \cdot T_v - 212{,}4$, where $L_{eff} = 0{,}5 \cdot (L_н + L_{кон}) + L_{тр}$,- effective length of heat pipe, T_v – saturated vapour temperature in K, has summarized the experimental data with deviation ±10 % for 8 tested heat pipes. Character of this curve corresponds with data [1]. More details on thermal performance of this heat pipes type are in [1, 7].

In order to provide the operation of heat pipes in thermal vacuum tests together with satellite (thermal model, engineering model, flight model) the satellite body was positioned in a vacuum chamber so that the plane of heat pipe bending was located in nearly horizontal position, and maximal deviation of two any points in this plane do not exceed 15 mm.

THERMAL OPERATION OF THE THERMAL CONTROL SYSTEM

After successful launch on the 22nd October 2001 with Indian PSLV (Polar Satellite Launch Vehicle, Shar Center, India), the first operation of BIRD thermal control system flight performance was evaluated in [7]. TCS worked as was predicted during satellite separation from sspacecraft and further - in stabilised phase. The variation of temperature non-isothermally over payload platform (difference between the maximum and minimum temperature on the platform) is inside of ±2 K. The temperature difference between the radiator and payload platform is inside of -2…+4 K, that corresponds to predicted (Fig.6). Payload platform has had the similar oscillatory character as radiator that corresponds with ground tests and analytical predictions.

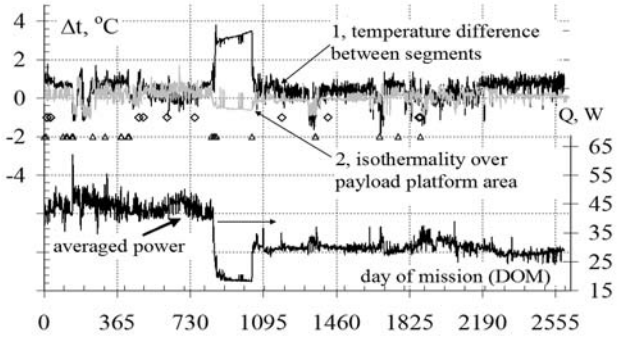

Fig.6 Temperature difference between segments (1) and temperature nonumiformity in payload platform (2) during processed period of satellite flight operation

Table 2 has summarized the obtained in flight experiments temperatures of major satellite units. All the instruments temperatures were inside of the design limits, used for payload and housekeeping equipment elaboration.

Table 2. Temperature variation of satellite equipment

Description of unit or electronic box	t_{min}/t_{max}, °C	
	Design limits	Obtained
Otpical box of infrared camera	-15/15	-9,9/ 9,0
Electronic box of infrared camera	-40/45	-2,0/ 44,4
Optical camera WAOSS	-15/30	-10,1/ 26,1
Platform for payload	-20/30	-2,7/ 24,1
Star sensors 1, 2	-25/30	-6,9/ 30,0
System of information processing SBC_A, SBC_B	-15/40	11,0/ 38,5
Board computers 1,2	-20/60	-2,5/ 37,1
Transmitters 1, 2	-20/60	-3,4/ 44,8
Main radiator	-15/35	-2,6/ 27,2
Electiral accumulators	-10/25	-0,6/ 30,0
Side solar panel +X	-120/100	-94,7/ 76,1
Side solar panel -X	-120/100	-96,0/ 73,4
Central solar panel -Z	-120/100	-78,1/ 88,9

CONCLUSIONS

During the period of 2001-2011 y.y. of space exploitation of microsatellite BIRD the thermal control system has hold their design characteristics in near-Earth orbit space conditions.

- The passive principle of thermal control system is applicable for low-Earth sun synchronous orbits. It was based on creation of centralized heat transfer system, in which the most of componenets are thermally attached to the main radiator and have similar to radiator temperatrure
- For the first time in space practice two axially grooved aluminium heat pipes have been used in microsatellite thermal design for heat transfer on distance about 0.5 m between two compartments of satellite.
- Elaborated heat pipe and another elements of thermal control system have proved their characteristics in ground tests and at long life space exploitantion
- First in Ukraine the qualification testing of axial grooved heat pipes with ammonia for space application was conducted according to the European standard of quality of heat pipes ESA PSS – 49 (TST - 01) "Heat pipe qualification requirements", 1983. The methodologies of thermophysical research of heat pipes became the foundation for creation of theoretical base and stand equipment at implementation of this standard.

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