HEAT PIPE RADIATIVE COOLING SYSTEMS FOR SPACE OPTICAL SENSORS

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ABSTRACT

The temperature level of 190…250 K is attractive for infrared sensors and other types of optical light receivers. To reach it on small satellite the radiative systems are proposed as alternative of active cooling. Having thermally connected radiator and sensor by heat pipe one can put the both units in the most appropriate location on the satellite. Heat pipe application in passive radiative cooling system is considered on the base of an analysis of thermal balance of consecutive thermal elements in the system „sensor - heat pipe – radiator - space". Critical points to reach the low temperature are heat leakage from mounting place and heat exchange with external surroundings. Enhanced way to avoid the negative influence of the external light fluxes – the most important constituent - is to use a set of radiators opposite oriented and thermally coupled by heat pipe. The prediction of system performance for missions in Earth vicinity and for the mission to Venus has shown a realizability of such design for radiator with reasonable sizes. The illustrations of technical implementation of proposed radiative systems are presented.

1. INTRODUCTION

Required temperature level of sensitive elements of optoelectronic devices, which are widely used on Earth observation and in IR technology, depends on material used, type of optical sensor, necessary signal-to-noise ratio and makes 190…260 K or less [1, 2, 3, 4, 5]. Own heat generation in sensitive element is small enough (tens-hundreds milliwatts), however design of receiver head has to foresee special measures for reducing of heat leakage from mounting place, having temperature 250...323 K. Typical design of receiver heads, having CCD (charge couple device) with sizes 15 x 11 mm, are characterized by additional heat inputs from mounting place in the range of 0,3…1 W in vacuum [1]. This value will dramatically rise with enlarging the receiver size, especially when CCD arrays are used. The temperature level of 190...260 K can be reached in the space by using thermoelectric coolers, radiation cooling system and their combination. The boundary conditions for heat sink play the key role at choice of cooling principle.

In presented report some design conceptions of thermal control system (TCS) on heat pipes for space light receivers are considered. Systems have been designed and manufactured in the National technical university of Ukraine "Kyiv Polytechnic Institute" (Ukraine) in cooperation with the Institute of Space Research of Russian Academy of Sciences (Moscow, Russia) for several International space projects.

2. THE BASIC PRINCIPLES OF RADIATIVE COOLING SYSTEM CONCEPTION

There are two main approaches of thermocontrol system (TCS) design for space sensor cooling (figure 1, a,b). The first one deals with the use of thermoelectric cooler. The light sensor or receiver head has perfect thermal contact with cold junction of the thermoelectric cooler, which ensures the required temperature level. Hot junction has connection with heat sink like as mounting places of spacecraft (SC), radiator or liquid cooling line.

Heat leakage Q_{mp} and heat released in matrix Q_d are input to thermoelectric cooler (they are its cooling productivity). Heat rejection from hot junction Q_{TB} is more than heat input $Q_{mp}+Q_d$ in 4…15 times. This heat has to be rejected by additional cooling system to mounting place or to radiator. The temperature of hot junction is on the level of 270…360 K. The temperature T_{MP} is typically within 250…323 K.

Radiative TCS uses the low temperature of environment as a heat sink and is passive (figure 1, b). Heat energy $Q_{mp}+Q_d$ is removed by heat conductor of any type with the thermal resistance R_c towards low temperature radiator(s) and is scattered to the space. In this scheme the most difficulty is to achieve the temperature of radiator(s) 180…250 K taking into account the external light disturbances (solar flux, planet fluxes, reflection from surrounding equipment) and heat leakage to radiator via mechanical supports and multy-layer insulation (MLI).

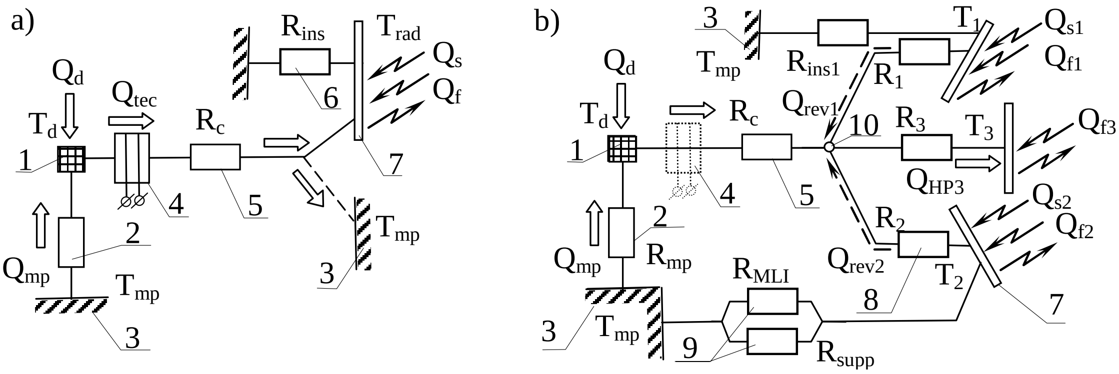
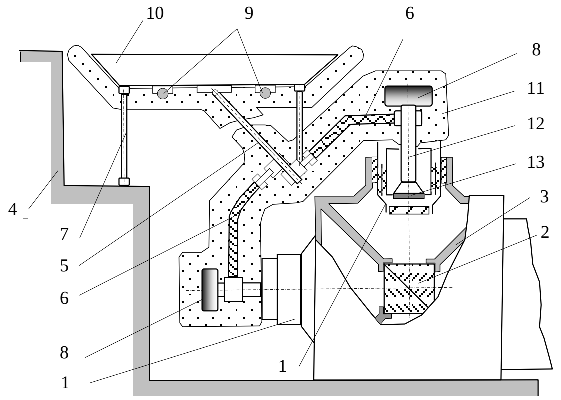


Figure 1. Thermal scheme of active TCS with thermoelectric cooler (a) and passive radiative TCS (b). 1 - device to be cooled; 2 - thermal resistance "mounting place-device"; 3 - mounting places (temperature T_{MP}); 4 - thermoelectric cooler, 5 – resistance of heat conductive line; 6 – resistance R_{ins} "radiator - mounting place"; 7 - radiators (temperature T_{rad},T_1, T_2, T_3); 8 - resistance $R_{1,2,3}$ between united point and radiator; 9 - components of resistance R_{ins}: R_{supp} and R_{MLI}; 10 - united point; Q_s and Q_f - sum of absorbed fluxes for Sun spectrum and IR range

Minimization of mass and overall sizes requires reduction of the thermal resistance of conducting line (one of variant is the use of heat pipe with resistance R_c less than 0,1…1 K/W), to decrease all contact resistances, to improve efficiency of radiator by optimizing radiator thickness, thermophysical properties and optical parameters of coating, to limit the external fluxes to radiator. Mechanical connection of receiver head with heat transfer line has to be flexible in order to provide the adjustment of optical axis and to avoid the excessive mechanical loads.

The typical specimen of passive radiative system is illustrated by design [1, 6], figure 2. TCS serves two CCD heads. Heat leak from mounting place to CCD heads is collected by flexible heat conductors 7, then it is transferred to heat pipe 5 and, finally, the heat is radiated to the space. TCS was designed to operate not less than 30 min in conditions of Sun light incident. The compensation of heat inputs to radiator is realized by enlarging of radiator mass and by use of melting type heat accumulators 9 (three units, mass 0,08 kg each, melting temperature 239 K), placed on the radiator, and accumulator 8 (one unit for CCD head, 0,01 kg, melting temperature 257 K), allocated on cold “finger” 12.



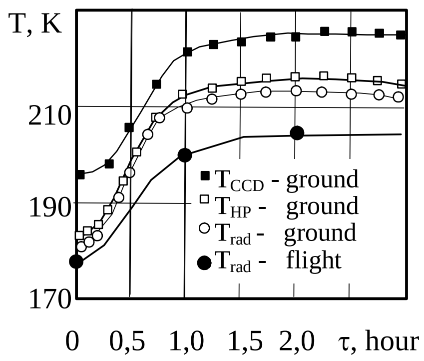


Figure 2. Scheme of cooling system: 1 – CCD heads; 2, 3, 4 – elements of optical system; 5 - heat pipe; 6 - flexible heat conductors; 7 - low conducting support; 8 – first stage melting heat accumulator; 9 – second stage melting heat accumulator; 10 - radiator; 11 - MLI; 12 – cold “finger” of CCD head; 13 – CCD in focal plate

Figure 3. Thermal behavior of system in vicinity of Venus orbit. Flight telemetric radiator temperature for regime K-4 for SC “VEGA-1” [1] is being compared with ground thermal vacuum test. T_{CCD}, T_{HP}, T_{rad}- temperatures of CCD, connection flexible line and heat pipe, radiator

Discussed TCS operate only for a limited time if the radiator is illuminated by Sun. Before an operation starts the radiator should be cooled down. In the cases if spacecraft (SC) should have the freedom in an orientation with respect to the Sun, and the receiver should be in constant readiness, the considered principle of TCS design meets the curtain difficulties in realization and a new approach should be elaborated.

3. TCS WITH REDUCED SENSIVITY TO EXTERNAL HEAT FLUXES

The major restriction of passive radiative systems to achieve temperature level of 190 ~ 210 K is the effect of heat fluxes Q_s and Q_f , which may cause the radiator temperature rise. This limitation could be estimated by the next radiator heat balance equation:

$$Q_d + Q_{mp} + \frac{T_{mp} - T_{rad}}{R_{supp}(F_{rad})} + \frac{T_{mp} - T_{rad}}{R_{MLI}(T_{rad}, F_{rad})} + Q_s(\tau) + Q_f(\tau) \le C_{rad}\frac{dT_{rad}}{d\tau} + \varepsilon F_{rad}\eta\sigma(T_{rad}^4 - T_o^4)\,,$$

where T_{rad} - feasible radiator temperature, R_{supp}, R_{MLI} - thermal resistance of mechanical supports and MLI package, insulating the radiator, C_{rad}, ε, F_{rad},. η - heat capacity, IR emittance, radiating area and radiator thermal efficiency. The most important value, defining T_{rad} in the most cases, is Q_s. One of components of Q_s - direct Sun illumination has the main priority.

The TCS, having several radiators variously oriented relative to the Sun and having thermal interconnection between radiators, is one of the promising technical solution to overcome the restriction of direct solar illumination. In this design one of radiators will always reside in favorable conditions (in shadow) and provide heat removal and demanded temperature level as well (figure 4).

An analysis of such TCS with 2-3 radiators [7] has shown that such approach is effective at solar constant up to 2700 W/m^2. The operation of the given system reaches the highest efficiency, if element, which thermally joints CCD and the radiator, has diode type thermal resistance, depending on direction of heat flux. This property is intrinsic to the heat pipe, named as thermal diode [8, 9], which has essential thermal resistance in reversal regime, when heat is transferred from hot (exposed on the Sun) radiator to a cold receiver head and low resistance - in direct regime. System will operate if Sun changes its position with respect to radiator in the opposite direction. Figure 5 defines the required radiator area for proposed principle of system operation. The tests with thermal mock-up of TCS confirms these theoretical approaches and possibility to reach the temperature level of 220 K by passive way.

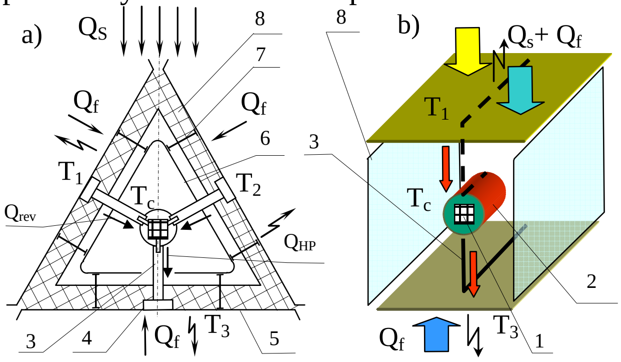


Figure 4. Design of passive multy-radiators cooling system: a) three joined radiators, b) two joined radiators. 1 - light receiver (CCD); 2- positioner and thermal joint point; 3 - heat pipe – thermal diode; 4 – heat pipe attachment to radiator; 5 – radiator; 6 – inner support structure; 7 – low thermal conductance supports; 8 – MLI blankets

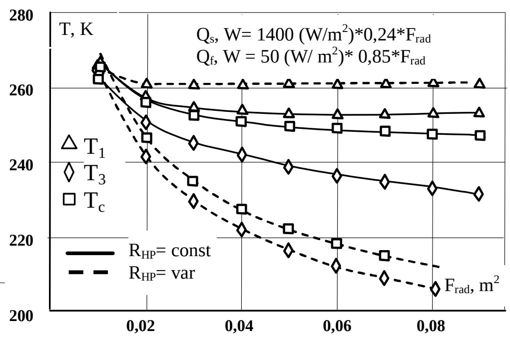


Figure 5. Required radiator area for 3-radiators system on near-Earth orbit with values Q_{mp}+ $Q_d \approx$ 2W. Solid lines - heat pipes constant resistance, R_{HP}=const = R_1 = R_2 = R_3 = 2 K/W in direct and reverse mode, dashed - variable resistance 2 K/W in direct and 100 K/W in reverse mode (R_{HP}=var)

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