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AUTONOMOUS HEAT PIPE THERMAL CONTROL SYSTEMS FOR CCD COOLING OF SPACE SCIENTIFIC EQUIPMENT

Baturkin V.
Heat Pipe Laboratory, National Technical University of Ukraine "KPI", Kyiv, Ukraine &
Department of System Conditioning, Institute of Space Systems, Bremen, Germany
Pr. Peremogy, 37, 03056, Kyiv, Ukraine
Robert-Hooke-Str. 7, 28359 Bremen, Germany
Phone: +49421 – 2442011610, fax: +49421 244201120, email: baturkinvm@mail.ru

ABSTRACT

The approach of heat pipes' implementation into passive radiative cooling system is considered for optical sensors (CCD), operating on the temperature level of 180…240 K in unsteady regime. Heat pipes have shown themselves as effective heat transfer element used for heat moving from sensor to radiator on distance up to 0.5 m and as heat redistribution element, being integrated into low temperature radiator. In order to avoid the negative influence of the external heat fluxes the system design with a set of thermally coupled radiators, interconnected with heat pipes (conventional and thermodiodes) is proposed. This design allows to keep the low temperature level of CCD at spacecraft maneuvers and to widen the operation range of solar constant.

KEY WORDS: sensor, passive, cooling, thermal control, heat pipe

1. INTRODUCTION

Required temperature level of sensitive elements of optoelectronic devices, which are widely used at the Earth observation and in IR astronomy, depends on type of optical sensor, acceptable signal-to-noise ratio and makes 80…260 K. Own heat generation in sensitive element is small enough (tens-hundreds milliwatts – watts), however heat leakage to sensor from mounting place, having the temperature within 253...323 K, could be one order more.

At the space exploitation of sensors the temperature level of 80...260 K can be reached by thermoelectric coolers (partly), radiation systems, systems with expendable substances and others ways (Donabedian et al. (2004)). The boundary conditions for heat sink, power consumption and operation duration play the key role at choice of cooling principle.

Design of sensor module, having CCD (charge couple device), for example, with sizes of 15 x 11 mm is characterized by additional heat inputs from mounting place in the range of 0.3…1 W in vacuum at 240 K (Avanesov et al. (1989)). This value rises with enlarging the CCD array size. For passive radiative system one of important parameter is the distance between CCD module and radiator, which defines the length of heat transfer, mass and dimension of transfer line (figure 1). Heat pipe (HP) is the promising candidate for this task (Gilmore et al. (2002)).

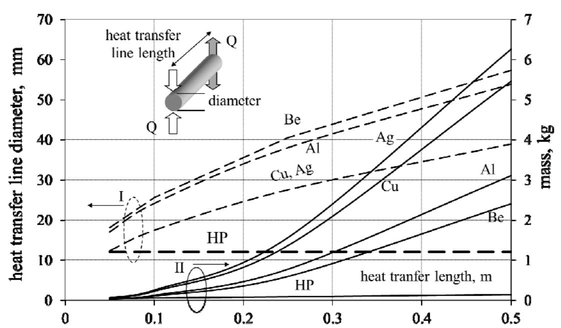

Figure 1. Comparison of mass and diameter of heat transfer line at fixed thermal resistance of 1K/W (configuration - rod) made of solids (Ag, Al, Be, Cu) and axial grooved heat pipe on temperature level of 183 K. Group I corresponds to external diameter of rod, group II – to mass.

2. THE BASIC PRINCIPLES OF RADIATIVE COOLING SYSTEM WITH HEAT PIPES

There are the following possible approaches to thermal control system (TCS) design for CCD cooling. The first one (active) deals with the use of thermoelectric cooler. The sensor or sensor module 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 device mounting places on 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 higher than heat input (Q_{mp} + Q_d) in 4…15 times. This heat has to be rejected by additional cooling system to mounting place, where device is installed, or to radiator. The temperature of hot junction is on the level of 270…360 K. Heat pipe could transfer the heat from sensor to thermoelectric cooler or from thermoelectric cooler to radiator.

Radiative TCS uses the low temperature of environment as a heat sink and is passive (figure 2). Heat energy (Q_{mp} + Q_d) is removed from CCD by heat conductors of any type with the thermal resistance R_c, R_1, R_2, R_3 towards low temperature radiator (or radiators) and is scattered to the space. In this scheme the main 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 nearby devices) and heat leakage to radiator via mechanical stands-off (st) and multilayer insulation (MLI).

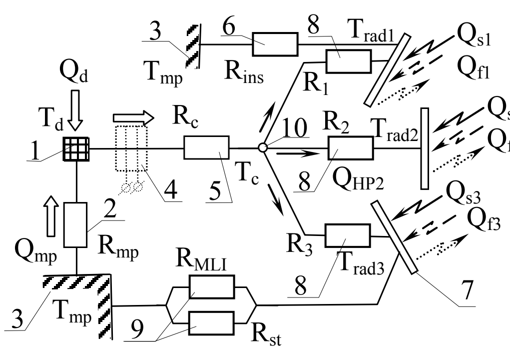

Figure 2. Thermal scheme of passive radiative TCS: 1 – CCD or device to be cooled; 2 – thermal resistance "mounting place – device"; 3 – mounting places; 4 – thermoelectric cooler (optional), 5 – resistance of heat conductor; 6 – resistance R_{ins} "radiator – mounting place"; 7 – radiators (temperatures T_{rad1}, T_{rad2}, T_{rad3}); 8 – resistances R_1, R_2, R_3 between central point and dedicated radiator(s); 9 – components of resistance R_{ins}: R_{st} and R_{MLI}; 10 – central point; Q_s, Q_f – absorbed by radiator heat fluxes in Sun spectrum and IR range. 1-3 radiators could be considered.

Minimization of TCS mass and its overall sizes requires the reduction of the thermal resistance of all conducting lines (one of variant is the use of heat pipe with resistance less than 0.1…1 K/W), decrease of all contact resistances, increase of radiator efficiency by optimizing its thickness, to optimize thermal scheme, to enhance the optical coating parameters, and to limit the external fluxes to radiator. Mechanical connection of CCD 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 with heat pipe was presented by Semena et al. (1986). TCS serves two CCD modules, functioning in parallel. Heat leak to every module from mounting place is collected by flexible cooper conductor, then it is transferred to heat pipe (external diameter 8 mm, stainless steel shell/metal fiber wick/refrigerant R22) and, finally, the heat is radiated into the space. TCS was designed to operate not less than 30 min in conditions of Sun light illumination. The compensation of heat inputs to radiator is realized by increasing the radiator mass and by use of melting type heat accumulators (3 units, mass 0.08 kg each, melting temperature 239 K). Figure 3 presents the operation function of such system (Avanesov et al. (1989)).

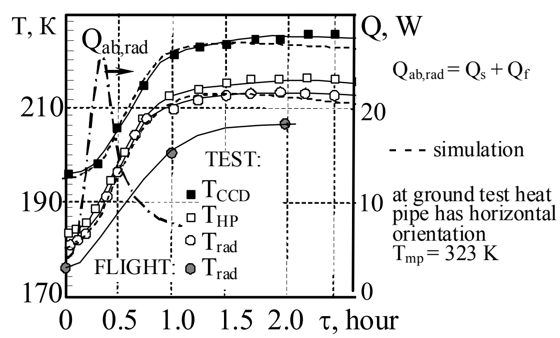

Figure 3. Thermal behavior of system in vicinity of Venus orbit. Flight telemetric radiator temperature for regime K-4 for spacecraft "VEGA-1" is being compared with ground thermal vacuum test. T_{CCD}, T_{rad}, T_{HP} – temperatures of CCD, radiator, connection of flexible with heat pipe.

Research of TCS with four CCDs modules, attached to one radiator (figure 4), has shown that without heat pipe, which re-distributes the heat over the radiator surface, not uniformity of places, where the flexible elements are attached, could reach 14 K (Baturkin et al. (1988)).

At integration of heat pipe (external diameter 10 mm, stainless steel shell/metal fiber wick capillary structure/refrigerant R22) into radiator design this difference is reduced by 3.5 K at heat load of 1.5 W per CCD module.

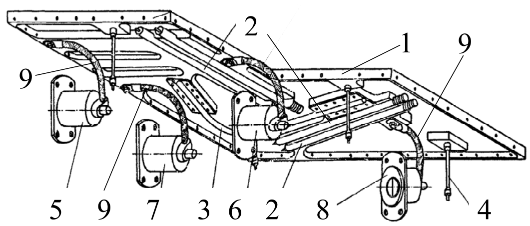

Figure 4. TCS with HP for four CCDs (figure by Dr. Kostenko V.): 1 – radiator (0.3 x 0.3 x 0.01 m); 2 – heat accumulators; 3 – HP; 4 – stands-off; 5, 6, 7, 8 – CCD modules; 9 – flexible transfer lines.

Choice of heat capacity and reducing the temperature non uniformity by embedded heat pipe allows to keep its temperature in steady and unsteady conditions, which occur at illumination of radiator by the Sun (angle of incidence of sunbeams φ_s). For this regime it was shown an ability to keep the radiator temperature $T_{rad} < 223$ K during 11 hours of TCS functioning at Phobos scanning by videospectrometric complex (figure 5).

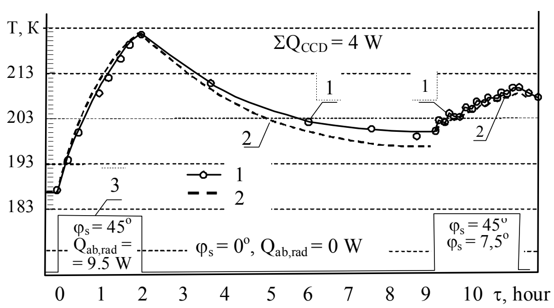

Figure 5. Average radiator temperature of TCS with 4 CCDs in regime, simulated movement of spacecraft near Phobos and approach with the surface: 1 – experimental data; 2 – simulation; 3 – profile of flux, absorbed by radiator $Q_{ab,rad} = f(\tau)$.

HPs in TCSs have bent configuration, the metal fiber wick with stepwise porosity change in evaporator, transport and condenser zones in order to reduce the total thermal resistance, saving heat transfer ability. Refrigerant R22 was selected due to its low melting temperature (113 K), possibility to operate in wide temperature range (170…300 K) and its compatibility with stainless steel, long life stability against factors of space and successful space qualification (Alekseev et al. (2006)).

In ground thermal vacuum tests of the assembly "TCS + device" and "device together with spacecraft", there is the obligatory requirement to provide heat pipe operation against gravity forces where heat has to be lifted up to $\Delta h = 250$ mm. Due to insufficient value of surface tension and heat of evaporation the refrigerants could not operate because of hydrodynamic crisis (figure 6). For such tests the subsidiary heat pipes with ammonia have been designed, having the same thermal resistance.

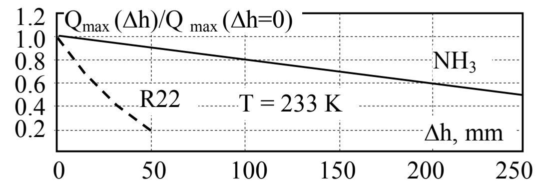

Figure 6. Comparison of maximal heat transfer ability of heat pipe with refrigerant R22 and ammonia NH_3 at different tilts against gravity.

Considered TCS operates only for a limited time, if the radiator is illuminated with the Sun. Before an operation starts the radiator should be cooled down. In the cases, if spacecraft should have the freedom in an orientation relative to the Sun, and the sensor should be in constant readiness for a long time, the considered principle of TCS design meets the evident difficulties in realization and a new approach should be elaborated.

3. CONCEPTION OF TCS WITH REDUCED SENSITIVITY TO EXTERNAL HEAT FLUXES

The major restriction of passive radiative systems to achieve the temperature level of 180…250 K is the effect of heat fluxes Q_s and Q_f, which cause the radiator temperature rise, and increasing of radiator sizes does not keep its required temperature. This limitation could be estimated by the following heat balance equation for the radiator:

$$Q_d + Q_{mp}(T_{CCD}, T_{mp}) + \frac{T_{mp} - T_{rad}}{R_{st}(F_{rad})} + \frac{T_{mp} - T_{rad}}{R_{MLI}(T_{rad}, F_{rad})} +$$

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

where T_{rad} – feasible radiator temperature; R_{st}, R_{MLI} – thermal resistances of mechanical stands-off and MLI package, insulating the radiator; C_{rad}, ε, F_{rad}, η – heat capacity, IR emittance, area and thermal efficiency of radiator, correspondently; σ – Boltzmann constant. The most important magnitude, defining T_{rad} in the majority cases, is Q_s. particular the direct Sun illumination.

The TCS, having several radiators, variously oriented relative to the Sun, and having thermal interconnection between radiators, is one of the promising technical solutions to overcome the restriction of direct solar illumination. In this design one of radiators will always reside in favorable conditions (in shadow), provide heat removal and keep the demanded temperature level as well (figure 7).

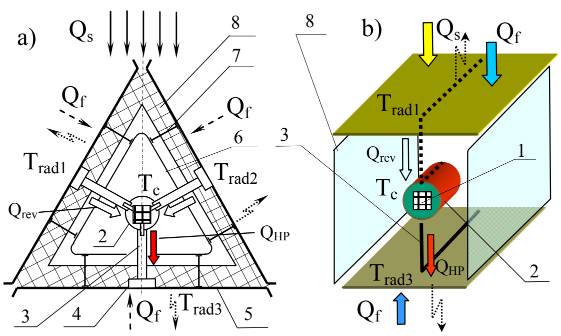

Figure 7. Design of passive multi-radiators' cooling system: a) with three radiators; b) with two radiators: 1 – CCD module; 2 – positioner and central point; 3 – heat pipe – thermal diode (TD); 4 – heat pipe attachment to radiator; 5 – radiator; 6 – inner support structure; 7 – stands-off; 8 – MLI blankets.

An analysis of such TCS with 2-3 radiators (curve R_{HP} = const, figure 8) has shown that such approach is more effective as compared with one radiator system. But to obtain essential reducing of CCD temperature, element which thermally joints CCD and the radiator, has diode type thermal resistance, depending on direction of heat flux (curve R_{HP} = var).

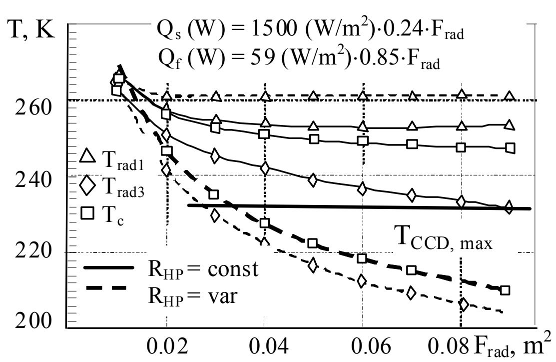

Figure 8. Required radiator area for three-radiators' system on near-Earth orbit at Q_{mp}+ Q_d = 2W. Solid lines – heat pipes of constant resistance, R_{HP} = const = R1 = R2 = R3 = 2 K/W in direct and reverse mode, dashed – variable resistance heat pipe with 2 K/W in direct mode and 100 K/W in reverse mode (R_{HP} = var).

This property is intrinsic to the heat pipe, named as thermal diode (Groll et al. (1978), Williams et al. (1978)), which has essential thermal resistance in reverse mode, when heat is transferred from hot (exposed on the Sun) radiator to a cold central point, and low resistance – in direct mode. The system will operate if the Sun changes its position relative to radiators, one of them should be in shadow.

The temperature of optical sensor could be less than 233 K at external heat fluxes in the range of 500…2700 W/m^2 that corresponds to the operation in vicinity of Mars, Earth and Venus (figure 9).

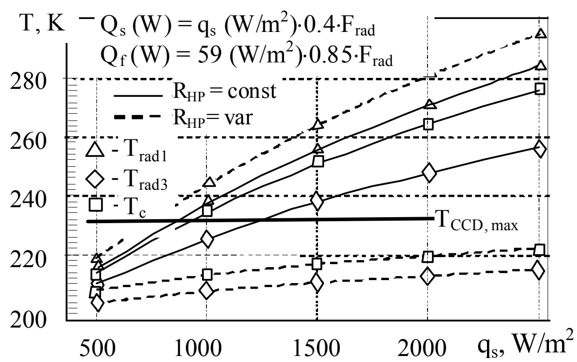

Figure 9. Achieved sensor temperatures for orbits of Mars, Earth, Venus for three-radiators' system with heat generation Q_{mp}+ Q_d = 2W. Solid lines are related to the heat pipes of constant resistance, R_{HP} = const = R_1 = R_2 = R_3 = 2 K/W in direct and reverse mode, dashed – to the variable resistance heat pipes with 2 K/W in direct mode and 100 K/W in reverse mode (R_{HP} = var).

One can find that the system, operating with thermal diodes could provide much low temperature of central point T_c as compared with constant resistance heat pipe system in considered range of external heat fluxes. For example, for Venus orbit these temperatures are 223 K and 275 K, correspondently.

4. VERIFICATION OF PROPOSED CONCEPTION OF MULTI-RADIATORS TCS

The theoretic approach has been proved on the thermal mock-up of star tracker TCS with two radiators (figure 10). In this system the heat generated by optical element, and heat leak are removed by constant conductance heat pipe to central point and then by two thermal diodes towards the radiators. The heat pipe system seats on the device cabinet, using low conductance stands-off. The radiators and heat pipe are protected from external fluxes by MLI.

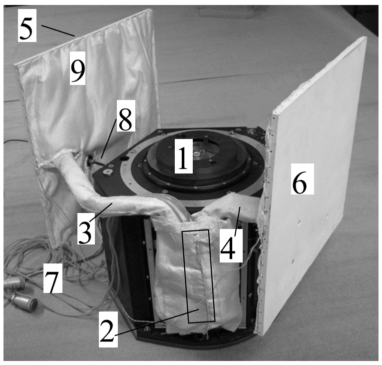

Figure 10. Design of passive two-radiators' cooling system: 1 – cabinet for sensor (CCD); 2 – central point and contact with constant conductance heat pipe; 3, 4, – thermal diodes; 5, 6 – radiators 1 and 2; 7 – harness; 8 – low thermal conductance stands-off; 9 – MLI blankets.

Thermal diode design uses the principle of liquid trap located in the evaporation zone (placed in central point). Material of heat pipe shell – stainless steel 12X18H9T, capillary structure – metal sintered fibers made of the same stainless steel, heat carrier refrigerant R22 (figure 11). Thermal diode shell was made of tube OD 10 mm and is bent in two planes according to the geometric requirements to be adapted to the device configuration.

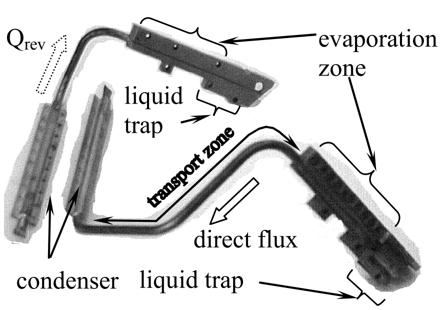

Figure 11. View of thermal diodes for two heat conductive lines.

The experimentally defined thermal resistance R_{rev} and heat flux Q_{rev} in reverse direction of heat transfer are given on figure 12. In initial moment the TD runs as conventional heat pipe with the changeable heat-carrier mass. After accumulation of the major quantity of working liquid in liquid trap the complete drying of the radiator zone and adiabatic zone occurs and heat transferred in this direction is decreased essentially.

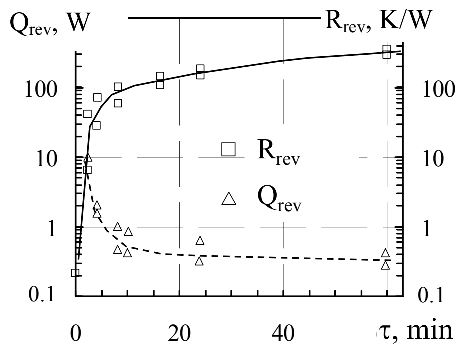

Figure 12. Summarizing of the heat flux (Q_{rev}) and thermal resistance of TD (R_{rev}) in reverse mode.

For chosen conditions the computation displays that thermal diode resistance grows up to the values of 100 K/W in the first 10 minutes that well agrees with experiment. Analyzing the common operation of two thermodiodes as components of thermal control system, it should be noted that when the system changes the orientation of radiator relative to the Sun, there is the time period, when one TD begins to close, and the second one yet is closed, because this radiator has not been cooled less than the temperature of the central point (figure 13, zone I).

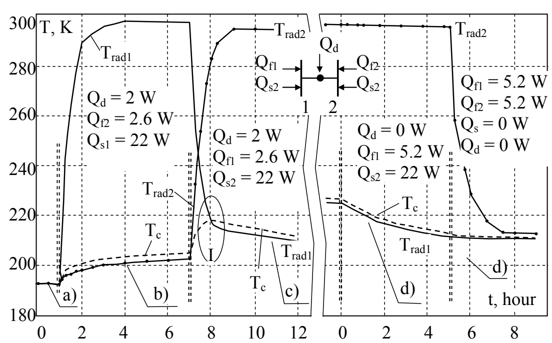

Figure 13 Experimental study of two-radiators' system with thermal diodes, functioning in regimes without sun flux (a, d) and with illumination of one of the radiators (b, c): $F_{rad} = 0.052\ m^2$, emittance $\varepsilon = 0.85$, solar absorptance $\alpha_s = 0.24$, I – zone of $dT_c/d\tau > 0$.

The system ensures the temperature level of 190...210 K for major regimes of optical sensor operation associated with the orientation changing: a) without solar illumination; b) direct solar rays hit on radiator 1; c) changing of the object orientation, and solar rays hit on the radiator 2; d) system is in non-working condition.

At stepwise change of radiator orientation relative to the Sun the derivative $dT_c/d\tau > 0$ for the temperature of central point (thermal joint of TD) T_c for zone I. This is explained by absence of heat output from this point for a short period of time as $T_c < T_{rad1}$ and $T_c < T_{rad2}$. After reaching the condition $T_c > T_{rad1}$ + (2…4 K) value $dT_c/d\tau < 0$. The simulation of this transfer regime at different heat capacity of central point C_c/C_{rad} has shown (figure 14) that the minimization of $\Delta T_c = T_{c(point\ B)} - T_{c(point\ A)}$ takes place at reducing the radiator heat capacity C_{rad} and increase in heat capacity of central point C_c, but to avoid absolutely this effect is imposible. The value of ΔT_c is within 4…20 K.

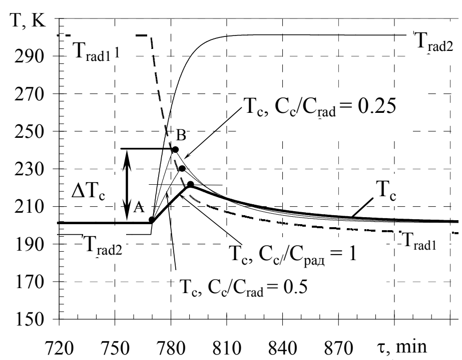

Figure 14. Dynamics of TCS at different heat capacity ratios C_c/C_{rad} = 0.25…1.

3. CONCLUSIONS

Principles of passive radiative thermal control system design with heat pipes for optical-electronic devices are proposed.

The tasks, which could be decided by the implementation of heat pipes into space thermal control radiative systems are the following:
- heat transfer from a device to a radiator with low thermal resistance;
- equalization of the radiator temperature field for its higher thermal effectiveness;
- providing of similar temperature level for several attached CCD modules;
- organization of directional heat fluxes in multi-radiators' systems by heat pipes – thermal diodes and reducing the thermal control system sensitivity to external light disturbances.

The heat pipes made of stainless steel metal felt wicks and refrigerant R22 are designed for operation in the temperature range of 180…300 K. The heat pipes with ammonia as heat carrier have been used in ground tests of scientific equipment on the system level when heat has to be lifted against gravity forces.

ACKNOWLEDGEMENT

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