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Passive Thermal Control Systems on Heat Pipes for Space Application and Terrestrial Technology

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ABSTRACT

The basic properties of heat pipes, loop heat pipes, thermal diodes and variable conductance heat pipes, which are intended for passive thermal control system design, are stated briefly. Among them there are thermal resistance as the function of power transferred and the sink temperature, heat flux input density, orientation relative to gravity, size limitations, montage flexibility, and complexity of fabrication.

The technical problems of the heat pipe implementation in autonomous cooling and thermostabilisation systems for electronic equipment of non-hermetic non-piloted satellites for near-earth orbits are considered:

- choice of the thermocontrol system design;
- simulation of heat transfer in the system;
- results of thermal tests and flight experiments.

Main attention is devoted to description of the following modifications of thermocontrol systems with heat pipes:

- systems for cooling of separate elements of electronic equipment (e.g., thermal receivers, high-power transistors and microcircuits);
- systems for cooling of device case surfaces (such as cold wall of device, cases of gyroscopic devices);
- systems integrated in the electronic block array (cooled electronic boards - heat pipes, isothermal substrates for microelectronics);
- systems for providing the isothermal mounting faces for the devices installed (e.g., honeycomb panels, all metal surfaces with heat pipes).

For systems being considered the main parameters of the estimation are presented in steady and non-steady regimes with utilisation of worked out programs for the heat pipe computation, for the computation of a device or block as a whole.

Experimental data are presented for real systems, and these data are obtained both in conditions of ground testing in vacuum chambers, and, partially, from the results of direct telemetric control.

The part of this lecture is devoted to consideration of the passive thermal control systems on heat pipes for energy saving, solar power engineering, electronics and PC cooling, technological processes. In energy saving technology as examples the gas/gas heat pipe heat exchangers are considered, in the solar power engineering – dish solar receivers on heat pipes, in electronics cooling – heat pipes for cooling of power components and PC microprocessors, in technology - isothermal plates, capsules, soldering tools.

The lecture consists of the following parts, which illustrate the typical heat pipe passive system application in considered areas, namely:

- ♦ Part 1. Passive Thermal Control Heat Pipe Systems for Space Electronic Components
  - ❑ 1.1. Passive Thermal Control Systems with Usage of Solar Energy for Operation
- ♦ Part 2. Systems for Providing of Isothermal Mounting Faces for the Devices Installed
  - ❑ 2.1. Thermal Stable Structures with Heat Pipe Usage
- ♦ Part 3. Low Temperature Heat Pipe Systems for Optical Sensors Cooling
- ♦ Part 4. Terrestrial Application of Passive Heat System
  - ❑ Solar Concentrating Program
  - ❑ PC Cooling
  - ❑ Welding, Soldering
  - ❑ Heat Exchanging Equipment.

The presented material can not cover all possible areas of heat pipe application in each topic, they are extremely wide, nevertheless, it gives the introduction into technical details, originating during the thermocontrol system elaboration.

INTRODUCTION

Systems utilising the heat pipes have shown themselves as reliable constructions for thermal control of elements and blocks of space technique and in terrestrial applications. These systems have remarkable advantages in comparison with the other thermal control systems. Existing long experience of heat pipe use has shown [1 - 4] workability of these systems in conditions of space exploitation and sufficient variety of their application:
from microelectronics cooling to providing the thermal stability of large dimensional space telescopes, hermetic flange connections or spacecraft containers. Gas filled heat pipes usage for thermal control of space radio electronics and computer blocks represent important enough directions of investigations and application because of essential technical parameters' dependence on exploitation conditions. Reducing of range of working temperature oscillations of electronic components and obtaining of optimum temperature level as well give opportunity to decrease in costs of electronic components.

The simplified thermal scheme of passive thermal control system with heat pipes is presented on figure 1.

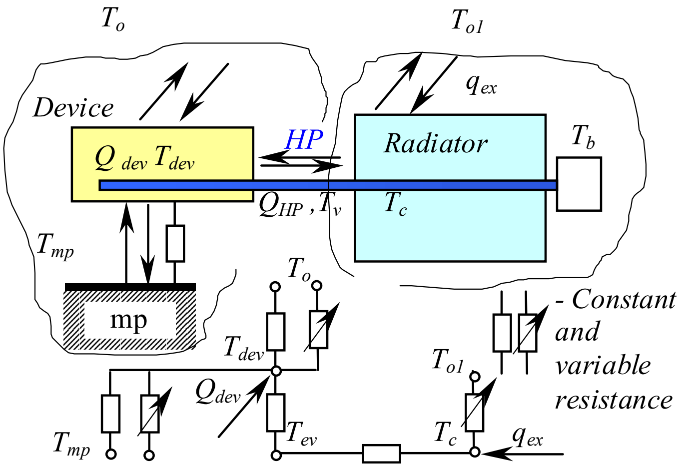


Figure 1. Thermal scheme of passive thermal control system:
Device (dev) - object to be thermally regulated; HP- heat pipe; Radiator- heat rejecting part of heat pipe, *o* , *o*1- surroundings ; mp –mounting place; ev – evaporator part of heat pipe; v- vapour core of heat pipe; c – heat pipe condenser; b- reservoir with gas or liquid; T- temperature; Q- heat power, W; q – heat flux, W/m^2; arrows –directions of heat exchange

The main tasks solved by the systems on the base of constant conductance (CC) and variable conductance heat pipes (VCHP), thermal diodes (TD), and loop heat pipes (LHP) are:

- gathering of heat energy generated by devices Q_{dev};
- providing of isothermal surface with temperature T_{ev} for devices mounting;
- heat energy transport toward surroundings or from surroundings to some distance (0.1 ÷ 2 m);
- heat rejection into surroundings with temperature $T_{01}(\tau)$;
- be an element of mechanical attachment;
- carrying out of organisation of thermal control function at :

- heat generation oscillation in device $O_{dev}(\tau)$;
- variable heat exchange between mounting places (temperature T_{mp}) and environment T_o;
- temperature oscillations of surroundings T_{o1} and external heat disturbances q_{ex};
- compensation of thermal balance at changing of thermal contact resistance, changing of optical properties of coats and so on.

The following thermal heat pipe properties are important for passive thermal control system synthesis:

- Operating temperature range
- Heat load range (minimal and maximal power and heat flux density)
- Transport length, gravity head to be overcome (or heat transport ability)
- Thermal resistance (conductance) of HP and interfaces

- Physical requirements (range of tube diameters or width x thickness, flexibility during assembly, minimal and maximal storage temperature, stability heat pipe characteristics and so on).

Typical temperature exploitation diagram for widely used heat carriers: ammonium NH_3, refrigerant–11 CCl_3F, acetone $(CH_3)_2CO$, methanol CH_3OH, ethanol C_2H_5OH, water H_20, thermex, sodium Na is presented on figure I-1. The comparison of heat transport ability (figure of Merit N or Liquid transport factor = surface tension · heat of vaporisation/liquid kinematics viscosity) as function of temperature for these heat carries is presented in figure I-2. The higher value of factor *N* produces higher transport ability of heat pipe under the condition of same type of capillary structure. The maximal heat ability of heat pipes is defined by type of capillary structure as well. Among them most used structure are: axial grooves , mesh screens, sintered fibres and powders, open annulus. The comparative summary of typical parameters such as capillary size (maximal wicking height) and permeability are presented in figure I-3 (according to Heat Pipe Design Handbook, by P. Brennen and E. Kroliczek, B&K Engineering, Inc, 1979). Typically structure with large effective radii such as grooves, mesh screens have higher permeability and can transfer higher heat fluxes at small tilts (a few mm – 50 mm), at lager tilts – more than 0.1 m, only fine-pore powders and porous materials can operate.

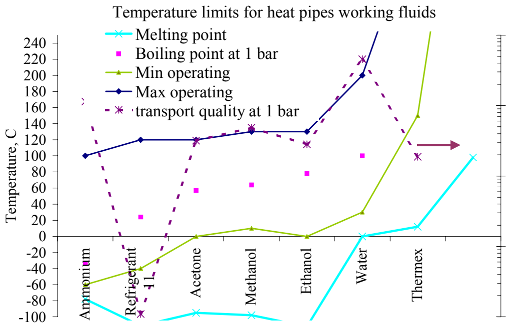


Figure I-1. Temperature exploitation limits

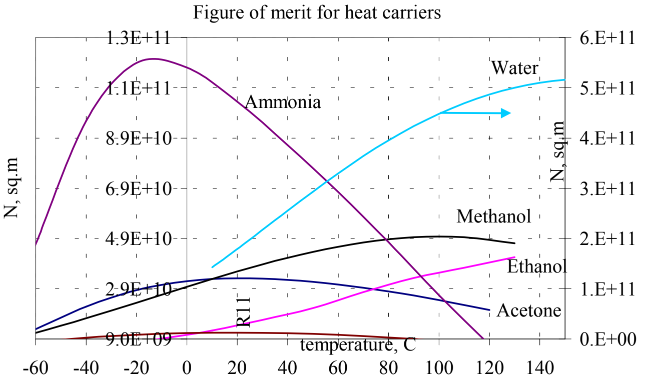


Figure I-2. Transport quality of working fluids

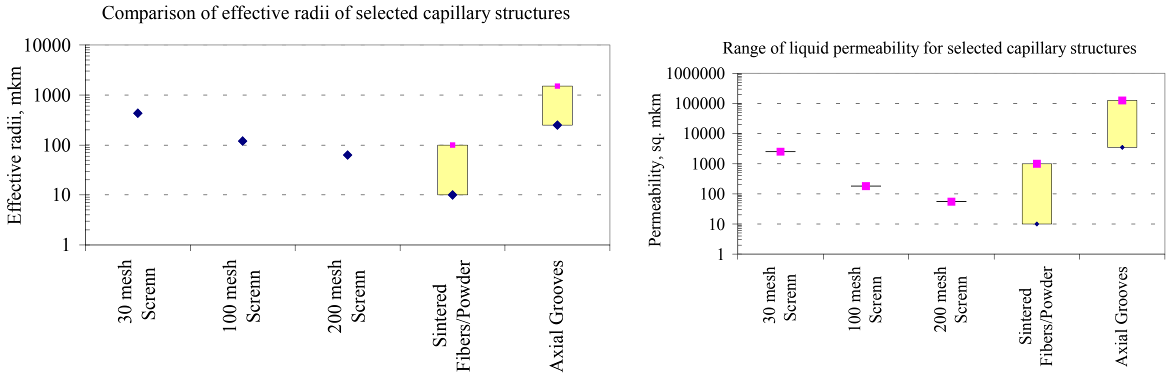


Figure I-3. Structural parameters of selected wick designs

The typical productivity of heat pipe by a diameter of 12 mm at 1 m transport length with ammonia at zero tilt makes 50 W for metal felt wick, 150 W - for axially grooved wicks. The potential heat productivity of the heat pipes should be more than in 1.2-2 times in comparison with estimated heat flux transported through them in the whole temperature range. The special heat pipes such as loop heat pipes and capillary pump loops have higher productivity. LHPs additionally are less sensitive to the tilt.

Operating characteristic $T_{ev} = f(Q, T_{sink})$ takes into account the values of inner heat transfer in evaporator and condenser zone and conductance between heat pipe and sink. Sometimes the heat pipe resistance as function of heat flux and vapour temperature $R_{hp} = f(Q, T_v)$ is useful. For constant conductance heat pipe the resistance of heat pipe changes slightly in the whole temperature range (figure I-4) and is independent from direction of flux. For rough estimation: 1m heat exchange length of tube of 12 mm diameter has resistance 0.03 K/W (1 sq. m of HP heat exchange surface has resistance less than 0.001 K/W). For VCHP and LHP the thermal resistance is evident function of heat flux transferred and changes more than in 10 times. Last heat pipe designs and TDs have additional useful properties as a sharp rise of thermal resistance at reverse flux (from condenser to evaporator).

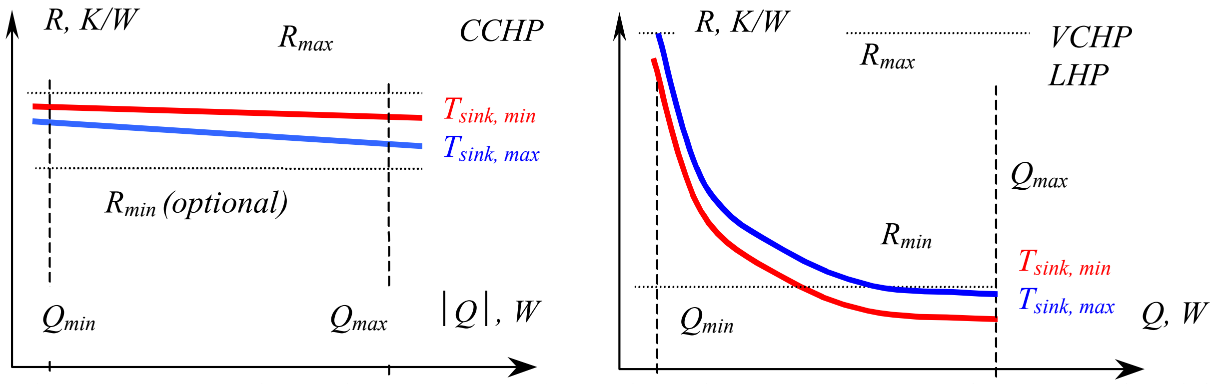


Figure I-4. Heat pipe resistance as function of heat flux for constant conductance and variable conductance heat pipes

These basic properties seem to be very important and useful for design of passive thermal control system. The variable conductance (resistance) can be applied for design of passive temperature regulators, and diode properties for - heat switches. Below presented parts of lecture illustrates the practical implementation of these properties for realisation of passive thermal control.

Part 1. Passive Thermal Control Heat Pipe Systems for Space Electronic Components

References:

- V. Baturkin et al. Autonomous Heat Pipe Systems for Electronic Components Thermostatting at Near-Earth Orbit Exploitation. Proc. of the 24th ICES, Friedrichshafen, Germany, 1994, rep. No.941302
- V. Baturkin et al. Passive Thermostatting System with Application of Gas-Filled Heat Pipes and Thermal Energy of Solar Radiation. Proc. of the 4th ESSECS, 1991, Florence, Italy; ESA, 1991, vol.2, p.769-774.

The integration of HP, VCHP into passive thermal control system for space electronic foresees the solution of the following task: joined design of heat pipe and electronic unit, thermal design of heat pipe, additional elements of thermal schemes such as insulation, heat conductive lines to provide the positive thermal balance of system – quantity of generated and incoming heat is enough to compensate the all types of heat leak. The good thermal coupling of the system to mounting place or to surroundings will produce a dominant influence of these boundary temperatures, and effect of thermal control system operation can be lost.

The conceptions of different extent of VCHP integration into electronic equipment have been shown in the literature:

a) heat pipes operate along with one single part or element of electronic block;

b) heat pipes provide thermal stability of an electronic block surface ;

c) heat pipes are construction elements of electronic plates;

d) heat pipes act as isothermal casing of electronic block.

Conditionally, above mentioned constructive conceptions are shown on figure 2 a, b, c, d.

Using each schemes is defined by concrete exploitation conditions and requires, usually, essential primarily analyze.

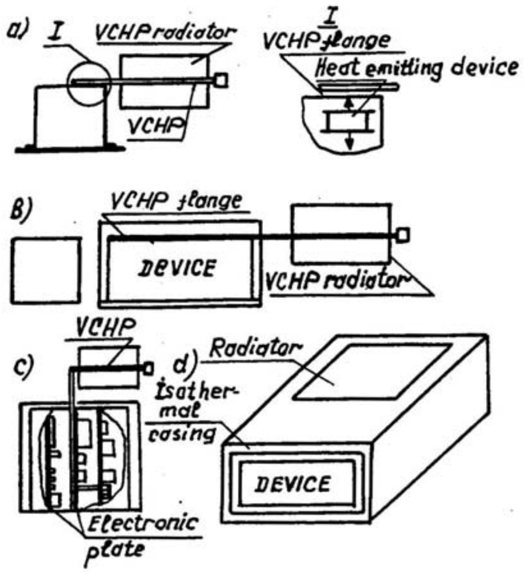


Figure 2. Conceptual principles

Creation conceptions of space electronic block constructions using VCHP for different purpose have been worked out in Kiev Polytechnic Institute and realized in cooperation with Special Design Bureau of Space Research Institute (Bishpec, Kirgizia).

The next main requirements, typical for space scientific blocks used in near-earth orbit, were took into account in this development:

- electronic blocks have dimensions no more than 360 * 240 * 155 mm;
- thermal control system (TCS) has to be absolutely autonomous and easy for mounting;
- radiate surface of TCS does not have to project from overall dimensions;
- possible versions of realization: a) isothermal block side; b) isothermal electronic panel;
- temperature level of the thermal stability was 283 K ... 323 K;
- mounting place temperature changes in the range from 253 K ... 323 K;
- range of heat output is 1.5 W ... 20 W;
- external disturbances are defined by effective temperature heat sink as 233 K ... 313 K or by values that are typical for the worst work conditions for which the attitude of normal from radiator surface is parallel with vector of speed.

CONSTRUCTIVE FEATURES OF THERMOSTATIC ELECTRONIC BLOCK (Conception B)

According to above mentioned requirements the construction shown on figure 3 turned out more attractive.

There are the next position on the figure 3: 1- electronic block; 2- removable block plane with TCS; 3- VCHP; 4- small dimensional controller of temperature; 5- low thermal conductive supports for mounting of the electronic block to the mounting places; 6- multi-layer isolation (stroke line); 7- heat input zone (evaporator of heat pipe); 8- heat pipe (HP) radiator zone; 9- balloon with non-condensable gas; 10- low conductance supports of radiator casing; 11- electronic communication connector of TCS; 12- electronic communication of block; 13- electronic plates with thermo conductance plates; A and B- radiator zones with different width of radiator elements.

Electronic block has easily removable upper cap 2 on which all TCS was mounted. Upper cap has thermal connection with electronic plates 13 having thermal conductivity bars for assembling of elements' heat and transporting it to the upper cap. For decreasing of external conditions' influence, the block was mounted on the low thermal conductive supports 5 and surrounded screen-vacuum isolation. TCS itself consists of VCHP (figure 4) with wicked balloon and small dimensional balloon temperature controller 4.

HP 3 has U-shape form that allows to decrease overall dimensions, bend radius of HP's casing was 30 mm. Casing construction and form of capillary porous structure (CPS) of HP is shown on the figure 4. CPS was manufactured from sintered metal fiber, porosity of which was 88%. All parts of the casing and CPS were made from stainless steel. Construction of CPS allows to transport no less than 20 W at temperature level 303 K, using methanol as a heat carrier. VCHP condensation zone has sectioned radiator soldered to surface of HP casing. Element width in zone A equals 5 mm, in zone B -- 3 mm. Distance between radiator ribs everywhere is the same and equals 0.5 mm. Ribs contact with hp's

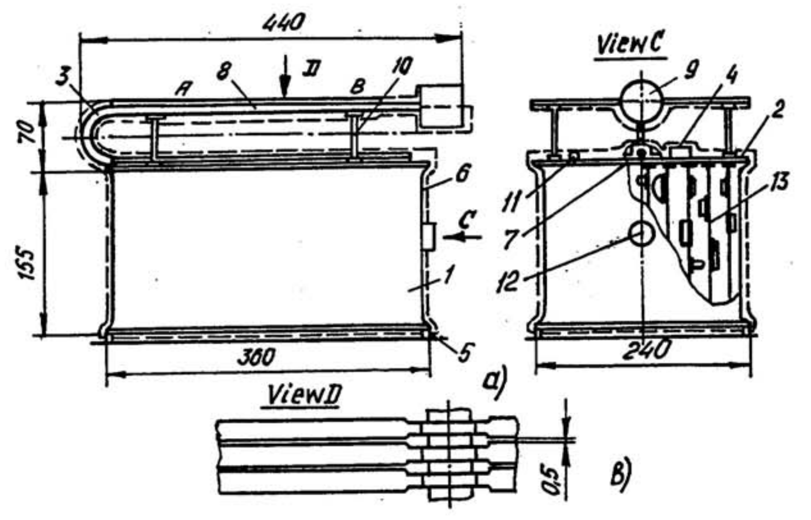


Figure 3. Electronic block with TCS on base of HP

casing on 90% of its surface. External and internal radiator surfaces were coated by optical enamel with emissivity factor e=0.85. TCS at its regular regime has to function with constantly balloon temperature at the level 0 °C. Achieved regulation accuracy at this is ± 2 K. In case of failure of balloon temperature controller TCS will work in regime with non regulated balloon temperature. Regulation accuracy at this falls up to ± 5 K.

TEST RESULTS (Conception B) - Results of thermo-vacuum tests at steady state regimes are presented on figure 5.

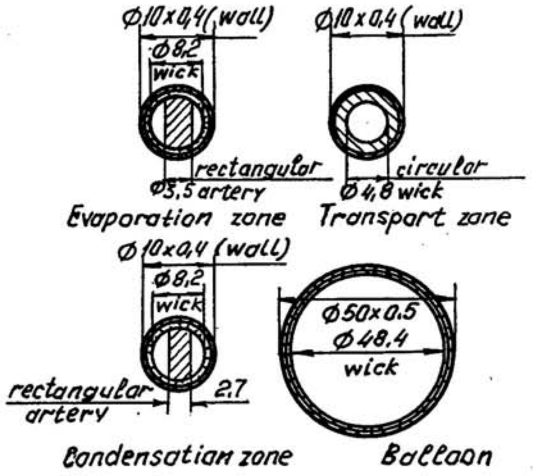
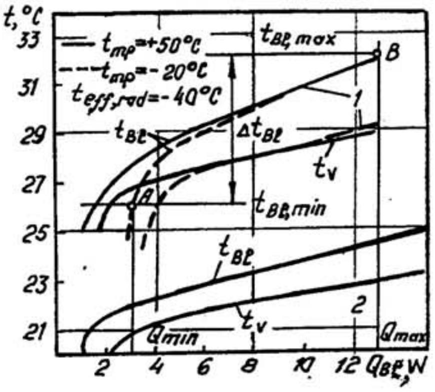


Figure 4. Cross section of VSHP's zones



1 - Complete set No.1; 2 - Complete set No.2

Figure 5. Dependence between t_{Bl} and Q_{Bl}

All system (block and TCS) operated in power dissipation diapason from 2.7 W to 17 W at effective radiator temperature -40 °C. For complete set No. 2 minimum values of operating diapason were reduced up to 1.5 W by improving of the isolation construction.

Influence of external heat fluxes (sun rays, earth radiation) is shown on figure 6.

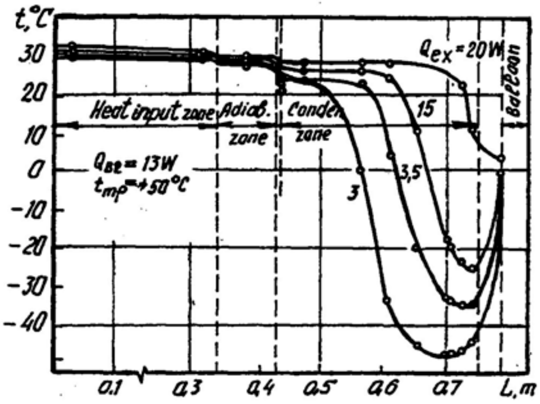


Figure 6. Influence an external heat flux in radiator

Values of heat flux absorbed by radiator were changed in diapason 120 ... 270 W/m^2 at $Q_{BL,max}$=13 W.

Figure 7 presents non-steady behavior along orbit circuit. Here Q_r- external heat absorbed by radiator; Q_b- external heat absorbed by balloon; t_{r1}, t_{r2}, t_{r3} - temperatures at begin, middle, and end of the radiator.

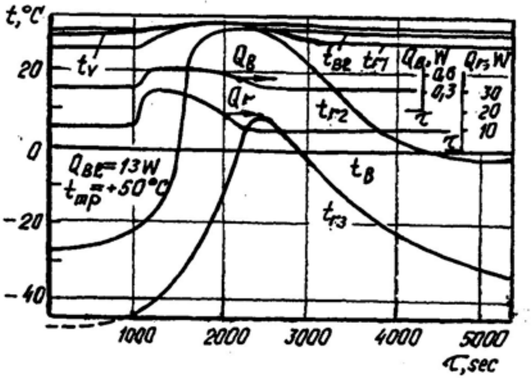


Figure 7. TCS reaction on external disturbances

Presented information shows that conception of electronic block design, joining electronic components and TCS is easy enough and the construction has good thermal characteristics.

DESIGN OF TCS FOR INTERNAL ELECTRONIC COMPONENTS (Conception C)

Temperatures of heat reject electronic components are defined by thermal resistance between elements and heat sink (heat sink for components means thermostatting surface). Because heat rejected and distance between electronic components and heat sink are increasing continuously in current and future electronic designs, reducing of their thermal resistance by application of more intensive methods of heat transfer are actual.

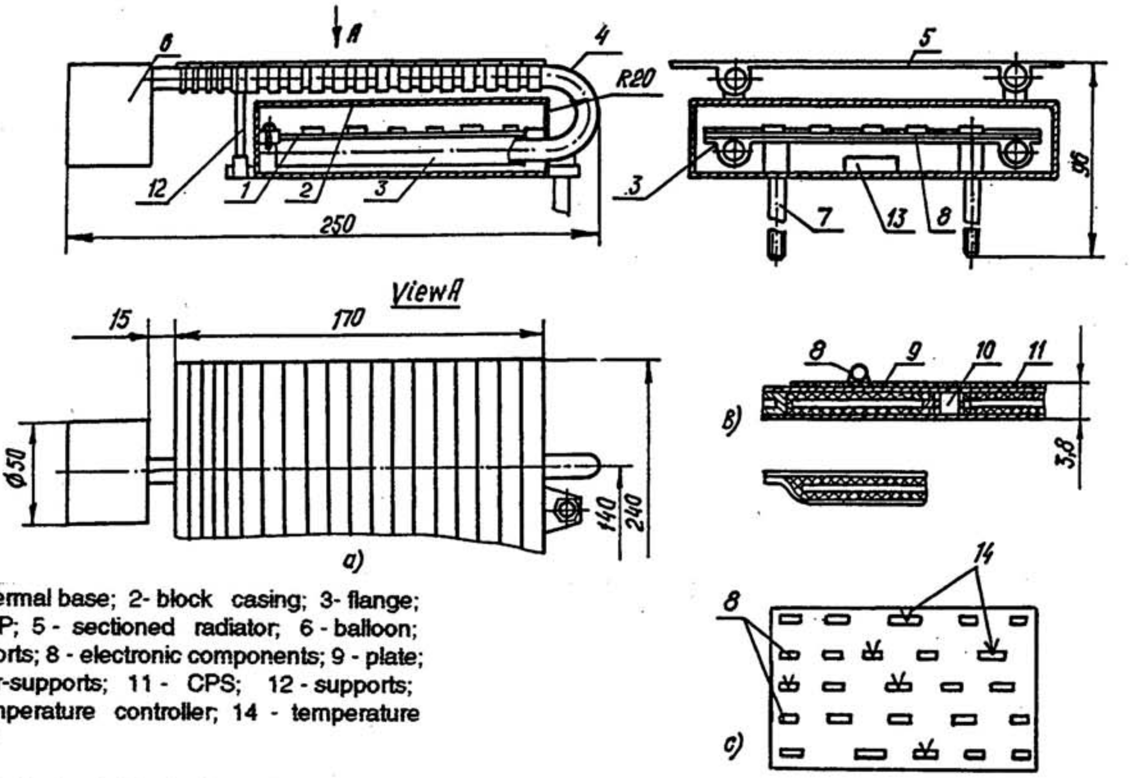
One of the way to solve this problem is to use intermediate heat pipes between electronic components and heat sink. Proposed design of electronic block is presented on figure 8.

The conception satisfies to previous technical requirements. Addition: maximum temperature of electronic components is no more than 70 °C. Correlation between maximum and minimum heat dissipation of components is 10:1.

Isothermal base 1 (IB), a flat heat pipe, is mounted into block casing 2 and connected with TCS. TCS consists of two parallel working VCHP 4. Contact between VCHP 4 and isothermal base is realized by flange 3. Condensation zones of VCHPs are joined with sectioned radiator 5. Low heat conductance supports 12 and 7, on their mounted places, are used for mechanical fixing of a radiator end and for balloon attaching. Heat losses into environment were decreased by using of multi layer isolation.

Isothermal base is a flat heat pipe with dimensions 180*130*3.8 mm. On one side of the isothermal base a dielectric covering was glued with placed on it electrical conductivity layers (figure 8 b, c). Function principle of the construction is the next. Heat dissipation of elements 8 is absorbed by isothermal base. Formed vapor of heat carrier performs heat transfer toward condensation zones where isothermal base is connected with VCHPs. Distance of the heat transfer does not have principle meaning (it was realized distance 0.5*0.5 m) that distinguishes this solution from one using a whole metal plate. VCHPs accomplish heat transfer toward the radiator and control the temperature at heat rejection oscillation of electronic elements (1 ... 10 W) and changing external conditions (mount places' temperature -20 ... +50 °C; external absorbed heat flux 100 ... 300 W/m^2). It was foreseen two work regimes:

- control of temperature of balloons containing non-condensable gas using controller 13 by electronic elements' temperature (feedback by temperature);
- passive work of VCHPs.



1- isothermal base; 2- block casing; 3- flange; 4 - VCHP; 5 - sectioned radiator; 6 - balloon; 7- supports; 8 - electronic components; 9 - plate; 10 - bar-supports; 11 - CPS; 12 - supports; 13 - temperature controller; 14 - temperature sensor

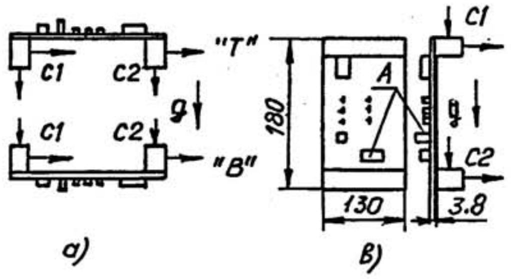
Figure 8. Electronic block with isothermal base

Constructions of heat pipes are following. Casing of isothermal base (overall dimensions are 180*130*3.8 mm) was made from stainless sheet steel with thickness 0.4 mm. CPS was created from sintered metal fibers (thickness is 0.5 mm, porosity is 80%). CPS keeps a heat carrier (methanol) at conditions of tests with gravity force and provides the liquid circulation.

VCHPs have cylindrical casings made from stainless steel with thickness 0.3 mm. CPS was created from sintered metal fibers and has constantly through zones' thickness (0.85 mm) and porosity (80%). Balloons with non-condensable gas (diameter is 50 mm, length is 40 mm) for decreasing of overall dimensions are attached so that they are outside the radiator plane.

The block constructions allowed to measure temperatures under electronic elements and in different zones of VCHPs.

TEST RESULTS (Conception C) - Before placing into the block, the isothermal base was exposed to autonomous tests. Heat output was performed by local coolers mounted on the places of VCHPs' fixing (figure 9).



a- horizon attitude of isothermal base.
b- vertical attitude of isothermal base,

Figure 9. Autonomous tests of isothermal base, where g - gravitation forces' direction; A - heat rejected elements; C1, C2 - liquid coolers;

It was examined influence of isothermal base orientation relatively to gravitation force, function features at disconnect one zone of heat output (for example, at failure one VCHP), influence of temperature level. It was determined that the base functioning at attitudes *T* and *B* (figure 9, a) does not influence on electronic elements' temperature (with accuracy ± 0.2 °C).

At vertical attitude (figure 9, b) of the isothermal base, base vapor medium temperature and elements temperature had stable level (with accuracy ±0.5 °C).

At disconnecting of the upper cooler C1, thermal resistance "vapor-condenser" went up because of liquid film enlarging the in lower condenser, and at disconnecting of cooler C2 - went down.

The test of electronic block with joined TCS had been performed in a vacuum chamber at vertical attitude of isothermal base. VCHPs were at this in horizon, that achieved the tests to the exploitation conditions at weightless state. Investigations of steady states were realized at three levels of radiator effective temperature: -60 °C, -40 °C, and 0 °C. These values corresponded to different conditions of autonomous block exploitation on the near-earth orbits.

Test results showed that difference between heat input zone temperature of VCHPs did not exceed 1 ... 2 K; TCS began to regulate at heat power 1 ... 1.5 W; maximum heat power (Q>10W) transferred by TCS at T_{eff}=-40 °C. There are some integral characteristics of electronic elements' temperatures and average temperatures of heat input zones of VCHP on the figure 10.

Curves were obtained at three temperature levels stipulated by values of external heat fluxes which radiator was absorbed: 90 W/m^2 (T_{eff}=-60 °C), 140 W/m^2 (T_{eff}=-40 °C), 270 W/m^2 (T_{eff}=0 °C).

Curves, with triangle-shape labels, correspond to the most heat rejected electronic component of the base. This electronic element emits 10% collective heat reject (Q_{ib}) of all base elements. Curves, with rectangle-shape labels, correspond to the least heat rejected electronic element of the base (1.1% of Q_{ib}.)

Curves, with circle-shape labels, correspond to the temperatures of the VCHPs' flanges. Data processing shows that at T_{eff}=const the following parameter has the meaning:

$$(\partial T_{fl}/\partial Q_{ib})^{-1} = 2.0\ \mathrm{W/K}$$
$$(\partial T_{mh}/\partial Q_{ib})^{-1} = 0.2\ \mathrm{W/K}$$
$$(\partial T_{lh}/\partial Q_{ib})^{-1} = 0.4\ \mathrm{W/K}$$

where T_{fl} - temperature of VCHPs' flange; T_{mh}- temperature of the most heated electronic element; T_{lh}- temperature of the least heated electronic element.

Temperature control accuracy of electronic components, mounted on the isothermal base, at using of system of VCHPs without controller, equals : 23±10 °C for elements mounted on the flanges of VCHPs' heat input zones; 40±25 °C for elements with heat rejection 0.1 * Q_{ib} and heat density up to 0.9 W/cm^2; 28±13 °C for elements with heat rejection 0.011 * Q_{ib} and heat density up to 0.6 W/cm^2. Data correspond to oscillation of external conditions: oscillation of mounted places' temperature in the range -20 ... +50 °C, Q_{ib}=1 ... 8 W, T_{eff}=-40 ... 0 °C.

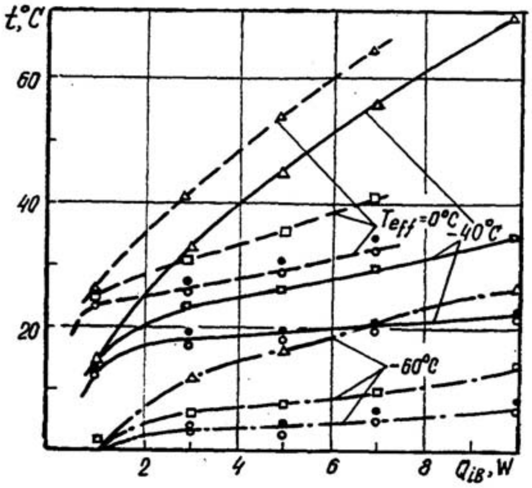


Figure 10. Regulation characteristics of the isothermal base function along with TCS

For comparison of obtained technical date with characteristics of other possible solutions of elements' cooling, it was performed the calculations for:

- system with heat transfer to mount places of device fixing;
- system with heat transfer to device casing that functions as radiator.

Calculations had been fulfilled for two versions of plate manufacturing: 1) on fabric-based laminate; 2) on metal basis from aluminum alloy. External and internal disturbances were the same as for block design: Q_{ib}=1 ... 10 W, T_{eff}=-40 ... 0 °C. For the system with heat transfer to mount places, the temperature of the most heated elements was -16 ... 100 °C even for metal base. For the system with heat transfer to device casing that functions as radiator, that temperature equaled -34 ... + 140 °C for fabric-based laminate base and -34 ... 90 °C for metal base.

For diminishing of the oscillation range of elements' temperature for mentioned system constructions , it is necessary to use a heat compensation (using of heaters) of elements' heat rejected. Required heat energy in this case is 8 ... 9 W at minimum power of block 1 W.

COOLING OF SEVERAL PRINTED CARD IN ELECTRONIC UNIT - For cases when an electronic block has more than one plate it had been proposed