

THERMAL CONTROL SYSTEM WITH HEAT PIPES AND SOLID SORPTION COOLERS

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Abstract

A new type of two-phase thermal control system insensitive to some "g" acceleration is suggested for space and ground application. This system is composed of a loop heat pipe (LHP), or capillary pumped loop (CPL) and a solid sorption cooler (SSC). The most essential feature of this system is that LHP and SSC are connected to the same evaporator, but are working alternatively. Such combination can be used also for the cryogenic fluid storage, when system is out of work at low pressure and room temperature, and for cryogenic thermal control system of spacecraft on the orbit (cold plate for infrared observation of the Earth, or Space), or efficient electronic components cooling device.

INTRODUCTION

Now the electronic components cooling is a key problem in the industry and space application. This problem can be solved successfully with coupled use of heat pipe and solid sorption coolers. Combination heat pipe - solid sorption cooler is beneficial for the power electronic components cooling (IGBT, thyristors, et.), for the computer cooling (chips, CPU of notebook PC) and for the space two-phase thermal control systems. In this paper we consider a combination loop heat pipe (LHP) and ammonia/(active carbon fiber + chemicals) solid sorption cooler. Such system extends the limits of the two-phase thermal control and ensures successful mode of electronic components cooling even in very harsh environmental conditions (ambient temperature 40 °C, or more).

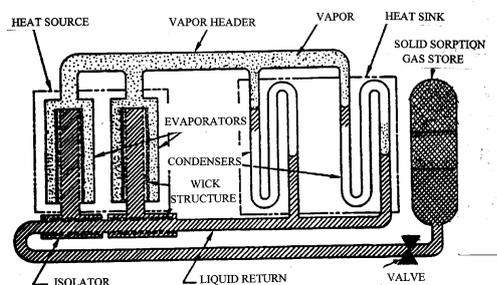


Fig.1 Schematic of CPL with a solid sorption gas storage device .

Two-phase thermal control system for space application is sensitive to the vehicle acceleration and vibration (spacecraft launching time, change of the orbit, etc). To avoid this inconvenience the coupling pair of CPL (LHP) and solid sorption cooler (SSC) is a good opportunity [1], Fig.1.

The active mode of cooling/heating of the electronic components, or the other equipment could be realised using SSC integrated directly into the two-phase heat transport system. The solid sorption cooler begins to function (to be switched on) when the cooling possibilities of heat pipe are exhausted (for example, the condenser is damaged, or covered by some insulation media, the special situation with LHP during the space vehicle launch on the orbit).

Actually a lot of low temperature heat pipes are used for space applications (as a cold plate for infrared observation of the Earth or Space), or effective electronic components cooling. Loop heat pipes (LHP) seems to be very promising heat transfer devices [2-4] for space applications in a large temperature range from 60 K up to 400 K. Heat releasing components may be placed inside the evaporator of such device [5], or to be in good thermal contact with the external surface of the heat pipe evaporator. In

this paper we consider hydrocarbons (propane) application as a working dielectric fluid and ammonia (water) like the most efficient conventional fluids for low-temperature heat pipes[6]. Actually [7-8] some hydrocarbons (ethane, methane, ethylene, propane, propylene, propadiene, butane, et.) are discussed as a vacant fluids for low temperature electronic equipment cooling, biological samples and perishable experiment materials for space missions duration of 3 up to 12 month. One of the most convenient (no noise, no vibrations) cooling systems is a heat pipe cooler (CPL, LHP or the others) , [2-4, 9].

Cryogenic LHP (hydrogen, oxygen, and nitrogen) needs to be protected against super pressure influence at room temperatures. The combination LHP with solid sorption gas storage canister can be useful to solve this problem [1]. There are some problems with start at cryogenic temperatures from supercritical state. New combination–cryogenic (oxygen , propane, ammonia) loop heat pipe + solid sorption gas storage system help to solve this problem. Solid sorption gas storage device facilitate the gas adsorption at the room temperature with low pressure cryogenic fluid, being adsorbed by the sorbent bed (active carbon).When the LHP condenser is cooling and the solid sorption gas storage system is heating the working fluid being desorbed from the sorbent bed is condensing in the condenser and sucked by the porous wick of the LHP evaporator. LHP is ready to cool the electronic components (infrared sensor).

In this paper the investigation of the heat transfer enhancement with propane, ammonia and water boiling inside different porous structures (Ti sintered powder and AL_2O_3 ceramic) is analyzed. Some preliminary results of the experiments with solid sorption cooler and LHP are presented also. Therefore combination heat pipe + solid sorption machine (cooler, heater, gas storage device) [1] can be used to extend the modes of its applicability.

It is interesting to compare possibilities of LHP and SSC to pump the working fluid in different gravity field values.

For LHP the maximum pressure rise due to the surface tension effects in the wick can be evaluated by LaPlace equation:

$$(p_c)_{\max} = 2\sigma / r_c \quad (1)$$

where σ -is a surface tension of the working fluid and r_c - is the effective capillary radius of the wick
In the real LHP design capillary pressure drop ΔP_c depends on some LHP parameters and need to be:

$$\Delta P_c \geq \Delta P_v + \Delta P_l + \Delta P_w + \Delta P_g, \quad (2)$$

where ΔP_v and ΔP_l - are the pressure drop in the vapor and liquid lines, ΔP_w - is the pressure drop in the wick pores and $\Delta P_g = \rho_l g L_{\text{eff}} \sin \theta$ - pressure drop due to the gravity field action. In the real devices this pressure head is less 1 bar.

For SSC the maximum pressure rise is determined by vapor pressure difference in the evaporator and adsorber due to Clausius-Clapeyron equation:

$$d \ln P / d(1/T) = - L/R, \text{ or } - \Delta H/R \quad (3)$$

For such fluids as ammonia the pressure drop for SSC could be 10 bars, it is 10 times more to compare with LHP.

For LHP the external source of energy is the heat input to the evaporator and the heat sink is the condenser.

For SSC the one external source of energy is also the heat input to the evaporator, the heat sink is the adsorber. The second external source of energy need to be used periodically for the adsorber regeneration. LHP can be used constantly, SSC need to be used periodically (or we need to use at least two adsorbers, working out of phase).

We can analyze different possibilities of LHP + SSC application:

- Cryogenic heat pipe (CPL, LHP), initially is out of work (room temperature), working fluid is accumulated in the solid sorption gas storage canister, pressure of gas drastically reduced - important for the cryogenic heat pipes. LHP is filled with fluid being cooled before the experiment.
- Heat pipe (CPL, LHP) and solid sorption cooler are joint to (alternatively) the same capillary pumped evaporator.
- Solid sorption gas storage canister can be used as a working fluid regulator for the variable conductance heat pipe.
- Solid sorption cooler is used for CPL, LHP to subcool liquid flow to increase the heat transfer rate in the evaporator.
- Solid sorption cooler is used for the fluid superheating (pressure swing). Intense volumetric two-phase heat transfer inside the wick is realized with a heat transfer enhancement 5 - 6 times.
- Heat flow recuperated in CPL, LHP condensers can be recovered to preheat the adsorber of a solid sorption cooler (sorbent bed preheating).
- The evaporator of the solid sorption cooler is used as a cold box (condenser) for the "spaghetti" heat pipes to cool the electronic components cabinet

THE EXPERIMENTAL SET-UP

The experimental set-up is composed with the loop heat pipe, a compact solid sorption cooler and valves. The core of this set-up is a capillary pumped evaporator with the inverted meniscus of the evaporation. Capillary pumped evaporator is a key element of LHP. The evaporator design (wick structure, geometry, internal volumetric surface of pores, surface of the liquid meniscus and surface of liquid entrance, thermal conductivity, permeability, et.) is the dominating factor in LHP design, Fig.2

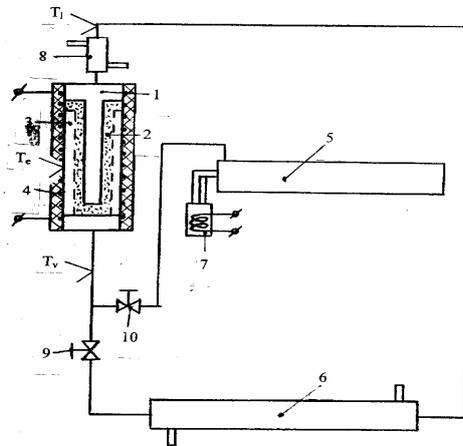


Fig. 2 Experimental set-up composed with LHP and SSC : 1 - liquid accumulator, 2 - wick structure , 3 - vapor channels, 4 - electric heater, 5-solid sorption cooler SSC, 6 - LHP condenser, 7 - SSC heater, 8 - LHP subcooler (SSC evaporator), 9 - valve, 10 - pressure regulated valve, T_1 - liquid temperature, T_e - evaporator wall temperature, T_v - vapor outlet temperature

This evaporator can be used alternatively as a loop heat pipe evaporator, or the evaporator of a solid sorption cooler. Naturally the performance of such evaporator need to be compatible with these two systems of cooling. Its performance depends on the transport properties of the wick, i.e. permeability, thermal conductivity, as well as structural characteristics.

In our experimental set-up the first evaporator was performed from Al_2O_3 ceramic with a heat releasing element (electric cartridge heater) inside the porous structure, Fig.3.

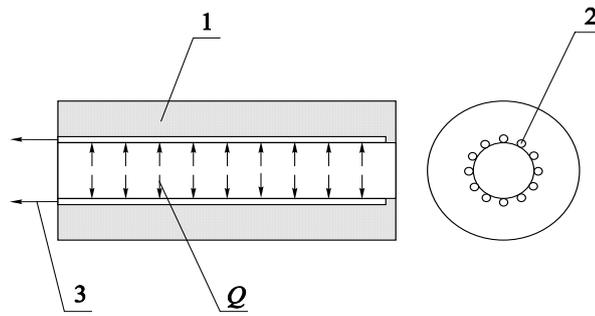


Fig. 3 Al_2O_3 ceramic evaporator 1 for LHP and SSC with internal source of energy (Q) and vapor channels 2 near the zone of a heat input (vapor generation 3).

A set of vapor and liquid channels inside the wick was performed to stimulate the boiling heat transfer, vapor output and also a capillary suction of a liquid. This design of porous structure guarantee necessary parameters of the evaporator. The working liquid for this LHP is propane.

The experiments with propane were carried out in the temperature interval $-10\text{ }^{\circ}\text{C}$ to $+40\text{ }^{\circ}\text{C}$, that corresponds to the saturation pressure range approximately $p = 3.45\text{-}13.8\text{ Bar}$ ($p^* = p/p_c = 0.081\text{-}0.323$, $p_c = 42.64\text{ Bar}$ – critical pressure of propane), the heat load was changed within $10^{-0.1}$ to 10^2 kW/m^2 toward the heat flux increase and decrease. In the sample No.1 four vapor channels ($d = 2\text{ mm}$) were situated along the heater near its surface in the wick (Photo 1).



Photo 1 Al_2O_3 ceramic evaporator with four vapor channels situated near the heat release zone. The sample is immersed into the propane pool.

In the sample No.2 (Photo 2) eight vapor channels ($d = 2\text{ mm}$) were situated near the heating surface and eight liquid channels were disposed along the sample near its cooling surface. The wick porosity is 50 %, pore diameter 0.15-0.20 mm. The samples were immersed into the propane pool, liquid suction was ensuring by the capillary forces, which guarantee the uniform liquid distribution in the porous structure of the wick. Dielectric porous wick is a good combination with hydrocarbon (propane) as a working fluid for LHP. This wick can be used in direct contact with the electronic component to stimulate its cooling by evaporation.

The experiments were performed at the liquid pool with the temperature $T_s = 30\text{ }^{\circ}\text{C}$ in the heat load interval $q = 0.02\text{ - }30\text{ kW/m}^2$. The wick thermal resistance R as a function of the temperature head between the wall and the vapor output ($\Delta T = T_w - T_v$) is shown on Fig. 4. This thermal resistance of Al_2O_3 porous structure is mostly depend on its vapour permeability (number of vapour channels). For 8 vapour channels R is two time lower to compare with 4 vapour channels.



Photo 2 Al₂O₃ ceramic evaporator with eight vapor channels situated near the heat release zone and eight liquid channels. The sample is immersed into the propane pool.

Heat flux as a function of the temperature head ($\Delta T = T_w - T_v$) for two samples of LHP Al₂O₃ wick is shown on Fig.5 and heat

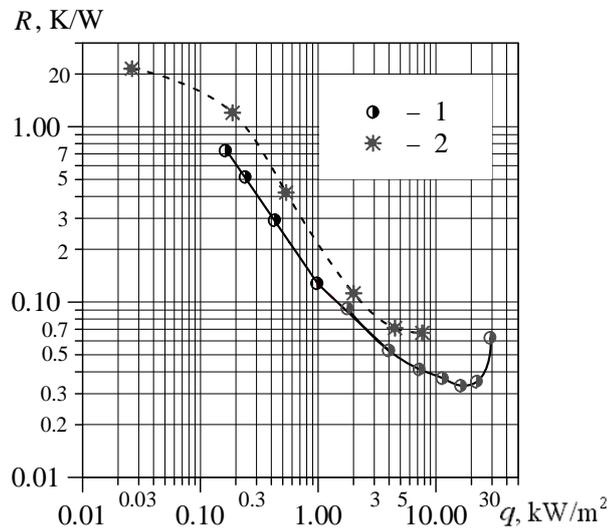


Fig.4 LHP evaporator thermal resistance as function of the heat flux (Al₂O₃ ceramic samples, propane pool).
1- eight vapor channels; 2 - four vapor channels

transfer intensity during the propane evaporation near the vapor channels surfaces is shown on Fig.6. From the experimental data it is clear, that the geometry and number of vapor channels have a strong influence on hydraulic resistance, thermal resistance and heat transfer intensity of this evaporator. The Al₂O₃ ceramic sample with 8 vapor channels situated near the heat releasing zone has at least 1.5 time less thermal resistance to compare with the 4 vapor channels sample for the heat flux near 10 kW/m², Fig. 4.

The third evaporator was made from Ti sintered powder as a compact cylindrical heat transfer device. This evaporator has a liquid accumulator inside it and a set of longitudinal and circumferential vapor channels (grooves) on the wick outer surface contacting with SS tube (heating element).

The Ti wick was used both for water and ammonia as a working fluids and was force-fitted within the stainless steel tube. Liquid (Fig, 2) is entering from the condenser to the liquid accumulator. Radial liquid flow occurs through the wick to the heated SS wall and the vapor is moving along the axial and circumferential grooves to the vapor outlet.

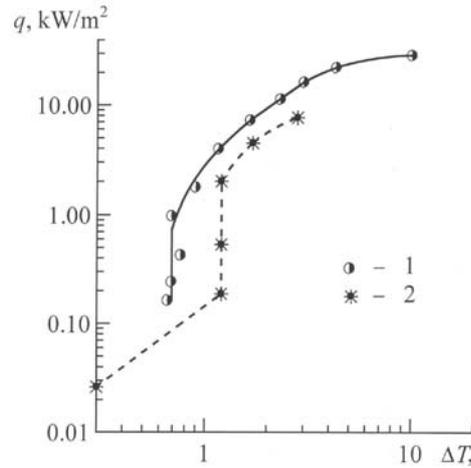


Fig. 5 Heat flux as a function of $(T_h - T_s)$ for the LHP evaporator. Al_2O_3 sample is immersed in the propane pool. 1 - sample with eight vapor channels; 2 - sample with four vapor channels

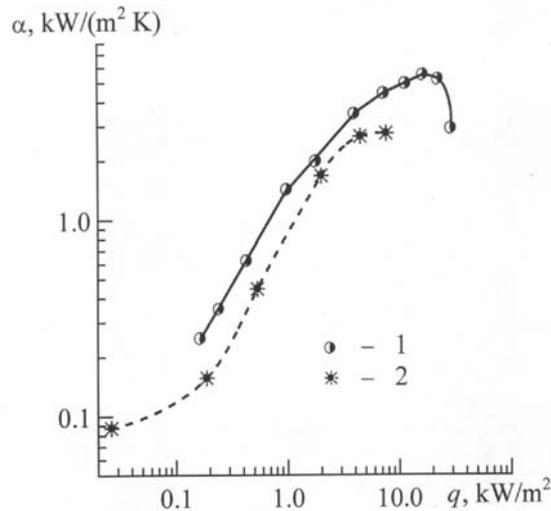


Fig. 6 Heat transfer coefficient as a function of the heat flux on the heated (by electric heater) surface for the LHP evaporator. Al_2O_3 sample is immersed in the propane pool. 1 - sample with eight vapor channels; 2 - sample with four vapor channels

The Ti wick structure has a porosity 45%, the length - 280 mm, the outer diameter - 38 mm, maximum pore diameter - 10 microns, medium pore diameter - 3-5 microns, wick thickness - 4 mm. The loop heat pipe condenser is made as a tube in tube heat exchanger. The heat output of the system is 1000 W (water), the thermal resistance of the evaporator - 0.03 K/W, pressure drop $\Delta P_{cap} = 200$ mbar. The heat transfer intensity was experimentally analyzed (Fig. 7-10) for the ammonia and water applications.

SOLID SORPTION COOLER

SSC experimental set-up is composed from two small adsorbers (sorbent bed - active carbon fiber "Busofit" saturated with salts). SSC is connected with LHP by the valve. The low temperature adsorber No.1 was filled with "Busofit" (60 g) and saturated with $BaCl_2$ salt (65 g). The high temperature adsorber No.2 was filled with "Busofit" (65 g) and saturated with $NiCl_2$ salt (70 g). The cold output is near 300 W [10].

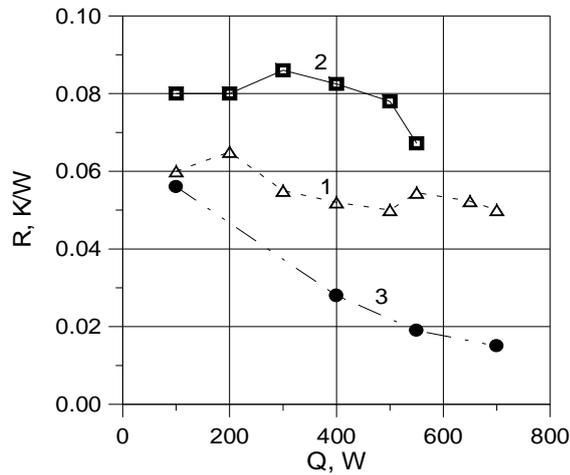


Fig. 7 LHP evaporator thermal resistance R_e as a function of heat transfer rate Q . ($R_e = (T_e - T_v) / Q$)
 1 - ammonia subcooled, 2 - ammonia saturated, 3 - water saturated

This SSC cooler can be used independently to subcool the liquid in the LHP entrance, or to cool the LHP evaporator directly for the case of emergency.

Solid sorption cooler (being switched on by the valve) increase the heat transfer intensity inside the porous evaporator due to the volumetric evaporation under the pressure drop (some bars). By choosing a working fluid having a large heat of the evaporation (water, ammonia) one may expect to dissipate significant heat flux in the evaporator. In this two-phase thermal control system the mass flow need to have any type of pumping device with energy consumption from an external source. For LHP this source of energy is a capillary pumped evaporator and the thermal sink is condenser. SSC evaporator is the same as LHP evaporator, but pressure head is due to superheated vapor in the sorbent bed and the thermal sink of SSC is adsorber.

The experimental set-up is composed of LHP and SSC connected with the pressure regulated valve. The schematic of such device is shown on Fig. 1 and Fig. 2, where it is seen, that the main difference of this set-up to compare with CPL [9] is the solid sorption storage canister with a valve.

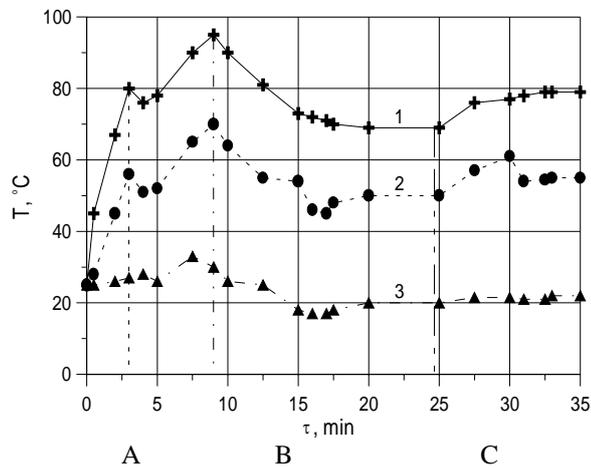


Fig. 8 LHP evaporator temperature field evolution in time during its heating:
 1 - evaporator surface contacting with a source of energy, 2 - vapor outlet temperature, 3 – liquid (entrance to the liquid accumulator) temperature.
 A - saturated liquid, B - subcooled (by SSC evaporator) liquid , C - saturated liquid

LIQUID SUBCOOLING

The heat transfer coefficient inside a capillary pumped evaporator of LHP depends on Q , LHP inclination and (important) liquid subcooling in the accumulator (Fig.8-10). Liquid subcooling was realised by SSC evaporator from 25 °C down to 15 °C .

LHP evaporator working with water has lower thermal resistance and is convenient to apply with power semiconductor cooling systems. As it is following from the LHP evaporator functioning the monoporous Ti wick structure is not the optimum structure and has a heat transfer coefficient near 2000 W/m^2 for saturated ammonia, $3000 - 3500 \text{ W/m}^2$ for subcooled ammonia and $3000 - 3400 \text{ W/m}^2$ for saturated water. Al_2O_3 ceramic evaporator with 8 vapor channels saturated with propane has a heat transfer coefficient comparable with Ti wick structure saturated with ammonia. The later heat transfer enhancement can be achieved with Ti biporous wick structure application and deep ammonia subcooling.

FLUID SUPERHEATING

When LHP evaporator is connected to SSC adsorber (through the valve 10, Fig.2) and is disconnected to the condenser (through valve 9, Fig.2) the intense fluid superheating is occurred inside the wick porous structure due to a sharp pressure decrease (pressure swing in the adsorber-evaporator system). The fast temperature field evolution in the LHP evaporator, liquid and vapor temperature decrease are shown on Fig.9. The heat input to the evaporator is constantly 300 W . For the first period of time A (4 min) the saturated liquid ammonia is still entering the liquid accumulator 1 (Fig.2). The evaporator "hot" wall temperature (60°C), vapor outlet temperature (52°C) and liquid entrance temperature (25°C) are being constant. For the second period of time B (12 min) a sharp heat transfer intensification occurred and the temperature of the evaporator T_e , the temperature of the liquid in the accumulator T_l and vapor outlet temperature T_v are becoming near the same order of merit due to the volumetric evaporation of the liquid inside the porous structure and vapor condensation inside the liquid accumulator (micro heat pipe phenomena is available inside the wick structure).

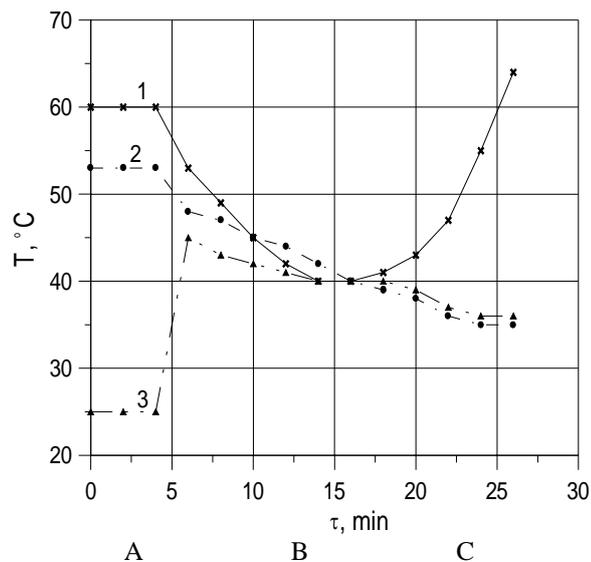


Fig. 9 Temperature field evolution in the LHP evaporator wall (1), vapor outlet (2) and saturated liquid entrance (3) as a function of time during the SSC switched on. A - constant cooling rate; B - transient enhanced cooling rate; C - porous wick partial drying

For the third period of time C (after 16 min of the SSC is switched on) the liquid inside the LHP accumulator is exhausted and the porous structure is becoming to superheat (heat transfer rate is limited by the thermal conductivity of the wick).

The heat transfer evolution during this 3B period of LHP functioning (cooled by SSC) is shown on Fig.10.

If we compare the heat transfer coefficient for three different cases of the LHP evaporator working with saturated liquid, subcooled liquid and superheated fluid (ammonia), we can prove the sharp heat transfer intensification during the liquid subcooling and superheating. For the case of superheating this heat transfer intensification is more than 6 times (from 2000 W/m^2 up to 12000 W/m^2), Fig.8 to compare with LHP evaporator.

This enhanced mode of LHP evaporator cooling can be stationary, if we use at least two solid sorption coolers switched on and off alternatively.

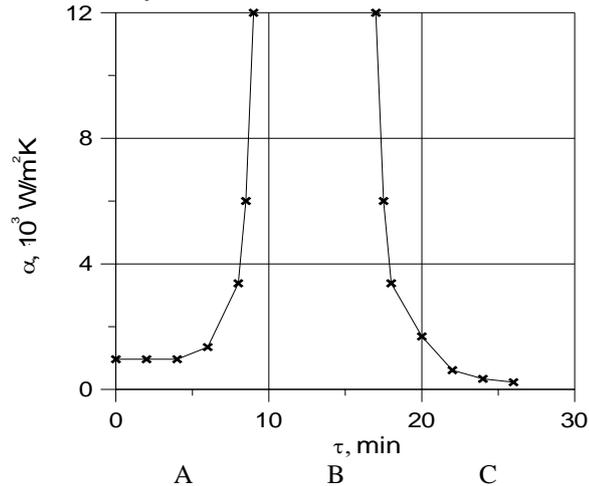


Fig. 10 Heat transfer coefficient as a function of time when LHP evaporator in cooled by SSC. Liquid superheating is reached due to the pressure swing. $Q = 300 \text{ W}$.

CONCLUSIONS

Different porous structures made from Ti sintered powder, of Al_2O_3 porous media are used as LHP+SSC evaporator with ammonia, or propane as a working fluid. Liquid subcooling and fluid superheating were analyzed as a possibility to heat transfer enhancement in the porous structure. The heat transfer intensity with propane boiling inside the wick for Al_2O_3 porous media was reached up to $1500 \text{ W/m}^2 \text{ K}$. Heat transfer intensity up to $3500 \text{ W/m}^2 \text{ K}$ was obtained for ammonia and water. At least 5 times heat transfer intensification was obtained for ammonia boiling in the Ti wick, when a solid sorption cooler was switched on.

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