Development of the low-temperature arterial heat pipes

Goncharov K.A., Heat pipe center of RSA, Lavochkin Association, Moscow, Russia
Kochetkov A.Yu., TAIS, Moscow, Russia
Antonov V.A., TAIS, Moscow, Russia

Abstract

Development of low-temperature and cryogenic thermal control systems used in spacecrafts is one of the difficult and interesting scientific task. Lavochkin Association has been designing such systems since 1968. Since 1972 the low-temperature thermal control systems with application of diode heat pipes, radiators with heat pipes, thermal storages with PCM have been successfully operating on board of spacecrafts “OKO” and “OKO-1”. In December 2003 the hundredth anniversary launch of the “OKO” family satellite is expected.

The present paper describes the recent developments of the low-temperature arterial Heat Pipes and technical solutions applied in cryogenic system of the “OKO-1” family. Latest satellite put in orbit in April 2003.
The paper briefly describes the following aspects:

- layout of the thermal control system;
- description of design and parameters of the low-temperature arterial heat pipes used in thermal control system;
- description and results of on-ground tests;
- telemetrical temperature data obtained during the system operation in obit;
- comparison of the thermal analysis and on-ground test results with the flight operation data.

The paper presents the conclusion of the possibility to obtain cryogenic temperatures for the high power systems (several watts) using passive facilities without application of vapor-compressive or sorption-diffusion machines.

•Investigations of Arterial PHs performed at Northrop, Grumman, OAO, TRW and NASA. A lot of papers and patents on Arterial HP issued in 70th also prove a great attention paid to these devices.
•Investigations of Arterial Heat Pipes in the USA and Europe have been stopped after series failures of flight experiments.
•After appearance of vapor bubbles in artery the critical situation occurred.
• «No bubble – no trouble!" – said David Antoniuk from TRW in 1997.

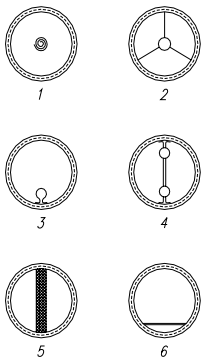


Fig.1

More than 300 ArHP with segment artery have been manufactured and tested in Lavochkin Association and TAIS company.
More than 160 ArHP with segment artery have been launched on board of the Russian spacecrafts. Many of such ArHP was operating on board of spacecrafts for more than 6 years. ArHP failures during flight and degradation of their parameters by the telemetric sensors were not observed.

Fig.2

Successful operation of ArHP integrated in the spacecrafts proves the correctness of the selected design of ArHP capillary structure. Arterial capillary structure have been used for ArHP with ring heat supply and for ArHP with heat supply from the side of artery.

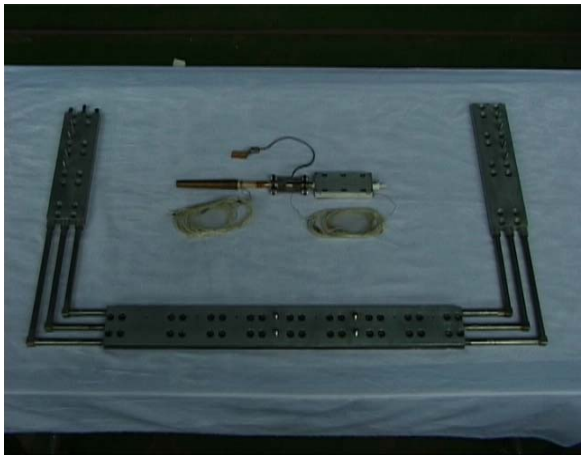


Fig. 3

Cryogenic ArHP, ArHP-diode, flexible ArHP, gas-controlled ArHP and ArHP of complicated configuration were developed.
ArHP of 12 and 16 mm diameters are developed for manufacturing. Artery height is 1.5, 2.4 and 3 mm. ArHP mass:
•145 g/m for 12mm
•220 g/m for 16mm

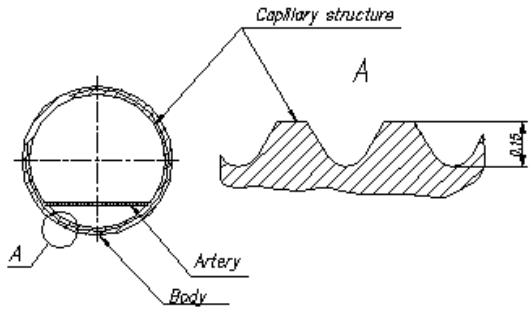


Fig. 4

To prevent the appearance of "excess vapor amount" in the artery and the disturbance of liquid flow in the artery by vapor bubbles, the holes are arranged along the artery length with certain pitch. Such holes provide the removal of vapor bubbles generated inside the liquid flow to vapor channel.

Dependency of required diameter of the holes on some ArHP design parameters can be presented by the following formula:

$$D \geq 0{,}9\sqrt{\frac{h_{art}\cdot\delta_{art}}{\cos\theta}\cdot\left(2-\frac{\delta_{art}\cdot\cos\theta}{h_{art}}\right)}$$

h_{art} - artery height

δ_{art} - artery mesh thickness.

Experimental data for Arterial HPs with ammonia (Onground test, horisontal position)

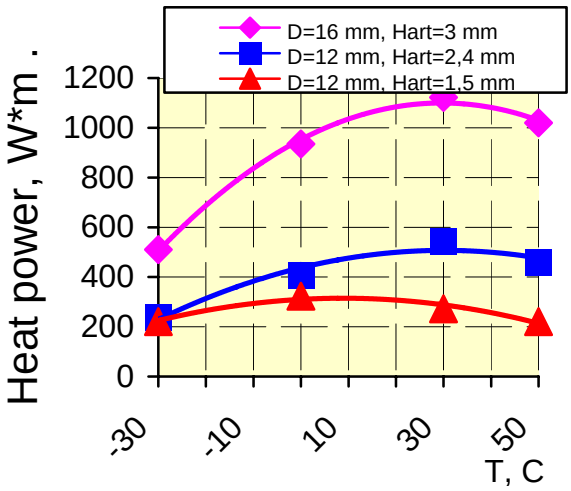


Fig. 5
Experimental data for Arterial HPs with ammonia (Onground test, horisontal position)

Total Length $L_{\Sigma} = 2{,}0$
mEvaporator Length $L_{Ev} = 0{,}3$
mCondenser Length $L_{Con} = 0{,}3$

Heat transfer coefficients for ammonia are as follows:

in evaporator 7000-10000 W/m^{2}K

in condenser 5000-8000 W/m^{2}KFor propylene the values of heat transfer coefficients are nearly half as low.

Comparative thermal characteristics of Arterial HP with different working fluids present in fig. 6.

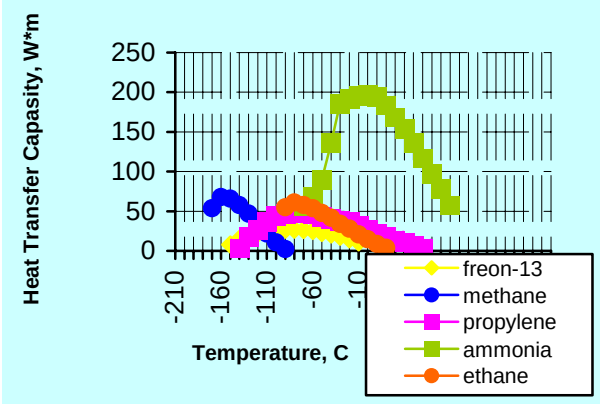


Fig. 6
Thermal performance of arterial heat pipe with different fluids for comparative:
Diameter of body - 12 mm,
Height of artery - 1,5 mm for ammonia
- 2.4 mm for other fluids

•Development of spacecrafts low-temperature and cryogenic thermal control systems (TCS) is one of the difficult and interesting scientific task. Lavochkin Association has been designing low-temperature thermal control systems with application of heat pipes since 1968.

Fig. 7

•Difference kind of heat pipes, thermal storages with PCM have been successfully operating on board of spacecrafts “OKO” and “OKO-1” since 1972.

•In December 2003 the hundredth anniversary launch of the “OKO” family satellite was launched.

Fig. 8
“Oko-1” is flying at the geostationary orbit.

Up to now six spacecrafts of this type have been launched. The last “Oko-1-6” spacecraft was launched on 24.04.2003.
The spacecraft conclude cryogenic thermal control system (TCS) for cooling of the payload down to 160K. TCS included 10 stainless steel (SS) - propylene heat pipes with segment artery. Heat pipe Center of Russian Space Agency in Lavochkin Association have manufactured ArHP for new spacecraft “Oko-1-6”.

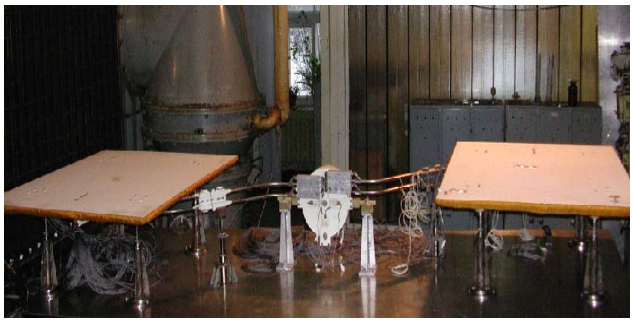


Fig. 9
Thermal-vacuum tests of TCS on base of HP

•Radiators shall operate within the temperature range from 110K to 320K. Using of diode arterial heat pipes allow to cool equipment up to 160K.

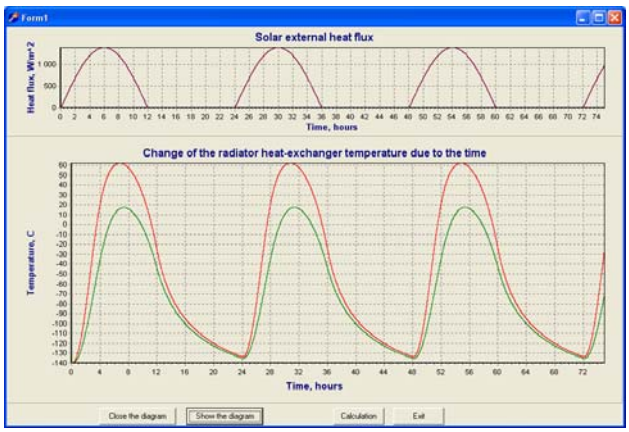


Fig. 10
Calculation results of heat flux and temperatures at radiators

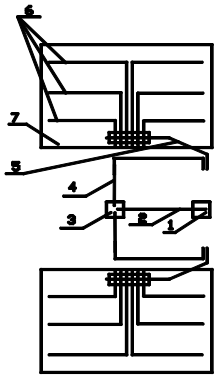


Fig. 11
TCS Layout

1. AGHP
2. Honeycomb panel of Radiator
3. Arterial reversible heat pipe
4. Arterial diode heat pipe
5. Arterial flexible heat pipe
6. Thermal storage with PCM
7. Cooling payload

•Flexible ArHP (5) connects PCM thermal storage (6) to cooling rotated payload (7).
•Arterial reversible (3) and diode (4) heat pipes allow to transport heat flux to considerable distance from thermal storage to radiators panels.
•Ammonia is not acceptable as a working fluid due to its freezing temperature (minus 78°C). Propylene (C_3H_6) with freezing temperature 85K is one of perspective working fluids.

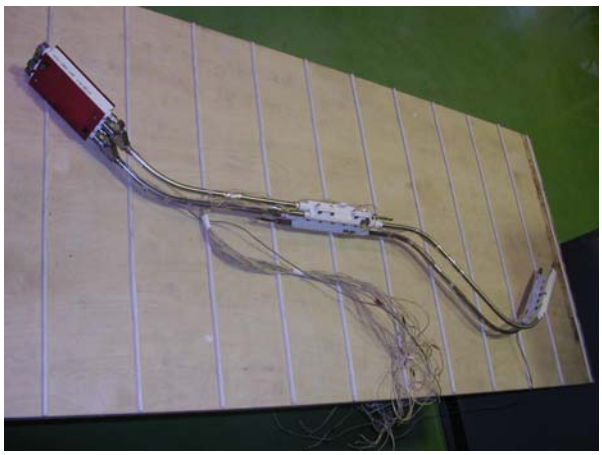


Fig. 12
Arterial reversible and diode heat pipes

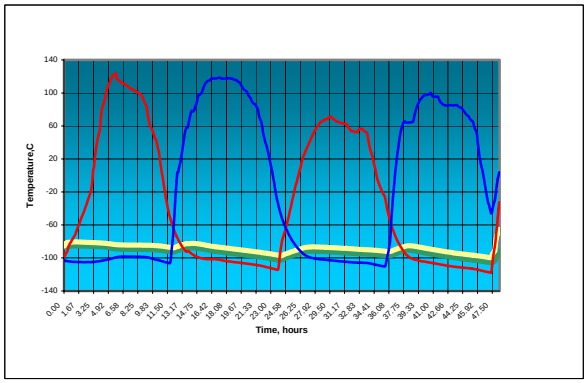
Body - SS
Artery - SS
Saddles - Al alloy
Fluid - Propylene
Weight - 3.25 Kg

Effective length of reversible ArHP - 832 mm. Effective length of diode ArHP 394 mm. Heat power at temperature minus 100ºC is 120 W. Thermal resistance in forward direction is no more than 0,12 K/W. Heat flux in reverse direction at the first hour is no more than 3 W, at the next hours is no more than 1 W.

Fig.13
Arterial flexible Heat Pipes

Body - SS
Artery - SSSaddles - Al alloy
Fluid - Propylene
Weight - 1.85 Kg
Length - 1651 mm

Heat power at temperature minus 100ºC is 32 W. Thermal resistance is no more than 0,2 K/W. Flexibility ± 8 angle degree 2 billion cycles.



east radiator west radiator thermal storage

Fig.14
TCS on base of HP temperature during the ground test with using IR sun simulator

east radiator west radiator thermal storage

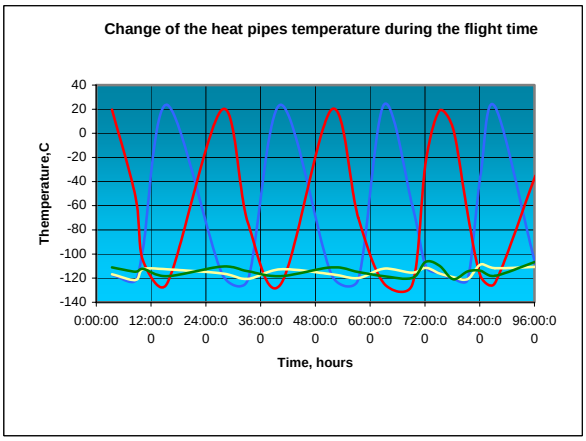
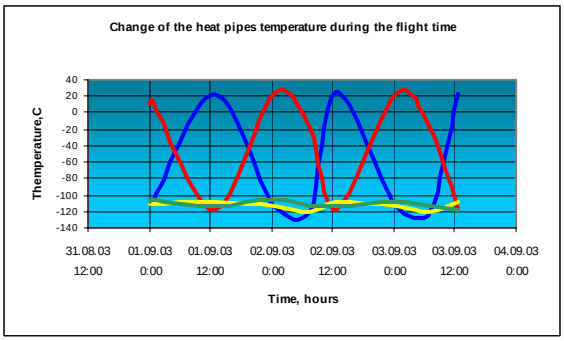


Fig.15
Flight result data from 30.04.03



east radiator west radiator thermal storage

Fig.16
Flight result data after 5 month of operating

Conclusion

- Heat pipes with segment arterial capillary structures have high thermal parameters and low weight.
- Reversible, diode and flexible low temperature heat pipes have been developed on base of segment arterial capillary structures.
- Repeatability of the parameters during on-ground tests and flight operation as well as the great number of such ArHP operated on board of spacecrafts proves the high reliability of the developed design.

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