17. Zhu Y., Jiang Y., Liang S., Guo C., Guo Y., Cai H. One-dimensional computation method of supercritical CO_2 labyrinth seal. *Appl. Sci.* 2020. Vol. 10. Iss. 17. Paper 5771. https://doi.org/10.3390/app10175771.
18. Gilgen R., Kleinrahm R., Wagner W. Supplementary measurements of the (pressure, density, temperature) relation of carbon dioxide in the homogeneous region at temperatures from 220 K to 360 K and pressures up to 13 MPa. *The J. Chem. Thermodynamics*. 1992. Vol. 24. Iss. 12. P. 1243–1250. https://doi.org/10.1016/S0021-9614(05)80264-2.
19. Anwar S., Carroll J. J. Carbon Dioxide Thermodynamic Properties Handbook: Covering Temperatures from-20° to 250° C and Pressures Up to 1000 Bar. John Wiley Sons. 2016. 608 p. https://doi.org/10.1002/9781119083948.
20. Yamada T., Gunn R. D. Saturated liquid molar volumes. Rackett equation. *J. Chem. and Eng.* 1973. Vol. 18. Iss. 2. P. 234–236. https://doi.org/10.1021/je60057a006.

DOI: https://doi.org/10.15407/pmach2021.04.027

UDC 629.78

RETROSPECTIVE REVIEW OF A TWO-PHASE MECHANICALLY PUMPED LOOP FOR SPACECRAFT THERMAL CONTROL SYSTEMS

[1] **Gennadiy O. Gorbenko**
gennadiy.gorbenko@ctph.com.ua

[2] **Pavlo H. Gakal**
p.gakal@khai.edu
ORCID: 0000-0003-3043-2448

[1] **Rustem Yu. Turna**
rustem.turna@ctph.com.ua
ORCID: 0000-0001-5773-1400

[2] **Artem M. Hodunov**
artem.hodunov@ctph.com.ua
ORCID: 0000-0001-8850-8367

[1] Center of Technical Physics
17, Chkalov str., Kharkov, 61070, Ukraine

[2] National Aerospace University
«Kharkiv Aviation Institute»
17, Chkalov str., Kharkov, 61070, Ukraine

The main issues associated with the development of two-phase mechanically pumped loops (2ϕ-MPL) for thermal control systems of spacecraft with large heat dissipation were formulated back in the early 80s. They have undeniable advantages over single-phase loops with mechanical pumping and two-phase capillary pumped loops at power more than 6 kW and heat transfer distance more than 10 meters. Intensive research and development of such systems started in the USA together with European, Canadian and Japanese specialists due to plans to build new high-power spacecraft and the Space Station Freedom project. In the 90's, S. P. Korolev Rocket and Space Corporation Energia (Russia) was developing a 2ϕ-MPL for the Russian segment of the International Space Station with the capacity of 20...30 kW. For this purpose, leading research organizations of the former Soviet Union were involved. In the last two decades, interest in two-phase heat transfer loops has significantly increased because of high-power stationary communications satellites and autonomous spacecraft for Lunar and Martian missions. The paper presents a retrospective review of worldwide developments of 2ϕ-MPLs for thermal control systems of spacecraft with large heat dissipation from the early 80's to the present. The participation of scientists and engineers of the Ukrainian National Aerospace University "KhAI" and the Center of Technical Physics is considered. The main directions of research, development results, and scientific and technical problems on the way to the practical implementation of such system are considered. Despite a large amount of research and development work done, there were no practically implemented projects of spacecraft with the high-power thermal control system until recent days. The first powerful stationary satellite with the 2ϕ-MPL was SES-17 satellite on the NEOSAT platform by Thales Alenia Space - France. The satellite was successfully launched into space on October 24, 2021 by onboard an Ariane 5 launcher operated by Arianespace from the Europe's Spaceport in Kourou, French Guiana.

Keywords: *spacecraft; thermal control system; two-phase mechanically pumped loop.*

Introduction

The progress of space technology leads to an increase in the power equipment of spacecraft, the power of which is up to tens of kW. The problem of heat dissipation from equipment and devices into space is acute for such spacecrafts.

With a large heat dissipation (more than 6 kW) and a large heat transfer distance (more than 10 meters), it is rational to build Thermal Control Systems (TCS) based on 2ϕ-MPLs.

A simplified schematic diagram of the TCS is shown as a single loop in Fig. 1.

The system includes a pump, heat exchangers (evaporators, heat sinks), a radiator with a condenser, and a hydraulic accumulator. The pump feeds the working fluid to the evaporators, in which heat from equipment is absorbed by the fluid and part of the fluid is evaporated. There is a two-phase vapor-liquid flow at the outlet of the evaporator. The two-phase flow is directed to condensers of radiator panels, where it is condensed and subcooled. The only way to remove heat from a spacecraft is by rejecting the heat from a radiator surface into the space.

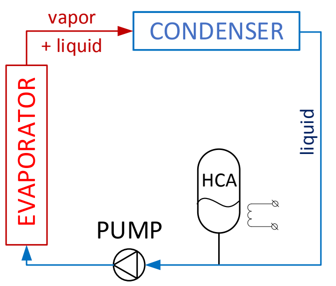

Fig. 1. Schematic diagram of the 2ϕ-MPL

In such loops, heat is accumulated and transferred as latent heat of vaporization, which allows a significant reduction in working fluid flow rate compared to systems based on single-phase loops. Heat exchange occurs with high intensity at evaporation and condensation. 2ϕ-MPL makes it easy to stabilize and control of payload units temperature. These properties of 2ϕ-MPL lead to significant savings in mass of TCS. A complex criterion, specific heat transfer coefficient K_T, is also used to assess the efficiency of TCS [1]:

$$K_T = \frac{Q \cdot L}{M},$$

where Q – heat flux, W; L – heat transfer distance, m; M – mass of the system, kg.

As shown in [2], at large heat output (more than 10 kW) and distances of heat transfer (more than 10 meters), 2ϕ-MPLs have the undeniable advantage in weight and energy consumption for own needs compared to heat pipes, single-phase loops and loop heat pipes.

Development of 2ϕ-MPLs

Intensive research and development of 2ϕ-MPL began in the USA in the 80's together with European, Canadian and Japanese specialists due to the plans to build high power spacecrafts and the Freedom orbital station project [3]. Ground studies of several 2ϕ-MPL schemes, in which the "thermal bus" concept was implemented [4, 5], were performed. The original two-phase loop (TPL) concept with a rotating fluid management device, which was subsequently selected as the main one for the Freedom station's thermal control system [8], was proposed by Sundstrand and Boeing [6, 7].

TPLs were also studied in Europe in cooperation with the Columbus space platform project [9].

In the 1980s, research on two-phase heat transfer began in the USSR, in the S. P. Korolev Rocket and Space Corporation Energia (RSC Energia, Russia). The National Aerospace University "KhAI" (Ukraine) took part in these studies. As a result of preliminary studies, in 1991, RSC Energia and "KhAI" co-authored a monograph [10] that included a detailed review of their own and the world's investigations on 2ϕ-MPL.

In 1992, RSC Energia and "KhAI" initiated a representative interdepartmental seminar [11], which provided an opportunity to coordinate and intensify further 2ϕ-MPL studies in leading scientific and technical organizations of the former USSR. During this seminar, big progress in the development of TPL with capillary pumped loop (due to the work of S. A. Lavochkin Research Center and Institute of Thermophysics of the Ural Branch of the Russian Academy of Sciences [12]) was noted. At the same time, the insufficient intensity of 2ϕ-MPL studies for high power satellites was noted.

In the 1990s, the TPL work was continued at NASA and at RSC Energia. RSC Energia has been working on 2ϕ-MPL with a capacity of 20...30 kW for the Mir-2 space station under development. After integration of Mir-2 and Freedom projects into International Space Station (ISS), the study on 2ϕ-MPL was continued. 2ϕ-MPL projects for the American and Russian segments of the ISS were carried out separately, but there was a broad exchange of scientific and technical information. The Keldysh Research Center (Russia) and the Center of Technical Physics (Ukraine) have been deeply involved in this research since 1993.

The design of the Central Two-Phase thermal control system of the International Space Station "ALPHA" Russian Segment (ISS RS) also implements the "thermal bus" concept [13, 14]. The schematic diagram of the ISS thermal control system is shown in Fig. 2 [15]. It is a closed loop, which includes pressure and bypass liquid lines 1 and 2, two-phase line 3. Pump forces ammonia to the pressure line, where it is fed to evaporative heat exchangers (EHEX). In the evaporative heat exchangers, the ammonia evaporates, collecting heat from the units and through the heat exchanger-regenerator (RHEX), separator (S), rotary hydraulic joint (RHJ), enters the Central Heat Exchanger-Radiator. Here it is condensed, mixed with bypass line, subcooled and flows back to the pump inlet.

The characteristics of the Central Two-Phase thermal control system ISS RS are as follows:

– working fluid – ammonia;
– heat load – 0…30 kW;
– maximum heat transfer distance – 50...100 m;
– ammonia boiling point in the evaporative heat exchangers – 10±2,5 °C;
– electric power consumption for own needs – not more than 200 W.

It was first proposed to use a heat-controlled accumulator (HCA) as an element that regulates the saturation pressure in the loop during the design of ISS TPS [16]. Currently, the element base of almost all 2ϕ-MPL projects in the world, as a rule, includes heat-controlled accumulator.

Work on the ISS TPS project was completed in 1999 by testing the experimental pumped loop of the LEU-1M flight experimental unit onboard Progress spacecraft as part of the Mir space station [11, 17]. The flight test telemetering data base was transferred to the Center of Technical Physics for interpretation and analysis. The results of these tests were summarized in several dissertations by RSC Energia, the Center of Technical Physics, and the Keldysh Research Center [15, 18, 19].

However, NASA eventually implemented a single-phase ammonia-based pumped thermal control system for its ISS segment, as it felt that the risks associated with the use of a fundamentally new two-phase heat transfer loop did not justify its advantages for this project.

The Russian segment of the ISS was assembled from modules that initially had individual liquid heat rejection subsystems. It was assumed that the centralized two-phase heat rejection system would be implemented in a separate Scientific Power Platform (also known by Russian initialism NEP), which would be launched at subsequent stages of the ISS assembly. However, this plan has not yet been implemented. A slightly reduced TPL design is expected to be implemented in an entirely new Science Power Platform module [20].

In the last two decades, interest in two-phase heat transfer loops has significantly increased due to high-power stationary communications satellites and autonomous spacecraft for Lunar and Martian missions.

The industry of stationary communication satellites is rapidly growing. If in the early 2000s, the number of active satellites in geostationary orbit was 958, in 2020, it already is 3371 (3.5 times more) [21].

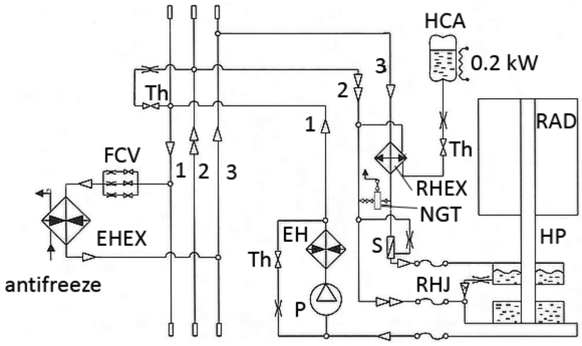

Fig. 2. Schematic diagram of "ALPHA" Russian Segment Two-Phase Heat Transport Loop:
HCA – heat-controlled accumulator;
RAD – central heat exchanger-radiator; P – pump;
RHJ – rotary hydraulic joint;
RHEX – heat exchanger-regenerator;
S – separator; EH – electric heater;
NGT – non-condensable gas trap;
FCV – flow control valve, HP – heat pipe;
—▷— – vapor line; —▶▶— – bypass line;
—■— – hydraulic joint; ▸◂ – valve; ≍ – throttle;
⊕ – heat exchanger; —▶— – pressure line

Fig. 3. Stand for the mechanically pumped TPL study at the Center of Technical Physics

One of the manufacturers of powerful stationary satellites is Thales Alenia Space – France. From 2003 to 2013, TAS-F, together with the Center of Technical Physics, have performed a large amount of experimental and theoretical work to select the optimal concept and structure of TPL for stationary space platforms with capacities from 7 to 20 kW [22, 23].

The Center of Technical Physics designed and built two experimental stands with freon 134A and ammonia as working fluids, on which (Fig. 3) joint studies of two-phase heat-transfer loops and element base were carried out in France and in Ukraine. Methods of design and calculation of characteristics of key elements of mechanically pumped TPL have also been developed: heat sinks, condensers, heat-controlled accumulator [24].

From 2014 to 2020, the Center of Technical Physics was involved in the 2ϕ-MPL development for the next-generation satellite SES-17, ordered by the telecommunications network provider SES S. A. [25, 26, 27].

Tests and certification of prototypes of the element base – heat sinks, condensers, heat-controlled accumulator – were performed. The satellite was launched into space on October 24, 2021 by onboard an Ariane 5 launcher operated by Arianespace from the Europe's Spaceport in Kourou, French Guiana [28]. For this project, heat-controlled accumulator was developed by the Center of Technical Physics and manufactured at the Ukrainian FED Corporation. The heat-controlled accumulator passed a set of qualification tests and is included in the regular thermal control system.

In the 2000s, work on 2ϕ-MPL continued in the USA, Europe, China, and Japan.

The work [29] points out the obvious advantages of using 2ϕ-MPL in comparison with single-phase solutions for satellites on low orbits and stationary satellites of 20...100 kW, which allows saving up to 50...80% of weight of the TCS. The authors note that, as of 2002, published information was not enough for engineers to confidently design a two-phase thermal control system for operation in microgravity conditions.

Mechanically pumped single-phase loops have also been used for thermal control of spacecraft in interplanetary missions [30].

Thermal issues on interplanetary spacecraft pose one of the greatest threats to achieving the goals of interplanetary missions. What is needed is a TCS that can simultaneously cope with the effects of a wide variety of environmental conditions, save energy consumption for heating and cooling objects and provide accurate instrument temperature control to reduce channel interference. Such capabilities are available through the use of 2ϕ-MPL and deeper heat control. Jet Propulsion Laboratory is currently developing a TPL-based thermal control system for spacecraft weighing up to 250 kg, which includes several evaporators and condensers [31, 32].

The NASA Technology Roadmap [33] classifies 2ϕ-MPLs as preferred for a series of future agency space missions, and also identifies the challenges faced during the implementation of TPL.

For the tasks mentioned in the NASA roadmap, Advanced Cooling Technologies, Inc. proposed an original TPL concept, in which the mechanism of separation and distribution of two-phase flow in the loop [34, 35] was improved compared to the previously developed TPL design with rotating fluid management device [6, 7]. The coolant is pumped by a mechanical pump coupled with two ejectors. Separation of phases after evaporators takes place in a special separator, which also serves as an accumulator.

A hybrid 2ϕ-MPL with combined pumping and capillary pumping can be proposed as an alternative design for medium power installations (2–10 kW) [36, 37]. In [38], the necessity of development of hybrid two-phase thermal control systems for spacecraft of a new class (H-TCS) for Lunar, Martian and Near-Earth Object projects is noted. They should perform the functions of simultaneous cooling and heating of objects under different gravity and temperature conditions. Hybrid 2ϕ-MPLs can fill the gap between capillary pumped loop and pumped TPL, successfully combining the advantages of pumped loops and capillary pumping of coolant.

A significant amount of work on two-phase heat transfer with capillary and pumped working fluid flow has been done at the National Aerospace Laboratory of the Netherlands since the 1980s up to the present time. The laboratory has performed extensive stand tests of the TPL and its elements [2, 27, 39].

The Alpha Magnetic Spectrometer instrument onboard the ISS was successfully launched in 2011, in which a small-sized TPL with mechanically pumped of carbon dioxide was used to thermally stabilize the object [40, 41].

National Aerospace Laboratory of the Netherlands has a long history of developing and practically implementing heat-controlled accumulators. National Aerospace Laboratory of the Netherlands was involved in the development of the two-phase accumulator concept for the Tracker Thermal Control System and in the design of the heat-controlled accumulator prototype for the Thales Alenia Space – France. Heat-controlled accumulator volumes may range from 10 to 40 liters, depending on the mission application [28].

During the last decades, extensive research on 2ϕ-MPL has been carried out in China [42, 43].

MIT, Zhongshan University, China Space Technology Center, National Aerospace Laboratory of the Netherlands, National Institute for Subatomic Physics, National Institute of Nuclear Physics of the University of Geneva, and other Chinese research centers have jointly developed an active thermal management system for the scientific research instrument, the AMS-02 Alpha Magnetic Spectrometer [44, 45]. The work [46] outlines the results of the study (carried out jointly with National Aerospace Laboratory of the Netherlands) of the characteristics of the TPL with the original model of flow-through heat-controlled accumulator, which is operable both on ground and in space.

2ϕ-MPL is a fundamentally new system for the spacecraft development practice. Despite a huge amount of research and development work [47], there are no practically implemented TCS projects with high-power TPL so far. The main reason is said to be the great risks associated with the insufficient study of the processes of two-phase heat transfer, hydrodynamics and heat exchange in microgravity [31], the lack of an element base qualified for space and the methodology of ground tests of 2ϕ-MPL. Therefore, concepts and methods that allow the qualification of the system on the basis of ground tests without mandatory tests in microgravity are important. Such concept is proposed in the Center of Technical Physics work [48].

The first powerful stationary satellite with the mechanically pumped TPL system was the SES-17 telecommunication satellite based on the Spacebus Near-Earth Object platform developed by Thales Alenia Space – France [49] and launched into orbit on October 24, 2021.

Conclusion

Mechanically pumped two-phase heat transfer loops for spacecraft TCS systems have been intensively developed for more than 40 years. They have undeniable advantages over single-phase loops with mechanical pumping and two-phase capillary pumped loops at power more than 6 kW and heat transfer distance more than 10 meters. The interest to them in the last two decades has increased significantly due to the projects of powerful stationary space platforms and various Lunar and Martian missions. Research and development are carried out in the USA, Europe, China, Japan, Russia. The "KhAI" and the Center of Technical Physics have been participating in these projects for a long time, since the 80's up to the present time.

Despite a large amount of research and development work done, there were no practically implemented projects of spacecraft with high-power thermal control system until recently. The first powerful stationary satellite with the mechanically pumped TPL system was SES-17 satellite on the NEOSAT platform by Thales Alenia Space – France. The satellite was successfully launched into space on October 24, 2021 by onboard an Ariane 5 launcher operated by Arianespace from the Europe’s Spaceport in Kourou, French Guiana.

References

1. Ollendorf, S. (1983). Recent and planned developments at the Goddard Space Flight Center in thermal control technology. *Proceeding of the International Symposium on Environmental and Thermal Systems of Space Vehicles*, Toulouse, France, pp. 45–51.
2. Delil, A. A. M. (1984). Some considerations concerning two-phase flow thermal bus systems for spacecraft: Report. National Aerospace Laboratory NLR, NLR Memorandum RL-84-028 U. http://resolver.tudelft.nl/uuid:7ca02b9b-faee-4a38-8a91-050583530e1e.
3. Raetz, J. & Dominick, J. (1992). Space station external thermal control system design and operational overview. *Proceedings of International Conference on Environmental Systems.* SAE International. https://doi.org/10.4271/921106.
4. Brady, T. K. (1988). Space station thermal test bed status and plans. *Proceedings of Intersociety Conference on Environmental Systems*. SAE International. https://doi.org/10.4271/881068.
5. Banaszynski, K., Hill, D. G., & Nguyen, D. C. (1992). A pump module for the space station freedom active thermal control system. *Proceedings of International Conference on Environmental Systems*. SAE International. https://doi.org/10.4271/921108.
6. Bland, T. J., Downing, R. S., & Rogers, D. P. (1984). A two-phase thermal management system for large space platforms. *Proceedings of 19th Thermophysics Conference.* American Institute of Aeronautics and Astronautics. https://doi.org/10.2514/6.1984-1758.

7. Hill, D. G., Hsu, K., Parish, R., & Dominick, J. (1988). Reduced gravity and ground testing of a two-phase thermal management system for large spacecraft. *Proceedings of Intersociety Conference on Environmental Systems.* SAE International. https://doi.org/10.4271/881084.
8. Chambliss, J. (1992). The evolution of the space station freedom thermal control system. *Proceedings of International Conference on Environmental Systems.* SAE International. https://doi.org/10.4271/921105.
9. Kreeb, H., Möller, P., & Wulz, H. G. (1985). Development of a two-phase thermal cycle for European platforms. *Deutsche Gesellschaft für Luftund Raumfahrt, International Symposium*. Towards COLUMBUS and Space Station, Bonn – Bad Godesberg.
10. Nikonov, A. A., Gorbenko, G. A., & Blinkov, V. N. (1991). *Teploobmennyye kontury s dvukhfaznym teplonositelem dlya sistem termoregulirovaniya kosmicheskikh apparatov* [Heat exchange circuits with a two-phase coolant for thermal control systems of spacecraft]. Moscow: Center for Scientific and Technical Information "Poisk", 302 p. (in Russian).
11. Romanov, S. Yu., Sementsov, A. N., Gorbenko, G. A., Gakal, P. G., & Yepifanov, K. S. (2002). *Analiz rabotosposobnosti dvukhfaznogo kontura teploperenosa v usloviyakh nevesomosti* [Analysis of the performance of a two-phase heat transfer circuit under zero gravity]. Proceedings of the Third Russian National Conference on Heat and Mass Transfer. *T. 5. Dvukhfaznyye techeniya. Dispersnyye potoki i poristyye sredy* [Vol. 5. Two-phase flows. Dispersed flows and porous media]. Moscow: Moscow Power Engineering Institute Publ., pp. 102–105 (in Russian).
12. Goncharov, K., Maidanik, Yu., & Fershtater, Yu. (1991). Capillary pumped loop for the systems of thermal regulation of spacecraft. *Proceedings of 4th ICES*, Florence, Oct. 21–24, 1991, pp. 125–129.
13. Gorbenko, G. A., Ganzha, Ye. P., Malukhin, K. A., Prokopenkov, A. A., Tsikhotskiy, V. M., Sementsov, A. N., & Linkova, I. Yu. (1996). *Dvukhfaznyy kontur teploperenosa Tsentralnoy sistemy teplootvoda rossiyskogo segmenta Mezhdunarodnoy kosmicheskoy stantsii «ALFA»* [Two-phase heat transfer circuit of the Central Heat Removal System of the Russian Segment of the International Space Station "ALFA]. *Aviatsionno-kosmicheskaya tekhnika i tekhnologiya – Aerospace engineering and technology*, pp. 136–147 (in Russian).
14. Grigoriev, Y. I., Cykhotsky, V. M., Prokhorov, Y. M., Surguchev, O. V., Gorbenko, G. A., Blinkov, V. N., Teniakov, I. E., & Malukhin, C. A. (1996). Two-phase heat transfer loop of central thermal control system of the International Space Station ALPHA Russian Segment. *Proceedings of National Heat Transfer Conference*. Houston, Texas, USA. pp. 9–18.
15. Sementsov, A. N. (2003). *Modelirovaniye dvukhfaznogo kontura teploperenosa tsentralizovannoy sistemy teplootvoda rossiyskogo segmenta mezhdunarodnoy kosmicheskoy stantsii v usloviyakh kosmicheskogo poleta* [Modeling of a two-phase heat transfer circuit of the centralized heat removal system of the Russian segment of the International Space Station in space flight conditions]: Ph.D. dissertation abstract. S. P. Korolev Rocket and Space Corporation Energia, Moscow (in Russian).
16. Cykhotsky, V. M., Sementsov, A. N., Grigoriev, Y. I., Prokhorov, Y. M., Gorbenko, G. A., Malukhin, C. A., & Ganja, E. P. (1999). Development and analysis of control methods of the International Space Station "ALPHA" Russian Segment Central Two-Phase Thermal Control System parameters. *AIP Conference Proceedings*, vol. 458, pp. 848–853. https://doi.org/10.1063/1.57706.
17. Tsikhotskiy, V. M., Prokhorov, Yu. M., Sementsov, A. N., Linkova, I. Yu., Gorbenko, G. A., Yepifanov, K. S., Bednov, S. M., Bednov, P. D., Vezhnevets, P. D., Golikov, A. N., Desyatov, A. V., & Lukyanov, Yu. M. (1999). *Letnaya eksperimentalnaya ustanovka – model dvukhfaznogo kontura teploperenosa rossiyskogo segmenta Mezhdunarodnoy kosmicheskoy stantsii* [Flight experimental setup - model of a two-phase heat transfer circuit of the Russian segment of the International Space Station]. *Aviatsionno-kosmicheskaya tekhnika i tekhnologiya – Aerospace engineering and technology*, iss. 13, pp. 41–49 (in Russian).
18. Iepifanov, K. S. (2004). *Parametrychna identyfikatsiia robochykh protsesiv enerhetychnykh ustanovok z dvofaznym teplonosiiem dlia kosmichnykh aparativ* [Parametric identification of working processes of power plants with two-phase coolant for spacecraft]: Ph.D. dissertation abstract. National Aerospace University "Kharkiv Aviation Institute", Kharkiv, 33 p. (in Ukrainian).
19. Khramov, S. M. (2004). *Eksperimentalnyye i raschetnyye issledovaniya perspektivnykh dvukhfaznykh sistem obespecheniya teplovogo rezhima kosmicheskikh apparatov i ikh elementov* [Experimental and computational studies of promising two-phase systems for ensuring the thermal regime of spacecraft and their elements]: Ph.D. dissertation abstract. Keldysh Research Center, Moscow, 23 p. (in Russian).
20. Basov, A. A., Leksin, M. A., & Prokhorov, Yu. M. (2017). *Dvukhfaznyy kontur sistemy obespecheniya teplovogo rezhima nauchno-energeticheskogo modulya. Chislennoye modelirovaniye gidravlicheskikh kharakteristik* [Two-phase contour of the system for ensuring the thermal regime of the scientific-power module. Numerical simulation of hydraulic characteristics]. *Kosmicheskaya tekhnika i tekhnologii – Space engineering and technology*, no. 2, pp. 80–89 (in Russian).

21. *Satellite Industry Association. State of the Satellite Industry Report: 2021* https://sia.org/news-resources/state-of-the-satellite-industry-report/
22. Merino, A.-S., Hugon, J., Cailloce, Y., Michard, F., Tjiptahardia, T., Larue de Tournemine, A., & Laporte, C. (2010). Development of a two-phase mechanically pumped loop (2ΦMPDL) for the thermal dissipation management of an active antenna. *Proceedings of 40th International Conference on Environmental Systems*. American Institute of Aeronautics and Astronautics. https://doi.org/10.2514/6.2010-6032.
23. Gakal, P. G., Ruzaykin, V. I., Turna, R. Yu., Chayka, D. V., Timoshchenko, V. M., & Ivanenko, N. I. (2011). *Eksperimentalnyy stend dlya issledovaniya teplogidravlicheskikh protsessov v sisteme termoregulirovaniya telekommunikatsionnogo sputnika* [Experimental stand for the study of thermohydraulic processes in the thermal control system of a telecommunications satellite]. *Aviatsionno-kosmicheskaya tekhnika i tekhnologiya – Aerospace Engineering and Technology*, no. 5, pp. 21–30 (in Russian).
24. Gorbenko, G., Koval, P., Yepifanov, K., Gakal, P., & Turna, R. (2020). Mathematical model of heat-controlled accumulator (HCA) for microgravity conditions. *SAE International Journal of Aerospace*, vol. 13, iss. 1, pp. 5–23. https://doi.org/10.4271/01-13-01-0001.
25. Hugon, J. & Larue de Tournemine, A. (2008). Development of a two-phase mechanically pumped loop (2ΦMPL) for the thermal control of telecommunication satellites. *Proceedings of International Two-Phase Thermal Control Technology Workshop*, ESTEC, The Netherlands.
26. Chaix, A., Hugon, J., Hugonnot, P., & Delmas, A. (2014). Development of a two-phase mechanically pumped loop (2ΦMPL) for the thermal dissipation management of spacecraft: Simulation and test results. *Proceedings of 44th International Conference on Environmental Systems*. Tucson, Arizona, 17 p. http://hdl.handle.net/2346/59598.
27. van Es, J., van Gerner, H. J., van Benthem, R. C., Lapensée, S., & Schwaller, D. (2016). Component developments in europe for mechanically pumped loop systems (MPLs) for cooling applications in space. *Proceedings of 46th International Conference on Environmental Systems*, Vienna, Austria, 14 p. https://ttu-ir.tdl.org/bitstream/handle/2346/67589/ICES_2016_196.pdf?sequence=1.
28. SES-17 Successfully Launched on Ariane 5. SES: official site. https://www.ses.com/press-release/ses-17-successfully-launched-ariane-5.
29. Ponnappan, R., Donovan, B., & Chow, L. (2002). High-power thermal management issues in space-based systems. *AIP Conference Proceedings*, vol. 608, iss. 1. https://doi.org/10.1063/1.1449709.
30. Bhandari, P., Birur, G. C., Bame, D., Mastropietro, A. J., Karlmann, P., Liu, Y., & Miller, J. (2013). Performance of the mechanically pumped fluid loop rover heat rejection system used for thermal control of the Mars science laboratory curiosity rover on the surface of Mars. *Proceedings of 43rd International Conference on Environmental Systems.* American Institute of Aeronautics and Astronautics. https://doi.org/10.2514/6.2013-3323.
31. Sunada, E. (2016). A two-phase mechanically pumped fluid loop for thermal control of deep space science missions. *Proceedings of 46th International Conference on Environmental Systems*. http://hdl.handle.net/2346/67545.
32. Furst, B., Sunada, E., Cappucci, S., Bhandari, P., Daimaru, T., & Nagai, H. (2017). A comparison of system architectures for a mechanically pumped two-phase thermal control system. *Proceedings of 47th International Conference on Environmental Systems*. http://hdl.handle.net/2014/46384.
33. (2015). NASA Technology Roadmaps, TA 14: Thermal Management Systems: Report. NASA, Washington D.C., 97 p. https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_14_thermal_management_final.pdf.
34. Ellis, M. C. & Kurwitz, R. C. (2016). Development of a pumped two-phase system for spacecraft thermal control. *46th International Conference on Environmental Systems*, Vienna, Austria, pp. 1–16.
35. (2013). Advanced Cooling Technologies Inc., Multi-phase pump system and method of pumping a two-phase fluid stream: Pat. US20140246095A1. USA.
36. Bugby, D. (2007). Multi-evaporator hybrid two phase loop cooling system for small satellites. *Proceedings of 21st Annual AIAA/USU Conference on Small Satellites*, Logan, Utah. https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=1501&context=smallsat.
37. Hoang, T. T., Baldauff, R. W., & Cheung, K. H. (2007). Hybrid two-phase mechanical / capillary pumped loop for high-capacity heat transport. *Proceedings of International Conference on Environmental Systems.* SAE International. https://doi.org/10.4271/2007-01-3198.
38. Lee, S. H., Mudawar, I., & Hasan, M. M. (2016). Thermal analysis of hybrid single-phase, two-phase and heat pump thermal control system (TCS) for future spacecraft. *Applied Thermal Engineering*, vol. 100, pp. 190–214. https://doi.org/10.1016/j.applthermaleng.2016.01.018.
39. Delil, A. A. M., Heemskerk, J. F., Mastenbroek, O., Dubois, M., van Oost, S., Coesel, M. J. N., Supper, W., & Aceti, R. (1995). TPX for in-orbit demonstration of two-phase heat transport technology-evaluation of flight &

post-flight experiment results. *Proceedings of International Conference on Environmental Systems*. SAE International. https://doi.org/10.4271/951510.
40. van Es, J., Pauw, A., van Donk, G., van Gerner, H. J., Laudi, E., He, Z., Gargiulo, C., & Verlaat, B. (2013). AMS02 tracker thermal control cooling system commissioning and operational results. *Proceedings of 43rd International Conference on Environmental Systems*. American Institute of Aeronautics and Astronautics. https://doi.org/10.2514/6.2013-3389.
41. Alberti, G., Alvino, A., Ambrosi, G., Bardet, M., Battison, R., Borsini, R., Cao, S., Cao, J., Chen, Y., Es, J., Gargiulo, C., Guo, K., Guo, L., Zhenhui, H., Zhencheng, H., Koutsenko, V., Laudi, E., Lebedev, A., Lee, S., Li, T., & Zwartbol, T. (2013). Development of a thermal control system with mechanically pumped CO_2 two phase loops for the AMS-02 tracker on the ISS. Cornell University. https://arxiv.org/abs/1302.4294.
42. Liu, J., He, Y. F., Zhou, E. Z., & Zhao, W. J. (2011). Experimental investigation on the accumulator liquid distribution of mechanically pumped cooling system. *Applied Mechanics and Materials,* vol. 84–85, pp. 254–258. https://doi.org/10.4028/www.scientific.net/amm.84-85.254.
43. Wang, Z. R., Zhang, X. B., Wen, S. Z., Huang, Z. C., Mo, D. C., Xue, Y. Q., & He, Z. H. (2017). Design and performance of a mechanically pumped two-phase loop to support the evaporation-condensation experiments on the TZ1. *Case Studies in Thermal Engineering,* vol. 10, pp. 650–655. https://doi.org/10.1016/j.csite.2017.11.008.
44. Zhang, Z., Sun, X. H., Tong, G. N., Huang, Z. C., He, Z. H., Pauw, A., van Es, J., Battiston, R., Borsini, S., Laudi, E., Verlaat, B., & Gargiulo, C. (2011). Stable and self-adaptive performance of mechanically pumped CO2 two-phase loops for AMS-02 tracker thermal control in vacuum. *Applied Thermal Engineering*, vol. 31, iss. 17–18, pp. 3783–3791. https://doi.org/10.1016/j.applthermaleng.2011.07.015.
45. Delil, A. A. M. (2002). Two-phase developments for the international space station ISS: – AMS-2 TTCS, a mechanically pumped two-phase CO_2 cooling loop for the alpha magnetic spectrometer tracker experiment-CIMEX-3, versatile two-phase loop for the fluid science laboratory. *Texas Academical Science*, vol. 48, pp. 107–118.
46. Meng, Q., Zhao, Z., Zhang, T., van Es, J., Pauw, A., Zhang, H., & Yan, Y. (2020). Experimental study on the transient behaviors of mechanically pumped two-phase loop with a novel accumulator for thermal control of space camera payload. *Applied Thermal Engineering*, vol. 179, Article ID 115714. https://doi.org/10.1016/j.applthermaleng.2020.115714.
47. Turna, R. Yu. & Godunov, A. M. (2021). *Sostoyaniye razrabotok dvukhfaznykh sistem termoregulirovaniya kosmicheskikh apparatov* [State of development of two-phase thermal control systems for spacecraft] *Aviatsionno-kosmicheskaya tekhnika i tekhnologiya – Aerospace Engineering and Technology*, no. 2, pp. 36–51 (in Russian).
48. Turna, R. Yu. (2021). *Razrabotka kontseptsii dvukhfaznoy sistemy teplootvoda sputnika* [Development of the concept of a two-phase heat removal system for a satellite]. *Aviatsionno-kosmicheskaya tekhnika i tekhnologiya – Aerospace Engineering and Technology*, no. 1, pp. 31–46 (in Russian).
49. SES-17 to launch on 22 October. SES: official site. https://www.ses.com/press-release/ses-17-launch-22-october.

Received 18 October 2021

Ретроспективний огляд розробок двофазних контурів теплопереносу з насосним прокачуванням теплоносія для систем забезпечення теплового режиму космічних апаратів

[1] Г. О. Горбенко, [2] П. Г. Гакал, [1] Р. Ю. Турна, [2] А. М. Годунов

[1] Центр технічної фізики «ЦТФ», 61070, Україна, м. Харків, вул. Чкалова, 17

[2] Національний аерокосмічний університет ім. М. Є. Жуковського «Харківський авіаційний інститут», 61070, Україна, м. Харків, вул. Чкалова, 17

Основні питання, пов'язані з розробкою двофазних контурів теплопереносу з механічним прокачуванням теплоносія для систем забезпечення теплового режиму космічних апаратів з великою енергоозброєністю, сформульовані ще на початку 80-х. Вони мають незаперечні переваги порівняно з однофазними контурами з механічним прокачуванням і двофазними контурами з капілярним прокачуванням за потужності понад 6 кВт і відстані теплопереносу понад 10 м. Інтенсивні дослідження і розробки таких систем розпочаті в США спільно з європейськими, канадськими і японськими фахівцями у зв'язку з планами створення нових космічних апаратів великої потужності і проєктом орбітальної станції Freedom. У 90-ті роки в РКК «Енергія» імені С. П. Корольова (Росія) велися роботи зі створення двофазного контуру теплопереносу з механічним прокачуванням теплоносія для російського сегменту Міжнародної космічної станції (МКС) потужністю 20–30 кВт. Для цього були задіяні провідні дослідницькі організації колишнього СРСР. Інтерес до двофазних контурів в останні два десятиліття істотно зріс через проекти потужних стаціонарних космічних платформ та різних *місячних і марсіанських місій. У статті поданий ретроспективний огляд світових розробок двофазних контурів теплопереносу з механічним прокачуванням теплоносія для систем забезпечення теплового режиму космічних апаратів з великою енергоозброєністю з початку 80-х років дотепер. Розглянуто участь у розробках вчених та інженерів Національного аерокосмічного університету «ХАІ» та Центру технічної фізики (Харків, Україна). Висвітлено основні напрями досліджень, результати розробок та науково-технічні проблеми на шляху практичної реалізації двофазної системи. Незважаючи на великий обсяг виконаних пошукових і дослідно-конструкторських робіт, до недавнього часу не було практично реалізованих проектів космічних апаратів з двофазним контуром теплопереносу великої потужності. Першим потужним стаціонарним супутником з двофазним контуром теплопереносу став супутник SES-17 на платформі NEOSAT компанії Thales Alenia Space-France. Супутник виведений на орбіту 24 жовтня 2021 року ракетою Ariane-5 з космодрому Куру, Французька Гвіана.*

Ключові слова: *космічний апарат; система терморегулювання; двофазний контур теплопереносу з механічним прокачуванням теплоносія.*

Література

1. Ollendorf S. Recent and planned developments at the Goddard Space Flight Center in thermal control technology. *Proc. Intern. Symposium on Environmental and Thermal Systems of Space Vehicles*, Toulouse, France. 1983. P. 45–51.
2. Delil A. A. M. Some considerations concerning two-phase flow thermal bus systems for spacecraft: Report. National Aerospace Laboratory NLR, NLR Memorandum RL-84-028 U. http://resolver.tudelft.nl/uuid:7ca02b9b-faee-4a38-8a91-050583530e1e.
3. Raetz J., Dominick J. Space station external thermal control system design and operational overview. *Proc. Intern. Conf. on Environmental Systems.* SAE International. 1992. https://doi.org/10.4271/921106.
4. Brady T. K. Space station thermal test bed status and plans. *Proc. Intersociety Conf. on Environmental Systems.* SAE International. 1988. https://doi.org/10.4271/881068.
5. Banaszynski K., Hill D. G., Nguyen D. C. A pump module for the space station freedom active thermal control system. *Proc. Intern. Conf. on Environmental Systems*. SAE International. 1992. https://doi.org/10.4271/921108.
6. Bland T. J., Downing R. S., Rogers D. P. A two-phase thermal management system for large space platforms. *Proc. 19th Thermophysics Conf.* American Institute of Aeronautics and Astronautics. 1984. https://doi.org/10.2514/6.1984-1758.
7. Hill D. G., Hsu K., Parish R., Dominick J. Reduced gravity and ground testing of a two-phase thermal management system for large spacecraft. *Proc. Intersociety Conf. on Environmental Systems.* SAE International. 1988. https://doi.org/10.4271/881084.
8. Chambliss J. The evolution of the space station freedom thermal control system. *Proc. Intern. Conf. on Environmental Systems.* SAE International. 1992. https://doi.org/10.4271/921105.
9. Kreeb H., Möller P., Wulz H. G. Development of a two-phase thermal cycle for European platforms. *Deutsche Gesellschaft für Luftund Raumfahrt, Int. Symp.* Towards COLUMBUS and Space Station, Bonn – Bad Godesberg. 1985.
10. Никонов А. А., Горбенко Г. А., Блинков В. Н. Теплообменные контуры с двухфазным теплоносителем для систем терморегулирования космических аппаратов. М.: Центр НТИ «Поиск», 1991. 302 с.
11. Романов С. Ю., Семенцов А. Н., Горбенко Г. А., Гакал П. Г., Епифанов К. С. Анализ работоспособности двухфазного контура теплопереноса в условиях невесомости. Тр. Третьей Рос. нац. конф. по тепломассообмену. Т. 5. Двухфазные течения. Дисперсные потоки и пористые среды. М.: Моск. энерг. ин-т, 2002. С. 102–105.
12. Goncharov K., Maidanik Yu., Fershtater Yu. Capillary pumped loop for the systems of thermal regulation of spacecraft. *Proc. 4th ICES*. Florence, Oct. 21–24, 1991. P. 125–129.
13. Горбенко Г. А., Ганжа Е. П., Малухин К. А., Прокопенков А. А., Цихоцкий В. М., Семенцов А. Н., Линькова И. Ю. Двухфазный контур теплопереноса Центральной системы теплоотвода российского сегмента Международной космической станции «АЛЬФА». *Авиац.-косм. техника и технология*: Сб. науч. тр. Харьков: Харьк. авиац. ин-т им. Н. Е. Жуковского, 1996. С. 136–147.
14. Grigoriev Y. I., Cykhotsky V. M., Prokhorov Y. M., Surguchev O. V., Gorbenko G. A., Blinkov V. N., Teniakov I. E., Malukhin C. A. Two-phase heat transfer loop of central thermal control system of the International Space Station ALPHA Russian Segment. *Proc. National Heat Transfer Conf.* Houston, Texas, USA. 1996. P. 9–18.
15. Семенцов А. Н. Моделирование двухфазного контура теплопереноса централизованной системы теплоотвода российского сегмента международной космической станции в условиях космического полета: автореф. дис. ... канд. техн. наук: 05.07.03 / Ракетно-космическая корпорация «Энергия» имени С. П. Королёва, М., 2003.

16. Cykhotsky V. M., Sementsov A. N., Grigoriev Y. I., Prokhorov Y. M., Gorbenko G. A., Malukhin C. A., Ganja E. P. Development and analysis of control methods of the International Space Station "ALPHA" Russian Segment Central Two-Phase Thermal Control System parameters. *AIP Conf. Proc*. 1999. Vol. 458. P. 848–853. https://doi.org/10.1063/1.57706.
17. Цихоцкий В. М., Прохоров Ю. М., Семенцов А. Н., Линькова И. Ю., Горбенко Г. А., Епифанов К. С., Беднов С. М., Беднов П. Д., Вежневец П. Д., Голиков А. Н., Десятов А. В., Лукьянов Ю. М. Летная экспериментальная установка – модель двухфазного контура теплопереноса российского сегмента Международной космической станции. *Авиац.-косм. техника и технология*: Сб. науч. тр. Харьков: Харьк. авиац. ин-т им. Н. Е. Жуковского, 1999. Вып. 13. С. 41–49.
18. Єпіфанов К. С. Параметрична ідентифікація робочих процесів енергетичних установок з двофазним теплоносієм для космічних апаратів: автореф. дис. ... канд. техн. наук: 05.07.05 / Нац. аерокосм. ун-т ім. М. Є. Жуковського «Харк. авіац. ін-т». Харків, 2004. 33 с.
19. Храмов С. М. Экспериментальные и расчетные исследования перспективных двухфазных систем обеспечения теплового режима космических аппаратов и их элементов: автореф. дис. ... канд. техн. наук: 05.07.05 / Исследовательский центр имени М.В. Келдыша, М., 2003. 23 с.
20. Басов А. А., Лексин М. А., Прохоров Ю. М. Двухфазный контур системы обеспечения теплового режима научно-энергетического модуля. Численное моделирование гидравлических характеристик. *Косм. техника и технологии*. 2017. № 2. С. 80–89.
21. *Satellite Industry Association. State of the Satellite Industry Report: 2021*. https://sia.org/news-resources/state-of-the-satellite-industry-report/.
22. Merino A.-S., Hugon J., Cailloce Y., Michard F., Tjiptahardia T., Larue de Tournemine A., Laporte C. Development of a two-phase mechanically pumped loop (2ΦMPDL) for the thermal dissipation management of an active antenna. *Proc. 40th Intern. Conf. on Environmental Systems*. American Institute of Aeronautics and Astronautics. 2010. https://doi.org/10.2514/6.2010-6032.
23. Гакал П. Г., Рузайкин В. И., Турна Р. Ю., Чайка Д. В., Тимощенко В. М., Иваненко Н. И. Экспериментальный стенд для исследования теплогидравлических процессов в системе терморегулирования телекоммуникационного спутника. *Авиац.-косм. техника и технология*. 2011. № 5. С. 21–30.
24. Gorbenko G., Koval P., Yepifanov K., Gakal P., Turna R. Mathematical model of heat-controlled accumulator (HCA) for microgravity conditions. *SAE Intern. J. Aerospace*. 2020. Vol. 13. Iss. 1. P. 5–23. https://doi.org/10.4271/01-13-01-0001.
25. Hugon J., Larue de Tournemine A. Development of a two-phase mechanically pumped loop (2ΦMPL) for the thermal control of telecommunication satellites. *Proc. Intern. Two-Phase Thermal Control Technology Workshop*, ESTEC, The Netherlands. 2008.
26. Chaix A., Hugon J., Hugonnot P., Delmas A. Development of a two-phase mechanically pumped loop (2ΦMPL) for the thermal dissipation management of spacecraft: Simulation and test results. *Proc. 44th Intern. Conf. on Environmental Systems*. Tucson, Arizona. 2014. http://hdl.handle.net/2346/59598.
27. van Es J., van Gerner H. J., van Benthem R. C., Lapensée S., Schwaller D. Component developments in europe for mechanically pumped loop systems (MPLs) for cooling applications in space. *Proc. 46th Intern. Conf. on Environmental Systems*, Vienna, Austria, 2016. 14 p. https://ttu-ir.tdl.org/bitstream/handle/2346/67589/ICES_2016_196.pdf?sequence=1.
28. SES-17 Successfully Launched on Ariane 5. SES: official site. https://www.ses.com/press-release/ses-17-successfully-launched-ariane-5.
29. Ponnappan R., Donovan B., Chow L. High-power thermal management issues in space-based systems. *AIP Conf. Proc*. 2002. Vol. 608. Iss. 1. https://doi.org/10.1063/1.1449709.
30. Bhandari P., Birur G. C., Bame D., Mastropietro A. J., Karlmann P., Liu Y., Miller J. Performance of the mechanically pumped fluid loop rover heat rejection system used for thermal control of the Mars science laboratory curiosity rover on the surface of Mars. *Proc. 43rd Intern. Conf. on Environmental Systems*. American Institute of Aeronautics and Astronautics. 2013. https://doi.org/10.2514/6.2013-3323.
31. Sunada E. A two-phase mechanically pumped fluid loop for thermal control of deep space science missions. *Proc. 46th Intern. Conf. on Environmental Systems*. 2016. http://hdl.handle.net/2346/67545.
32. Furst B., Sunada E., Cappucci S., Bhandari P., Daimaru T., Nagai H. A comparison of system architectures for a mechanically pumped two-phase thermal control system. *Proc. 47th Intern. Conf. on Environmental Systems*. 2017. http://hdl.handle.net/2014/46384.
33. NASA Technology Roadmaps, TA 14: Thermal Management Systems:Report. NASA, Washington D.C. 2015. 97 p. https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_14_thermal_management_final.pdf.
34. Ellis M. C., Kurwitz R. C. Development of a pumped two-phase system for spacecraft thermal control. *Proc. 46th Intern. Conf. on Environmental Systems*, Vienna, Austria. 2016. P. 1–16.

35. Advanced Cooling Technologies Inc., Multi-phase pump system and method of pumping a two-phase fluid stream: Pat. US20140246095A1. USA, 2013.
36. Bugby D. Multi-evaporator hybrid two-phase loop cooling system for small satellites. *Proc. 21st Annual AIAA/USU Conf. on Small Satellites,* Logan, Utah. 2007. https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=1501&context=smallsat.
37. Hoang T. T., Baldauff R. W., Cheung K. H. Hybrid two-phase mechanical / capillary pumped loop for high-capacity heat transport. *Proc. Intern. Conf. on Environmental Systems.* SAE International. 2007. https://doi.org/10.4271/2007-01-3198.
38. Lee S. H., Mudawar I., Hasan M. M. Thermal analysis of hybrid single-phase, two-phase and heat pump thermal control system (TCS) for future spacecraft. *Appl. Thermal Eng.* 2016. Vol. 100. P. 190–214. https://doi.org/10.1016/j.applthermaleng.2016.01.018.
39. Delil A. A. M., Heemskerk J. F., Mastenbroek O., Dubois M., van Oost S., Coesel M. J. N., Supper W., Aceti R. TPX for in-orbit demonstration of two-phase heat transport technology-evaluation of flight & post-flight experiment results. *Proc. Intern. Conf. on Environmental Systems.* SAE International. 1995. https://doi.org/10.4271/951510.
40. van Es J., Pauw A., van Donk G., van Gerner H. J., Laudi E., He Z., Gargiulo C., Verlaat B. AMS02 tracker thermal control cooling system commissioning and operational results. *Proc. 43rd Intern. Conf. on Environmental Systems*. American Institute of Aeronautics and Astronautics. 2013. https://doi.org/10.2514/6.2013-3389.
41. Alberti G., Alvino A., Ambrosi G., Bardet M., Battison R., Borsini R., Cao S., Cao J., Chen Y., Es J., Gargiulo C., Guo K., Guo L., Zhenhui H., Zhencheng H., Koutsenko V., Laudi E., Lebedev A., Lee S., Li T., Zwartbol T. Development of a thermal control system with mechanically pumped CO_2 two phase loops for the AMS-02 tracker on the ISS: Research Paper. Cornell University. 2013. https://arxiv.org/abs/1302.4294.
42. Liu J., He Y. F., Zhou E. Z., Zhao W. J. Experimental investigation on the accumulator liquid distribution of mechanically pumped cooling system. *Appl. Mech. and Materials*. 2011. Vol. 84–85. P. 254–258. https://doi.org/10.4028/www.scientific.net/amm.84-85.254.
43. Wang Z. R., Zhang X. B., Wen S. Z., Huang Z. C., Mo D. C., Xue Y. Q., He Z. H. Design and performance of a mechanically pumped two-phase loop to support the evaporation-condensation experiments on the TZ1. *Case Studies in Thermal Eng*. 2017. Vol. 10. P. 650–655. https://doi.org/10.1016/j.csite.2017.11.008.
44. Zhang Z., Sun X. H., Tong G. N., Huang Z. C., He Z. H., Pauw A., van Es J., Battiston R., Borsini S., Laudi E., Verlaat B., Gargiulo C. Stable and self-adaptive performance of mechanically pumped CO2 two-phase loops for AMS-02 tracker thermal control in vacuum. *Appl. Thermal Eng*. 2011. Vol. 31. Iss. 17–18. P. 3783–3791. https://doi.org/10.1016/j.applthermaleng.2011.07.015.
45. Delil A. A. M. Two-phase developments for the international space station ISS: – AMS-2 TTCS, a mechanically pumped two-phase CO_2 cooling loop for the alpha magnetic spectrometer tracker experiment-CIMEX-3, versatile two-phase loop for the fluid science laboratory. *Texas Acad. Sci*. 2002. No. 48. P. 107–118.
46. Meng Q., Zhao Z., Zhang T., van Es J., Pauw A., Zhang H., Yan Y. Experimental study on the transient behaviors of mechanically pumped two-phase loop with a novel accumulator for thermal control of space camera payload. *Appl. Thermal Eng*. 2020. Vol. 179. Article ID 115714. https://doi.org/10.1016/j.applthermaleng.2020.115714.
47. Турна Р. Ю., Годунов А. М. Состояние разработок двухфазных систем терморегулирования космических аппаратов. *Авиац.-косм. техника и технология.* 2021. № 2. С. 36–51.
48. Турна Р. Ю. Разработка концепции двухфазной системы теплоотвода спутника. *Авиац.-косм. техника и технология.* 2021. № 1. С. 31–46.
49. SES-17 to launch on 22 October. SES: official site. https://www.ses.com/press-release/ses-17-launch-22-october.