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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.
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 2\(\phi\)-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.

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. 2\(\phi\)-MPL makes it easy to stabilize and control of payload units temperature. These properties of 2\(\phi\)-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]:

\[
K_T = \frac{Q}{L \cdot M},
\]

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), 2\(\phi\)-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 2\(\phi\)-MPLs

Intensive research and development of 2\(\phi\)-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 2\(\phi\)-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 2\(\phi\)-MPL.

In 1992, RSC Energia and "KhAI" initiated a representative interdepartmental seminar [11], which provided an opportunity to coordinate and intensify further 2\(\phi\)-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 2\(\phi\)-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 2\(\phi\)-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 2\(\phi\)-MPL was continued. 2\(\phi\)-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 pres-
sure 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].
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 inten-
sively developed for more than 40 years. They have undeniable advantages over single-phase loops with me-
chanical 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 pro-
jects of powerful stationary space platforms and various Lunar and Martian missions. Research and devel-
opment 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 imple-
mented projects of spacecraft with high-power thermal control system until recently. The first powerful sta-
tionary 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
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місячних і марсіанських місій. У статті подані ретроспективний огляд світових розробок двофазних конту- рів теплопереносу з механічним прокачуванням теплоносія для систем забезпечення теплового режиму косміч- них апаратів з великою енергоємністю з початку 80-х років дотепер. Розглянуто участь у розробках вчес- них 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-конструкційних робіт, до недавнього часу не було практично реалізованих проектів космічних апаратів з двофазним контуrom теплопереносу великої потужності. Першим потужним станційним супутником з двофазним контуrom 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 Куро, Фра- нцузька Гвіана.

Ключові слова: космічний апарат; система терморегулювання; двофазний контур теплопереносу з меха- нічним прокачуванням теплоносія.

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