Evaluating the potential of modular passive cooling systems

P M Savchenkov
National Research University "MPEI", Russia, 111250 Moscow, Krasnokazarmennaya, 14
Savchenkovpm@gmail.com

Abstract. The article describes the possibilities prospects and technical-economic efficiency of using the modular cooling systems, especially passive cooling systems, for cooling various types of electronic equipment and infrastructure facilities. They are especially interesting when applied in scalable systems, which allows to obtain significant savings in design, production, installation and operation of such systems.

1. Introduction
Nowadays, energy saving is becoming a priority issue of the majority of the technical systems. One of the ways to improve the energy efficiency in maintaining the required temperature regimes of fuel equipment, as well as creating the necessary environmental conditions is the use of passive heat transfer devices used to create the required thermal mode of operation. Passive cooling systems do not use additional energy sources that require financial costs during operation. This is most often the consumption of electrical energy for its functioning. These systems allow to cool, heat, or maintain temperature using a variety of heat transfer mechanisms at no additional cost.

Passive systems can be divided into several types:
- systems using the mechanism of heat conduction when removing heat from a cooled object with its subsequent dissipation into the environment using natural or forced convection;
- systems using free cooling, in fact, replacing powerful refrigeration units for cooling rooms with high heat dissipation, with minimal energy consumption to drive fans to create an efficient heat dissipation mode;
- systems using mechanisms of phase transitions of evaporation-condensation, such as heat pipes and thermosyphons of various designs;
- systems using the mechanisms of phase transitions melting and solidification, which are actually heat or cold accumulators, etc.;
- various combinations of the types mentioned.

Nowadays, a large number of passive devices and systems have been described, but it should be noted that the described typical systems often do not have standard solutions, which necessitates individual design, significantly increasing design costs. There is also the problem of objectively choosing a specific device or system for solving various problems, due to limited resources, aggressive promotion of certain brands and types of equipment, as well as the qualifications and outlook of the designer of these systems. In this regard, it is necessary to develop universal methods for choosing a cooling system for heat-generating equipment, one of which is modular passive cooling systems.

Modular systems used for passive cooling allows:
- to standardize the choice of the type of this system depending on the cooling object;
• it will provide a reduction in investment in standard equipment and in the cost of its installation;
• it will speed up the design process, which will also affect the final cost, and also reduce operating costs.

2. Use of modular cooling systems
Currently, modular systems are used for cooling:
1. Data centers:
   a. Computing centers;
   b. Data storage centers;
2. Cell towers;
3. Infrastructure facilities;
4. Computers;
5. Electronic devices;
6. Any scalable systems.
A fundamentally important condition at such facilities is the compact placement of heat-generating, including computing power, that is, a high density of equipment placement, and, therefore, an increased need for compact dimensions and high efficiency of cooling equipment, but these requirements often contradict each other, and in addition, increase the cost of powering such equipment.
Similar problems with increased requirements for compactness of placement also arise when cooling radio-electronic equipment in computer technology, on aircraft and spacecraft. All this ultimately affects the cost of such objects.
Unlike the traditional approach, the modular approach allows you to take into account several technical and economic factors at the same time. The traditional approach (Fig. 1) allows you to choose the type of cooling system based on the knowledge and skills of the designer, and sometimes his financial interest in promoting certain types of equipment. In this case, there is a high probability that the most efficient cooling systems, in particular, passive ones, will remain unconsidered in the framework of assessing energy, and then economic efficiency.

![Flowchart](image)

**Figure 1.** Traditional approach.

The modular approach (Fig. 2) requires preliminary investment of time and resources to assess the potential of existing passive cooling systems in relation to various objects and to create a generalizing databank, a comprehensive assessment based on criteria for energy and economic efficiency.
Free cooling systems cannot be considered a zero-energy system. Operating costs should take into account not only the cost of electrical energy, but also the depreciation of equipment. Although the amount of this energy is significantly lower than the consumption of traditional systems.
The energy efficiency for similar cooling systems that use a reduced amount of energy, for example, systems with free cooling or free cooling, is recommended to be calculated in terms of energy efficiency, as the ratio of useful heat to consumed:

$$\eta_\varepsilon = \frac{Q_r}{Q_{in}} \tag{1}$$

where $Q_r$ - amount of heat removed from the object, W, $Q_{in}$ - power expended to drive the blowers, most often electric power, W.

The efficiency of completely autonomous systems, for example, with heat pipes or with heat-conducting radiators, should preferably be calculated according to the exergy efficiency indicators:

$$\eta_e = \frac{E_{out}}{E_{in}} \tag{2}$$

where $E_{out}$ - the exergy flow at the exit from the object, W, $E_{in}$ - the exergy flow at the entrance to the object, W.

The indicators of the economic efficiency of such passive modular systems will be the payback period and the total discounted costs that determine the economic effect. The feasibility study of the effectiveness of the use of a modular passive cooling system is based on comparing the costs of upgrading and saving fuel and energy resources.

The economic effect is calculated as follows:

$$\mathcal{E} = \sum_{t=0}^{T_p} (\Delta \mathcal{E}, - H_t, - K_t) \times (1 + E_a)^t \tag{3}$$

where $\mathcal{E}$ - summary economic effect, $\$$; $\Delta \mathcal{E}$ - the saving cost estimate of the s in operating costs when introducing the technology, $\$$/year.; $K_t$ - costs for the implementation of technology and work, $\$$/year; $H_t$ - annual costs excluding depreciation charges; $T_p$ - the estimated period equal to the service life of the main equipment, year, $E_a$ - average discount rate. It is difficult to accurately estimate the savings in operating costs due to the need to take into account the mutual influence of the determining factors, therefore it is recommended to use an expert judgment method.
The main influencing factors are:
- use of natural heat and cold;
- reduction in operating costs;
- savings in the consumption of spare parts while reducing the number of moving equipment;
- savings in operating consumption for energy resources - electricity, fuel;
- use of secondary energy resources, utilization and regeneration;
- others.

3. Advantages and disadvantages of modular passive cooling systems

3.1. Advantages

1. Low energy consumption

As noted above, systems with passive cooling [7-8] most often require energy costs, however, compared with forced cooling, so, when comparing these costs for electricity for free and machine cooling systems (Fig. 3) for air-conditioned rooms offices for different operating conditions, the difference is 2-5 times.

![Figure 3. Cost-efficiency ratio of various cooling systems.](image)

2. Reliability

The use of systems with passive cooling allows you to reduce the number of equipment with moving parts, and therefore, the likelihood of failures and recovery time, as well as the time of planned and unplanned repairs and the number of components for repairs, are reduced, that is, material costs are reduced.

The modularity of the system further increases its maintainability, since it allows the equipment to be restored by changing the blocks that have become unusable. The repair of the units themselves can then be carried out under stationary conditions in the service centers of manufacturers or equipment dealers, which significantly improves the quality and increases the resource.

In [9], an example of a modular architecture of a cooling system for electronic equipment (Fig. 4) is given, which makes it easy to replace system elements both depending on the load and due to failure.

Reducing the fire hazard of the system as a whole is also an important factor in reliability.

3. Compactness

The advantages in the system size of compactness in all types of modular systems are given in the works [1-6]. The modular cooling system described in the paper [4] is a self-cooled rack cabinet for high-density equipment in data centers. The modular cooling system is designed to complement the existing traditional data center cooling system and allow more computing power without increasing the current heat load in the data center. In addition, by allowing hard-ware to be placed at three times the power density of a standard rack, the modular cooling system increases data center reliability.
The types and forms of passive cooling systems for electronic devices amaze the imagination, combining compactness with design. For example, passive radiators for cooling LED technology (Fig. 5) can have almost any cross-sectional shape, device height, rib shape [11-12]. Increases the compactness of the system and the absence of electrical wiring in passive systems.

4. **Cheapness**
The cost of a modular system compared to active cooling can differ 2-7 times. The cost of design is reduced, and it becomes possible to select cooling systems from a databank, taking into account a modular approach. Operating costs are reduced due to reduced consumption of electricity and other resources.

5. **Compliance with the requirements of the technical task**
The scalability and variability of the modules will make it possible to meet the requirements for the regular functioning of the cooled equipment, first of all, the observance of the operating temperature of the operated equipment, the removed heat flow, local overheating, etc.

6. **Use of secondary sources**
Recirculation, regeneration, used in cooling systems, increase their efficiency, reduce the already low energy consumption from external sources, make it possible to utilize and redistribute heat flows.

7. **System flexibility**
The flexibility of modular systems is due to the standardization of cooling equipment, the interchangeability of its elements.

8. **Performance characteristics**
Modular systems provide ease of installation and maintenance, reducing time and, accordingly, operating costs.

9. **Environmental safety**
Environmental protection is due to the use of standard equipment, which ensures a higher quality of manufacture, reduces accidents, the number of equipment, and energy consumption during operation.

3.2. **Disadvantages**
1. **Power and efficiency**
Passive systems cannot always ensure the removal of the required amount of heat, have difficulties with the ability to regulate heat transfer, and are limited by the distance of heat transfer. For example, the effective heat transfer limit of heat pipes.

2. **Working conditions**
Despite the advantages in the compactness of modular systems, it is not always possible to find a place for them. These devices operation occurs at high temperatures, dust, low humidity, local over-loads, etc.

3. **Cost**
Some of the modular passive cooling systems of the system are high-tech, and therefore have a higher cost.

4. The influence of the external environment

The efficiency of operation of passive devices strongly depends on weather conditions and time of day, the presence of forced natural convection, and other various external influences.

4. Conclusions

Today, one of the main problems in the design of cooling systems is the lack of a unified approach that ensures the maximum technical and economic effect from the use of one or another cooling system. The recommended approach to assessing the effectiveness of passive modular cooling systems is to calculate the total discounted costs and economic effect that determines the payback period of these systems. The advantages of using passive cooling systems are increased when using modular systems. The use of passive systems in cases, for example, with the cooling of buildings and structures, will reduce capital costs, since the equipment of such systems is much cheaper than traditional ones. However, for cooling systems for electronic equipment, these systems can be either cheaper or more expensive, depending on the technology used. A modular approach to the design, production and use of passive cooling systems will reduce operating costs by 2-5 times.

In this regard, the proposed modular approach will allow designing cooling systems based on a data bank with maximum economic efficiency.

5. References

[1] Soloviev AV 2016 Modular cooling systems in server rooms and data centers, Avtrom.ru/news/2016/09/05/
[2] Cortes T M, James L 2016 Quantitative Analysis of a Prefabricated vs. Traditional Data Center White Paper 9 U 4
[3] Kolpakov A 2010 Cooling in high power systems. Power Electronics, № 3, 2010 pp. 62-66
[4] Rapp S 2014 Russia. Custom solution to heat dissipation problems Control Engineering. №2 (50),
[5] Muratov A V, Tsipina N V 2007 Methods of ensuring the thermal regimes of the RES (GOUVPO "Voronezh State Technical University" Textbook Voronezh)
[6] Merkulieva A Yu, Goryachev N V, Yurkov N K 2013 Cooling systems for semiconductor electrical radio products Young scientists. № 11 (58), p. 143-145.
[7] Malyavina E G, Frolova A A, Silaev A S 2014 Energy and economic evaluation of free and machine cooling systems for air-conditioned office premises AVOK Air conditioning. №1, 2014
[8] Belarbi R, Allard F 2001 Development of feasibility approaches for studying the behaviour of passive cooling systems in buildings. Renewable Energy 22 (2001) p. 507–524
[9] Mishkinis D, Usakovs I, Nasibulin D 2018 Novel Modular Evaporator Architecture for Electronics Cooling Applications. Paper 338, proc. 19th International Heat Pipe Conference and 13th International Heat Pipe Symposium, Italy.
[10] Herrando M, Markides C N 2016 Hybrid PV and solar-thermal systems for domestic heat and power provision in the UK: Techno-economic considerations. Applied Energy, 161, 2016, p. 512–532
[11] Lothar N 2010 Cooling and temperature control of LEDs. Semiconductor lighting engineering №3, 2010
[12] Facusse M 2015 Passive cooling enclosure system and method for electronics devices United States Patent US 9,036,351 B2.
[13] Heydari A, Gross K C 2012 Modular absorption heat sink United States Patent US 8,276,394 B2
[14] Gagarin V G 2010 Macroeconomic aspects of the substantiation of energy-saving measures when increasing the thermal protection of building envelopes. Stroitelnye materialy № 3.
[15] Blank I A. 2007 Investment Management (Moscow Elga-N) p.448
[16] Yuzvovich L I, Degtyareva S A, Knyazeva E G 2016 Investments: textbook for universities (Yekaterinburg: Ural Publishing House. un-ta) p 543