Concerning the issue of alternative cold supply for building climate control systems

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Abstract. The possibility of using alternative cold supply in the life support systems of buildings for the climatic conditions of the Central Black Earth region is considered. The results of calculations and selection of an absorption chiller with an array of solar collectors for an office building planned for construction in Voronezh are presented. The analysis of the efficiency of the heat collectors by the average efficiency showed that for the cold supply of the building taking into account the actual actinometric indicators of the region the use of flat devices was the most appropriate. Vacuum collectors for the solved task under the indicated climatic conditions, despite the generation of a high-potential thermal regime, upon reaching the maximum temperature of the coolant, are characterized by a decrease in efficiency as a result of significant losses to the environment. With justified priority use of flat devices capturing solar radiation, for a deeper extraction of alternative energy, an innovative design of devices of this class is proposed making it possible to increase their efficiency. The use of such devices will reduce their number in the array.

1. Introduction
Improving the energy efficiency of buildings is a priority for the development of the modern construction industry. This provision is clearly reflected in state regulatory documents that fix the trends in the development of energy industry in Russia. It shall be implemented through the use of the latest technical solutions contributing to reducing energy intensity both in production processes and in the resource supply of structures [1,2].

Among engineering systems of buildings, air conditioning installations are characterized by an extremely high degree of consumption, and, in particular, their cold supply in the warm season. In addition, the current trend of increasing requirements for indoor microclimate annually increases the demand for cold production. According to the forecasts of the International Energy Agency, the growth in cold supply demand from 3.5 EJ/year in 2020 will increase to 9 EJ/year by 2050 [3]. This is primarily due to the fact that most air conditioning systems use vapor compression refrigeration units, the cycles of which require significant energy, especially at peak loads in the warm season. This situation in air conditioning systems can be avoided if, instead of traditional technical solutions, absorption refrigeration machines (ABRM) are used with their thermal energy demand met with the use of solar collectors.
2. Materials and methods
The use of solar systems to obtain the heat necessary for the functioning of ABRMs was considered as a set of promising cold supply systems in a number of scientific and practical works [4-12]. It was previously revealed that this technology from the point of view of technical and economic indicators is advisable to apply with the cold demand from 100 kW. Therefore, the effective use of ABRM technology in air conditioning systems at this stage is possible within the framework of large construction projects of public or industrial purposes. However, the main problem in the development of this technology is the high level of capital costs. The second problem is the lack of a simple and effective methodology for determining the investment attractiveness of alternative cold supply systems. The first problem can be successfully solved through the use of solar collectors with increased radiation absorption efficiency [13] and low cost. At the same time, models of flat solar collectors are considered, as the cheapest ones in terms of capital costs and operation, as well as reliability.

Extremely promising in this regard is the use of hybrid solar systems including, among other things, the innovative design of the collector shown in Figure 1 [14]. This device is characterized by a relatively low cost and high efficiency of radiation conversion processes. In addition, when obtaining hot water in the collector, it can be used to compensate for the power consumption of the pumps of the solar water circuit, which ensures its autonomy and increases reliability. The placement of semiconductors on polymer tubes contributes to their timely cooling, and, accordingly, to increase of the electricity generation process efficiency [15].

![Diagram of a multifunctional flat solar collector](image)

**Figure 1.** Diagram of a multifunctional flat solar collector: 1 - housing; 2 - thermal insulation; 3 - translucent case; 4 - absorbing panel (absorber); 6 - thin metal mesh with a small mesh size; 8 - polymer tubes; 9, 10 - upper and lower segments of soldered polymer tubes; 11 - photoconverters

We will consider the possibility of using innovative solar collectors with increased conversion efficiency in the conditions of the Central Black Earth region for alternative cold supply of building life support systems. To justify the technical solutions, calculations were performed for a two-story office building (Figure 2), designed for construction in Voronezh. Maintaining optimal parameters of the internal environment during the warm season of the year with air conditioning systems can be ensured by covering the cold load due to the absorption chiller with a capacity of 176 kW. For its stable operation in the summer season in the climatic conditions of the Voronezh region, 262 kW of heat will be required, which can be obtained by converting solar energy in an array of collectors installed on a flat roof of the upper story.

When choosing the design of radiation-receiving devices, one of the main guidelines for decision-making is efficiency. To determine it, it is recommended to use the following expression [16,17]

$$\eta = \eta_0 - k_1 \frac{\Delta T}{I_k} - k_2 \frac{\Delta T^2}{I_k}$$

(1)

where \(\eta_0\) is the effective optical efficiency of the solar collector; \(k_1, k_2\) are factors characterizing the possible loss of heat into the environment, respectively, through heat transfer and radiation of a heated absorber, W/m²·°C; \(I_k\) is the density of the total flux of solar radiation entering the collector.
glazing, W/m²; $\Delta T$ is the difference between the average temperature of the coolant in the collector and the ambient temperature, °C, determined by the dependence:

$$\Delta T = 0.5 (T_{in} + T_{out}) - T_{amb},$$

(2)

where $T_{in}$, $T_{out}$, $T_{amb}$ is temperature, respectively, of the coolant at the inlet of the collector, at the outlet of the collector and the ambient air, °C.

![Figure 2. General view of the main facade of a two-story office building designed for construction in Voronezh.](image)

The daily change in solar radiation and the regulation of the coolant flow rate in the circuit of solar collector arrays leads to different temperature differences, therefore it is advisable to analyze the average achieved efficiency in various devices for the climatic conditions under consideration. To determine the averaged indicator, we integrate expression (1) under the assumption of a discretely fixed solar flux in accordance with the equation

$$\bar{\eta} = \frac{1}{\Delta T_{max}} \int_0^{\Delta T_{max}} \left( \eta_0 - k_1 \frac{\Delta T}{I_K} - k_2 \frac{\Delta T^2}{I_K} \right) d(\Delta T),$$

(3)

where $\Delta T_{max}$ is the maximum possible difference between the average coolant temperature and the ambient temperature for the considered type of collector design, °C.

After integration we get

$$\bar{\eta} = \eta_0 - k_1 \frac{\Delta T_{max}}{2I_K} - k_2 \frac{\Delta T_{max}^2}{3I_K},$$

(4)

For flat collectors, the parameters in expressions (1, 4) are taken equal to $\eta_0 = 0.863$, $k_1 = 3.66$, $k_2 = 0.0169$, for vacuum collectors $\eta_0 = 0.7$, $k_1 = 1.33$, $k_2 = 0.0071$ [16, 17]. As a rule, the reached maximum temperatures are indicated in the technical specifications from the manufacturers of solar equipment. However, as shown by the long-term operation of these devices [16-19], the maximum temperature for flat collectors is 100-110 °C, and for vacuum collectors - 120-200 °C.

3. Results

Let's consider the average values of the efficiency of solar plants of the two types listed for the summer season in the climatic conditions of Voronezh, corresponding to its latitude 51°41' N
average solar radiation flux during daylight hours in July in the region is $I^L_{k} = 545.9$ W/m$^2$, the average monthly outdoor temperature in July reaches 25.9 $^\circ$C [20].

Let's suppose that the temperature of the coolant entering the collector during heating of the pipelines due to heat exchange with the environment will be lower than the outside temperature by 5 $^\circ$C. Then, taking into account the design features of the collectors by means of the declared maximum possible temperature of the coolant at the outlet, we obtain, in accordance with expression (4), the average values of the efficiency of solar installations, given in Table 1.

**Table 1.** The average efficiency $\eta$ of solar collectors in the conditions of operation of the warm period of the year in the Voronezh region.

| Thermal performance | Collector type | flat | vacuum |
|---------------------|---------------|------|--------|
| Maximum coolant temperature at the collector outlet, $^\circ$C | 100 | 110 | 120 | 160 | 180 | 200 |
| Average efficiency | 0.735 | 0.714 | 0.637 | 0.623 | 0.585 | 0.566 |

Analyzing the obtained values (Table 1), we can conclude that, in the climatic conditions of the Central Black Earth region, to solve the problems of alternative cold supply, flat solar collectors should be used, the efficiency of which exceeds vacuum by 12-30%.

In order to extract more useful heat with fewer devices for capturing and converting solar energy, further development of solar technology can go in the direction of increasing optical efficiency and reducing losses to the environment. The technical solution presented in Figure 1 [14], corresponds to the identified priorities. If the standard dimensions of the panel are used for its manufacture, then heat loss to the environment through convection will have the same predicted values as for this type of collector. The design features of the device (Figure 1) are aimed at increasing the optical efficiency by placing a metal mesh under the glazing, which absorbs radiation, including from a heated absorber, reducing losses to the environment. At the same time, an increase in the absorptive capacity of the collectors through innovative solutions within 4% will increase the average efficiency to 7%.

To cool the designed building (Figure 2), the possibility of using typical flat solar collectors, the required area of which was determined in accordance with the expression, was considered

$$A^p_{k} = \frac{Q_{therm}}{\eta \cdot I^L_{k} \cdot \varepsilon_A},$$

(5)

where $\varepsilon_A$ is the conversion coefficient of the absorption refrigeration unit, for the selected chiller brand it is equal to 0.67; $Q_{therm}$ is thermal power consumed by the chiller, W.

The required thermal power $Q_{therm} = 262.5$ kW for the production of cold will be provided by collectors with an estimated area of 976.5 m$^2$, and their number will be 489 pcs. In the transitional period of the year, an array of typical collectors is able to compensate for part of the building’s heat load on heating and hot water supply. Given the decrease in the density of solar radiation flux and the efficiency of these devices, the amount of heat obtained by an alternative method in the conditions of the autumn and spring seasons, on average, is 152 kW.

To assess the investment attractiveness of the alternative refrigeration system, it is advisable to use the value of the payback period of the system. At the stage of design work, the payback period can be expressed in terms of the ratio of capital costs to the resulting economic benefits from energy-saving measures. Capital costs are the sum of expenses for the purchase of equipment, the cost of the project and installation work. The economic benefit is considered as a reduction in payments for the consumed electricity, compared with a similar vapor compression installation, as well as by compensating for part of the heat load of heating systems and hot water supply when using heat...
received from an array of solar collectors during the transition period of the year and during the heating season.

The capital cost of arranging alternative refrigeration for the projected building will amount to 14 million rubles. The calculation of the reduction in annual payments, in rubles/year, for electricity and heat consumed, subject to partial compensation of the building load, was carried out in accordance with the dependencies

\[ E_{el} = (C_{el} \cdot N_{chil} - C_{el} \cdot N_{ABRM}) \cdot n_{MSWD} \cdot Z_{WPY}, \]

\[ E_{therm} = \sum_{i=1}^{9} Q_i \cdot Z_{op} \cdot C_{therm} \cdot 3600 \cdot 24 \cdot 238.8 \cdot 10^{-9}, \]

where \( C_{el} \) is the cost of electricity, rub./kW·h; \( N_{ABRM} \) is electric power consumed by the ABRM, kW·h; \( N_{chil} \) is the average consumed electric power of a vapor compression chiller with a similar capacity, kW·h; \( n_{MSWD} \) is the average number of hours of operation of the air conditioning system, h/day; \( Z_{WPY} \) is the number of days in the warm period of the year, days; \( Q_i \) is thermal power generated by solar collectors in the \( i \)-th month of the cold season, kW; \( C_{therm} \) is the cost of thermal energy, rub./Gcal; \( Z_{op} \) is the duration of the heating period, days; 238.8·10 -9 is conversion factor from kJ to Gcal.

When calculating according to formulas (6), (7), the climatic parameters of the city of Voronezh and utility tariffs were taken into account, which as of November 2019 were: for electricity \( C_{el} = 5 \) rub./kW·h, for heat energy \( C_{therm} = 1514.08 \) rub./Gcal. In terms of calculation, the values of consumed capacities were taken equal to \( N_{ABRM} = 15 \) kW·h, \( N_{chil} = 93 \) kW·h.

The annual benefit from lower payments for energy will reach 1.65 million rubles, with a payback period of 8.5 years. To conduct a comparative analysis, the economic benefits of the use of multifunctional solar collectors in the solar array were calculated. Their use will reduce the payback period to 7 years. This will be achieved by increasing the absorption efficiency of solar radiation, which will require fewer solar collectors (up to 410 pcs.), and, accordingly, capital costs.

4. Findings

As can be seen from the above technical solutions, the use of a cold supply system for air conditioning based on ABRM and solar systems in the city of Voronezh at this stage is economically justified only in the framework of large investment projects. Reducing the payback period and the active spread of alternative systems to medium and small volumes can be achieved by reducing capital costs for their arrangement. Since 56% of the total costs are in an array of solar collectors, a solution to this problem is being considered in the direction of increasing the efficiency of solar installations. An increase in the degree of absorption of solar radiation and a reduction in losses by collectors will lead to a decrease in their number, and as a result, to a decrease in capital expenditures.

Thus, the ABRM technology using solar energy in air conditioning systems is quite effective for the middle latitudes of the Russian Federation and, as a result, is extremely promising in the southern regions. But at the stage of modern technical solutions, the use of alternative refrigeration is advisable only at large public and industrial facilities.

References

[1] Energy strategy of Russia for the period until 2030. Approved by the order of the Government of the Russian Federation No. 1715-r dated 11/13/2009
[2] Federal Law No. 261 "Concerning energy conservation and improving energy efficiency and amendments to certain legislative acts of the Russian Federation" No. 261-FZ dated 11/23/2009 (latest revision).
[3] Solar cold supply: 34th information note on refrigeration technologies (April 2017)

Refrigeration equipment 7 4–7
[4] Schukina T V, Shevchenko R S 2017 Solar heating of buildings. Design basics subject to a reduction in the period of consumption of traditional resources S.O.K. 4 58–60

[5] Kolinko A V 2017 Efficiency analysis of the use of solar energy in absorption refrigeration machines Improving the science methodology in order to develop science pp 33–37

[6] Usenkov R A 2019 Improving the parameters of the refrigeration unit as one of the ways to reduce the negative impact on the environment Bulletin of Novgorod State University named after Yaroslav the Wise 4(116) 61–64

[7] Garkaviy K A, Bzhevday S N 2017 Solar conditioning systems Bulletin of the Belgorod State Technological University named after V.G. Shukhov 7 58–62

[8] Mirmov I N, Mirmov N I 2011 Use of solar energy and secondary sources of heat to produce cold Refrigeration equipment 9 44–48

[9] Ward D S 1979 Solar absorption cooling feasibility Solar Energy 22(3) 259–268

[10] Linjawi, Majid & Talal, Qazi & Al-Sulaiman, Fahad 2017 Evaluation of solar thermal driven cooling system in office buildings in Saudi Arabia E3S Web of Conferences. World Renewable Energy Congress-17 23 05001. DOI:10.1051/e3sconf/20172305001

[11] Ari Rabl 1985 Active Solar Collectors and Their Applications (Published by Oxford University Press, Inc.) p 517

[12] Beccali Marco, Cellura Maurizio, Longo Sonia, Guarino Francesco 2016 Solar heating and cooling systems versus conventional systems assisted by photovoltaic: Application of a simplified LCA tool Sol. Energy Mater. and Sol. Cells. 156 92–100

[13] Ilya Kurasov, Tatiana Shchukina, Mariya Zherlykina and IgorPotekhin 2020 Increase in energetic and exploitation stability of solar systems with array of flat collectors E3S Web of Conferences TPACEE-2019 164 13008. DOI:10.1051/e3sconf /202016413008

[14] Schukina T V, Chudinov D M, Kuznetsova N V 2015 Multifunctional solar collector Patent 2538152, IPC F24J 2/26 State educational institution Voronezh State University of Architecture and Civil Engineering No. 2012125107/06, Bull. No. 1, p 6

[15] Schukina T V, Tarkhanov A K, Chudinov D M 2014 Combined solar modules and reliability of life support systems S.O.K. 1 82–84

[16] Duffney J, Beckman W 2013 Fundamentals of solar thermal power (Dolgoprudny: Publ. House "Intelect") p 888

[17] Zemskov V I 2014 Renewable energy in the agricultural sector (St. Petersburg: Publishing House "Lan") p 368

[18] A da Rosa 2010 Renewable energy sources. Physicotechnical basis (Dolgoprudny: Publishing House "Intelect"; Moscow: Publishing house of MPEI) p 704

[19] Bogoclovsky VN, Kropnov B A, Skanavi A N et al 1990 Internal sanitary facilities ed I G Staroverov and Yu I Schiller. In 3 parts P I Heating - 4th ed., updated and revised (Moscow: Stroyizdat) p 344

[20] SP 131.13330.2018. "SNiP 23-01-99* Construction Climatology" (Moscow: Ministry of Construction of Russia) p 107