

Reversible Energy-Accumulating System Using the Energy of Phase Transition of Liquid Heat Carrier

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Abstract: The option of reversible heliothermal system on the basis of the Multipurpose Solar Panels (MSPs) for effective round-the-clock maintenance of favorable temperature condition in rooms at sharp differences of day and night ambient temperatures is presented in the study. In hot time of day of MSPs carry out function of the cooling protective surfaces due to transition of the liquid heat carrier to a vaporous state. With fall of temperature through MSP the heat carrier heated in hot time of day is pumped over, selecting energy from the thermal accumulator. Energy in the thermal accumulator collects upon transition of the heat carrier from vaporous in a liquid state after run via the compressor.

Key words: Energy of solar radiation, temperature condition, reversible heliothermal power heat-sink system, multipurpose solar panel, thermal accumulator, liquid heat carrier, phase transition

INTRODUCTION

Sharp differences of day and night ambient temperatures in districts with sharply continental climate significantly complicate process of the round-the-clock maintenance of favorable temperature in inhabited and production rooms. During hot weather, the premises have to draw and use the air-conditioning system and at night often necessary heating of air to maintain a favorable temperature. Traditionally, used central airs consume a significant amount of electric energy and are ineffective for open and extended rooms.

STATEMENT OF PROBLEM

Researchers conduct researches of options of realization of reversible Heliothermal Power Heat-Sink System (HTES) on the basis of the Multipurpose Solar Panels (MSPs) which allows providing automatic maintenance of necessary temperature condition in rooms of geographical districts with sharply continental climate (Akhmetov *et al.*, 2013; Samarin and Kharitonov, 2011). The system can be carried to a class of reversible systems owing to its serial work in the mode of the thermal pump and a heating system of the room and in both modes as the heat exchanger the multipurpose solar panel is used which big surface of contact with environment provides an effective mutual heat transfer.

Reversibility of process of selection of energy of environment in the heat carrier through surfaces of MSP and the subsequent return of the saved-up thermal energy

in environment can be provided with use of phase transition of the liquid heat carrier in vaporous and vice versa as it is realized for example in thermal pumps. Since, the middle of the last century they have been successfully used in the USA and Europe for heating of rooms. And in many cities hundreds of large constructions have a capacity at the level of average combined heat and power plant work. For example, already today thermal pumps provide with heat Stockholm, using as a low-potential source the Baltic Sea with average annual water temperature only +8°C. In Sweden thermal pumps provide a half of all heat in the USA (37%) in Russia (0.1%) (data on Kazakhstan it wasn't succeeded to find, unfortunately) (Spiridonov and Shubin, 2012). According to forecasts of World Energy Committee (WEC) by 2020 in the developed countries the share of heating and hot water supply by means of thermal pumps will make not <75%.

OPTION OF REALIZATION OF THE GTPP

The offered option of structure of reversible heliothermal power heat-sink system is given in Fig. 1. The term “reversible” as we mentioned above, reflects possibility of work of system in the mode of the thermal pump and in the mode of heating of the room and both in that and in other the modes the same heat exchanger with environment MSP is used.

On structure the system is similar to heliothermal power heat-sink system of the GTPP (Akhmetov *et al.*, 2013) in which energy of solar radiation will be

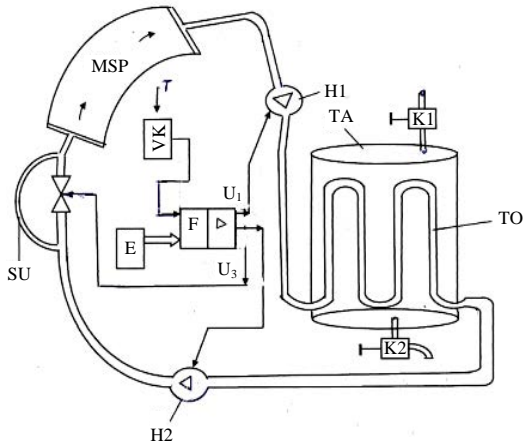


Fig. 1: Structure of reversible heliothermal system on the basis of MSP

transformed by means of MSP in thermal and collects in the Thermal Accumulator (TA). Key functional element of the offered heliothermal system is MSP included in a contour of circulation of the liquid heat carrier as a part of the pump and the thermal accumulator.

The additional pump compressor H1 of the increased productivity and the Narrowing Device (ND) is also entered into system at the expense of which at hit of the liquid heat carrier in MSP its phase transition to a vaporous state is provided. This transition is caused by sharp decrease of absolute pressure in MSP after ND and decrease thus of temperature of steam formation of the liquid heat carrier. In the course of steam formation of the liquid heat carrier abnormal absorption by surfaces of MSP of thermal energy from environment takes place at almost invariable temperature.

MSP advantage in comparison with traditional heliothermal panels is possibility of bilateral absorption and return of thermal energy through MSP surfaces at their use as absorbers and radiators of thermal energy respectively. The heliothermal system presented in Fig. 1 can function in three modes, respectively:

- The RN normal mode air T temperature indoors is in T_v limits $\geq T \geq T_n$, where T_v and T_n , respectively the top and lower values of favorable air temperature indoors
- The mode of selection and accumulation of MSA selection of energy of solar radiation and air from surfaces of MSP and its accumulation in TA thermal accumulator at $T > T_v$
- The RP mode heating of air indoors by the thermal energy which is saved up in THAT at $T < T_n$ and radiated MSP

Table 1: The formation of control actions U1, U2, U3

State of control actions	Ttemperature		
	PH mode $T_n \geq T \geq T_0$	POH mode $T > T_n$	PII mode $T < T_n$
U1	0	1	0
U2	0	1	1
U3	0	0	1

Automatic control of working hours of system is provided by means of the microprocessor shaper F with three powerful exits of U1, U2 and U3. To the input of the F shaper there are connected VK sensor of the air temperature T in the room and the unit E lower T_n and top T_v values favorable temperature. The formation of control actions U1, U2 and U3 in the device F is carried out in accordance with Table 1.

In the PH mode all elements of management (except the VK sensor and the shaper F) are de-energized, the liquid heat carrier in a heat exchange contour practically doesn't circulate and energy consumption of system from a source of electric food is insignificant. Air temperature indoors is in a favorable zone.

In the RON mode at temperature increase of T of air indoors above T_v the pumps H1 and H2 turn on, the EV electromagnetic valve is blocked pressure in MSP minimum because of course of the liquid heat carrier via the narrowing device DN. The heat carrier after SU passes into a vaporous state and its temperature sharply decreases according to Charles law for the closed system $P/T = \text{const}$.

In the set mode internal cavities of MSP can be considered as conditionally closed system as its volume of V is constant as well as the integrated mass of the liquid heat carrier in this volume. For normal work of heliothermal system in this mode performance of a condition is obligatory: $T_0 < T_c$ where T_0 is the temperature of the phase transition of the fluid from liquid to vapor and T_c -ambient temperature.

The external surfaces of MSP cooled up to T_0 temperature intensively absorb thermal energy from air both outside and indoors, lowering thereby T temperature indoors. Due to operation of the pump compressor H1 pressure at its exit considerably exceeds atmospheric therefore steam in the Heat Exchanger (HE) is condensed and temperature sharply increases. Upon transition of the heat carrier from a vaporous state in liquid the heat exchanger HE gives thermal energy to the tank of thermal accumulator TA filled with water. Due to existence of the K2 crane hot water from TA can be used for technical needs and via the K1 crane there is made replenishment of a water-supply in the tank.

Modification by means of the microprocessor shaper F of the RON mode for the forced accumulation of thermal energy in TA until fall of temperature of T of air indoors to the minimum favorable value T_n is possible.

Actually in the RON mode the system carries out functions of the thermal pump which is selecting thermal energy of environment outside of MSP and air indoors.

At fall of temperature $T < T_n$, the control system passes into the RP-mode parallel to the narrowing SU device the section of the EK electromagnetic valve through passage opens and the liquid heat carrier heated in the RON mode is pumped over by the pump H2 from the HE heat exchanger in MSP. The pump H1 in this mode is de-energized. The heating of air indoors from MSP surfaces up to the favorable temperature is provided.

PROCESSES OF PHASE TRANSITION TO THE GTPP

Let's consider in details physical processes in heliothermal system in the RON mode. Figure 2 shows the diagram of work of a reversible heat engine called the Carnot cycle by the name of its researcher a French engineer of the 19th century (Bazarov, 1983). Carnot's cycle consists of two isothermal and two adiabatic processes:

- Adiabatic compression of vapors by means of the pump compressor H1 (a curve 1-2)
- Isothermal condensation of vapors in the tube connecting H1 exit to the heat exchanger entrance (a curve 2-3)
- Adiabatic expansion of liquid in MSP with transition of the heat carrier to a vaporous state (a curve 3-4)
- Isothermal steam formation of the heat carrier in MSP (a curve 4-1)

Carnot's cycle is two-temperature that is heat exchange happens between two sources:

- A cold source (evaporator) which is at a temperature T_2 absorbs heat Q_0 from the environment

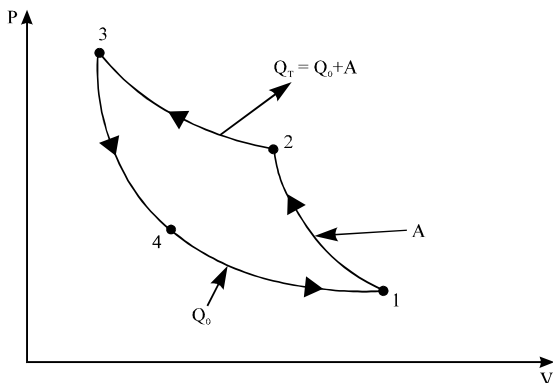


Fig. 2: The Carnot cycle for an ideal heat pump

- Hot spring (heat exchanger) which is at a temperature T_1 radiates heat to the TA thermal accumulator

The effectiveness of the k_T process of accumulation of thermal energy in TA can be defined as the ratio:

$$k_T = \frac{Q_T}{A} = \frac{Q_0 + A}{A}$$

where, A the work spent for compression of the liquid heat carrier. Other form of representation k_T :

$$k_T = \frac{1}{\eta} = \frac{T_1}{T_1 - T_2}$$

Allows to determine efficiency of process by values of temperatures T_1 and T_2 . For example at $T_1 = 333$ K and $T_2 = 283$ K we have $k_T = 6.66$ that is we will receive approximately, 6 fold conclusion of thermal energy in TA in comparison with energy costs of ensuring process of direct and return phase transition and transportation of the heat carrier from MSP to the HE heat exchanger.

The coefficient of adiabatic expansion of the heat carrier has essential impact on efficiency of selection of thermal energy from environment upon transition from a liquid state to the vaporous. At different liquids this coefficient is various. Water possesses the maximum coefficient of adiabatic expansion upon transition from a liquid state to the vaporous. Density of water vapor changes from 0.01 kg/m^3 with a residual pressure of 10 mbar to 2.669 kg/m^3 with a pressure of 5 Bars. Respectively, change of volume of a certain mass of water upon transition to steam will make $2.669/0.01 = 266.9$ times. Besides water possesses the greatest specific heat in a liquid state among all substances, known on the globe: $q = 4.32 \text{ kJ}\cdot\text{kg}\cdot^\circ\text{C}$ or $1 \text{ kcal}\cdot\text{kg}\cdot^\circ\text{C}$. Warmth of steam formation and condensation of Q_p of 1 kg of water makes about $Q_p = 2368 \text{ kcal}\cdot\text{kg}$ (exceeds $500 \text{ kcal}\cdot\text{kg}$).

In Fig. 3, graphic dependence of temperature of boiling of water on absolute pressure over a surface of the water is presented.

Remaining invariable in the course of phase transition, temperature of phase transition at clear water with a normal atmospheric pressure makes 100°C and lies ranging from 7°C with a residual pressure 10 mbar to 275°C with a pressure of 60 bars. When mixing water with ethylene glycol the essential decrease in temperature of phase transition of mix proportional to a percentage ratio of ethylene glycol in water solution to clear water is observed.

Figure 4 shows a diagram of the operating cycle of a real heat pump without reference to the scale (for water,

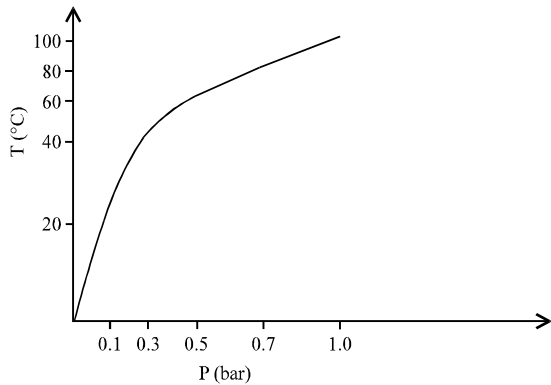


Fig. 3: Dependence of temperature of steam formation of water from absolute pressure

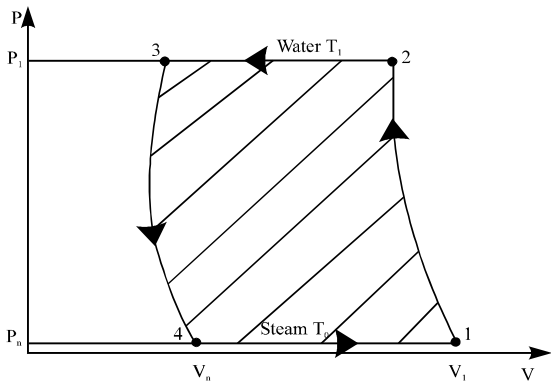


Fig. 4: The duty cycle of a real heat pump (not to scale)

this chart is wide enough horizontal). As process of adiabatic expansion of water vapor will happen in the MSP internal channels, all extensive external surfaces of MSP will be rather cold for intensive selection of thermal energy from environment.

Considering general availability and unique properties of water and also possibility of ensuring temperature of boiling of the mix “water-ethylene glycol” from 273 K and above with an absolute pressure from 10 mbar, there are all bases to carry water to the most perspective options of the liquid heat carrier in relation to reversible GTPPs.

THE ESTIMATED CHARACTERISTICS OF THE GTPP

We will execute calculation of characteristics of heliothermal reversible system for the room with a useful area of MSP $S_p = 40$ of m^2 , ambient temperature from 253-333 K, temperatures of steam formation of $T_0 = 280$ K and temperatures of $T_1 = 340$ K in the HE heat exchanger.

Taking into account the maximum preference to process of photosynthesis for plants indoors, we will choose light green or light yellow color of the liquid heat carrier or we use cellular polycarbonate of this color with coefficient $\gamma = 0.25$ selections of energy from the falling stream of solar radiation.

We will estimate the specific power of the thermal energy E_{ud} which is selected from the stream of solar radiation influencing external surfaces of MSP on the equation:

$$E_{ud} = E_{cp} \cdot \gamma$$

Where:

γ = Coefficient of selection of energy from the falling stream of solar radiation

$E_{cp} = (E_{MAX} - E_{MIN})/2$ = Average value of power of a stream of solar radiation on $1 m^2$ of a surface, orthogonal to a stream during daylight hours

When known for example for Kazakhstan $E_{max} = 1380$ W (clear sunny summer day), $E_{min} = 80$ W (cloudy day) have $E_{cp} = 650$ W per $1 m^2$ orthogonal to the flow surface. For light yellow coloring of MSP it has $\gamma = 0.25$. Then, $E_{ud} = 650 \cdot 0.25 = 162.5$ W on $1 m^2$ useful area of MSP.

We will estimate an hourly average limit of the thermal energy of the E_c which is selected from a useful area of $40 m^2$ of surfaces of MSP from a stream of solar radiation:

$$Q_c \geq S_{\pi} \cdot E_{ud} = 40 \cdot 162.5 = 6.5 \text{ kBT}$$

MSP surfaces turned inside greenhouses will provide additional selection of thermal energy from air which value can be estimated on a formula:

$$Q_B = k_r \cdot A$$

where, k_r : efficiency of the GTPP as thermal pump; $A = (p_1 - p_0) \cdot 10^5 \cdot (V_0 - V_1)$: the work made by the pump H1 for increase of absolute pressure from p_0 till p_1 in J; p_0 and p_1 : absolute pressure in MSP and in the heat exchanger, respectively (on an entrance and an exit of the pump H1, respectively) in Pa; V_0 and V_1 , respectively a volume of saturated steam in MSP and volume of the water condensed from the portion of steam which filled internal cavities of MSP in m^3 .

The formula of work A is received as a production of the parties of a running cycle of the real thermal pump (Fig. 4). At $k_r = T_1 / (T_1 - T_0) = 340 / (340 - 280) = 5.66$ (we will accept taking into account unaccounted losses $k_r = 5$) and $V_0 = 0.3 m^3$ (for $40 m^2$ of a useful area of MSP from 8 mm of

cellular polycarbonate), taking into account change of volume of a certain mass of water upon transition to steam close to 266.9, we will determine the mass of a portion of the m_0 water received from the saturated steam condensed from volume $V_0 = 0.3 \text{ m}^3$:

$$m_0 = (V_0/266.9) \cdot \xi_w = (0.3/266.9) \times 1 = 0.00112 \text{ kg}$$

where, ξ_w is specific density of water. At known warmth of steam formation and condensation of Q_p of 1 kg of Q_p water = 2368 kcal·kg, we will receive:

$$Q_B = m_0 \cdot Q_p = 0.00112 \times 2368 = 2.652 \text{ kcal}$$

Having accepted time of commission of one running cycle of the GTPP as t_u is 10 sec time of a global exchange of a portion of saturated steam in MSP, we can define quantity of the thermal energy absorbed by MSP from within the room within an hour:

$$Q_{ch} = Q_b \cdot (t_{ch}/t_u) = 2.652 \times 3600/10 = 954.72 \text{ kcal}$$

General thermal energy Q_{total} the selected MSP from environment for accumulation in TA can be determined by a equation:

$$Q_{total} = Q_c + Q_{ch}$$

Taking into account that 1 kcal = 0.001163 kWh will receive:

$$Q_{total} = 6.5/0.001163 + 900/4.1868 = 5588.9 + 954.72 = 6543.7 \text{ kcal/h}$$

Having accepted the maximum time of selection of energy Q_{total} TA $t_{Max} = 7 \text{ h}$ within a day, we will determine the necessary capacity of the thermal accumulator filled with water:

$$V_{Ta} = Q_{total} \cdot t_{Max} / (T_1 - T_H) = 6543.7 \cdot 7 / (340 - 280) = 763.4 \text{ L}$$

We will accept $V_{ta} = 765 \text{ L}$. Formula of the demanded volume V_{ta} is received, proceeding from requirement of downloading in TA 100% of energy of the environment absorbed by MSP. At the designated values $T_1 = 340 \text{ K}$, $T_0 = 280 \text{ K}$ as the heat carrier possibly use of water with addition of ethylene glycol for decrease of temperatures of boiling and prevention of freezing of the heat carrier in winter time. The maximum quantity of thermal energy which is saved up in THAT can be determined by a equation:

$$Q_{max} = Q_{total} \cdot t_{Max} = 6543.7 \cdot 7 = 45805.9 \text{ kcal}$$

We will estimate the hourly average Q_c resource of thermal energy on heating of air indoors, having

accepted time of daily heating of $t_c = 10 \text{ h}$: $Q_c = Q_{Max}/t_c = 45805.9/10 = 4580.6 \text{ kcal h}^{-1}$ that is equivalent to costs of electric energy of maintenance of comfortable temperature in volume:

$$E_n = Q_c \cdot \xi = 4580.6 \times 0.001163 = 5.32 \text{ kW/h}$$

where, $\xi = 0.001163$ the conversion kcal per kW. In this case, it made as provided SNiP the rate of energy expenditure to maintain a favorable temperature in residential premises from 1 kW per 10 m^2 of floor space.

When the equipment proposed by the system of the premises with a useful area of $>40 \text{ m}^2$, it is advisable to use a modular design system to service each module from $40\text{-}60 \text{ m}^2$ of useful floor space. A modular approach will significantly improve the survivability of the system as a whole; reduce electricity costs and also costs of the acquisition, extension and service connection piping system. In addition, it is possible to provide in each module, include privacy curtains, different technological regimes maintain a comfortable temperature.

Taking into account the value defined earlier k_r = the 5th efficiency of the GTPP as thermal pump, we find the recommended electric power of Re consumed on functioning of system on a known ratio:

$$P_{ae} \geq Q_c/k_r = 6.5/5 = 1.3 \text{ kW}$$

We will choose as the pump compressor H1 (Fig. 1) the FubadAIR Master kit compressor with a power of 1.8 kW and as H2 the pump 145313 from the 60 W Indesit washing machine.

Results of the carried-out calculation confirm possibility of realization of the offered reversible GTPP on the basis of MSP with use of energy of phase transition of the liquid heat carrier for maintenance of comfortable temperature in extended rooms.

OPTIONS OF USE OF THE GTPP ON THE BASIS OF MSP

Possibility of equipment by the offered system of extended rooms (galleries, transitions, corridors, etc.) opens prospect of development of the new direction of central airs creation of the modified systems a chiller-fankoil the centralized, polyzonal air conditioning systems in which the heat carrier between the central cooling car (chiller) and local heat exchangers (by knots of cooling of air and fankoil) is the cooled liquid circulating under rather low pressure ordinary water (in tropical climate) or water solution of ethylene glycol (in a temperate and frigid climate). Instead of lengthy tubes quality of the distributed heat exchangers

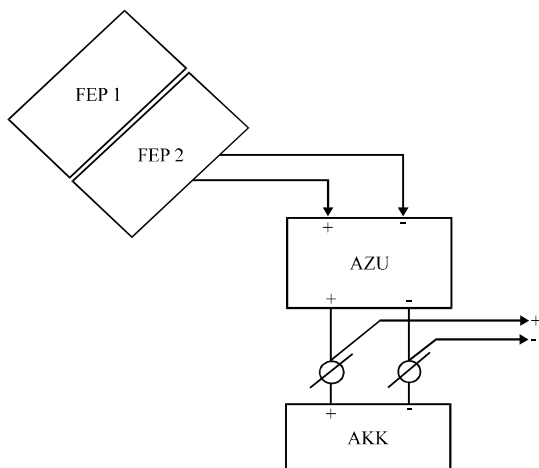


Fig. 5: Option of autonomous system of the uninterrupted electric food for heliosystem

in the modified systems of this type MSP which are carrying out functions as heat exchangers and a decorative exterior of rooms will be used.

It is expedient to provide uninterrupted electric food of lighting of rooms and actuation mechanisms of the reversible GTPP from system of uninterrupted power supply as a part of photo-electric panels, the automatic charger and the electric accumulator. In Fig. 5, the option of an autonomous power supply system for heliosystem as a part of the FEP 1 and FEP 2 photo-electric panels, the AZU automatic charger and the AKK electric accumulator is presented.

The executive N1, N2 and EK elements in heliosystem can be chosen with supply voltage 24 V and as FEP 1 and FEP 2 to use, for example, the MONO serial solar panels 200 24 of V included in parallel.

The general specific costs of equipment by the offered heliothermal system with an exterior of rooms will make about 50 USD (10 000 tenges) for 1 m² of a useful area of polycarbonate. When equipped with the proposed greenhouse gas turbine for example the cost of acquisition, installation and maintenance of the system will be returned within 2 years cost-grown productions.

It should be noted that when used in the proposed power plant known method for controlling light transmission (Vishnikin and Kharitonov, 2010) a possible implementation of the function “non-mechanical curtains” on the premises, the exterior of which is used by SME (MSP).

POSSIBLE RISKS AND OPTIONS OF MINIMIZATION OF THEIR CONSEQUENCES

Restriction of broad use of the offered GTPP for heating of rooms is inverse relationship of coefficient of

power efficiency from a difference of temperatures between the heat exchanger (consumer) of T_1 and a source of warmth (heat carrier T_0 vapour-forming temperature). It imposes certain restrictions on use of systems like “air water”. Real values of effectiveness ratio of kT of modern thermal pumps make $k_T = 2.0$ order at a source temperature -20°C and $k_T = 4.0$ order at a source temperature $+7^\circ\text{C}$. It leads to that for providing the set temperature condition of the consumer at low air temperatures it is necessary to use the equipment with a considerable excess power that is interfaced to irrational use of capital investments (however, it concerns also any other sources of thermal energy). In relation to the GTPP as to option of conditioning of favorable temperature in districts with sharply continental climate, achievement of rather high coefficient of power efficiency is possible. For example, if $T_1 = 340\text{ K}$ and $T_0 = 280\text{ K}$, $k_T = 5.66$ that is the cost of electrical energy for providing electrical operation of the gas turbine power plant with regard to its power efficiency ratio will not exceed 20% of the accumulated in TA thermal energy.

At rather high power efficiency and technological effectiveness of production of MSP and also the acceptable costs of realization of the offered GTPP, it is necessary to pay attention to high requirements for ensuring tightness of all contour of circulation of the liquid heat carrier and especially all cavities of MSP. At depressurization of any site of MSP this site has to be localized and excluded from a circulation contour to a complete recovery of tightness in a hydraulic system. Minimization of this risk is promoted by the modular principle of building of the GTPP. Besides, use in MSP of cellular polycarbonate with a protective external layer of the increased mechanical firmness is possible.

CONCLUSION

- The option of reversible heliothermal power heat-sink system on the basis of MSP with use of energy of phase transition of the liquid heat carrier allows supporting comfortable conditions in rooms at considerable differences of day and night ambient temperatures
- Owing to bilateral heat exchange between MSP and air the offered option of heliothermal system differs in the increased power efficiency
- For rooms with a big useful area and also extended rooms (galleries, transitions, etc.) the modular principle of building of heliothermal system is preferable
- Taking into account rather high acceptable steam formation temperature in the GTPP use as the liquid heat carrier of ordinary water with ethylene glycol addition is possible

- The GTPP on the basis of MSP can form a basis for design and broad use of the modified fankoil-systems of maintenance of comfortable temperature in corridors, galleries, transitions and other open and extended rooms

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