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STUDYING POSSIBILITIES OF SEASONAL COLD FOR APPLICATION IN MULTIFUNCTIONAL HEAT SUPPLY UNITS

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ABSTRACT

This article discusses theoretical foundations and engineering approaches to capturing and conservation of seasonal cold potentials by means of phase transformation of heat intensive materials and synthesis of energy intensive chemical substances for subsequent usage in multifunctional heat supply units on the basis of heat pumps. This article estimates possibility and develops methods of cold potential accumulation in the form of heat of phase transition of various substances, as well as in the form of chemical bonds, the most optimum cold accumulating substances have been analyzed and selected, their required amount for demands in conditioning of individual residential building has been calculated, the main testing principles of cold accumulator are described.

Keywords: cold accumulator, phase transition, heat pump, conditioning, energy conservation, heat recovery, seasonal cold.

INTRODUCTION

Rational usage of cold in industry and national economy is obviously an important issue, its solution is stipulated by deficit of fuel and power resources [1-5].

A possible approach to solution of this problem is cold accumulation [6-8]. Cold accumulators would provide optimum operation modes of equipment, eliminate possible mismatching between cold production and consumption, increase reliability of cooling systems, reduce load on power supply during electricity peak consumption both for commercial and private demands, decrease installed capacity of refrigerators as well as expand the scopes of application of natural cold [9-11].

This article discusses capturing and accumulation of seasonal cold, analyzes modern technologies of accumulation and application of existing heat storing materials (HSM) in innovative efficient designs of cold accumulators.

METHODS OF ANALYSIS OF COLD POTENTIALS AND PROCEDURES OF ITS CAPTURING FOR SUBSEQUENT TRANSFER INTO ACCUMULATORS FOR VARIOUS REGIONS OF THE RUSSIAN FEDERATION

Natural sources of cold exist in ambient environment and their temperature decreases as a consequence of natural processes. Upon cooling heat is taken from cooled body. Ice on rivers and water sources, snow, cold ambient air in winter, water of Mountain Rivers, night air in areas with sharply continental climate, permafrost arrays, artesian water can be used as natural sources of cold.

Thermal potential of cold of natural coolers is restricted by natural conditions, it is exposed to fluctuations, cannot be controlled, and mostly its action is restricted by time frames. Thus, in industry and everyday human life energy consuming artificial cooling methods are mostly used. In southern regions of Russia with hot climate, where demand for cold is especially high, the sources of natural cold are not numerous, their temperature is higher. In northern regions the sources of cold are numerous but demand for them is lower. Thus, demand for cold, for instance for comfort conditions of human life, and supply of natural cold are mismatched.

Analyzing average monthly temperature of the hottest month in a year, it is perhaps possible to state that high demand for conditioning does not exist, since the average air temperature for southern regions does not exceed +24°C. However, in southern regions of Russia maximum air temperature in summer are higher than +35°C, it is possible to conclude that conditioning in these regions is a very urgent issue [12].

In southern and southeastern regions of Russia the soils are characterized by permafrost. The distribution range of permafrost in Russia occupies about 11 million km^2, that is, about 65% of Russia. These territories are characterized by no periodic thawing. The permafrost regions are located in upper portion of Earth crust, its temperature for a long time (from 2-3 years to several thousand years) is not above 0°C. In the permafrost area ground water exists in the form of ice, its depth can exceed 1000 meters [13]. While analyzing the maps of permafrost in Russia it is possible to conclude that conditioning in this territory of Russia is not required.

The most available sources of thermal potential of cold are ambient air and ground.

On the basis of conclusions regarding urgent character of conditioning in various regions of Russia it is required to consider possible sources of thermal potentials of cold in winter season. Capturing of thermal potential of cold from air in winter is quite prolonged and efficient.

While analyzing average monthly temperature of January it is clear that in the area of interest, required for conditioning, the average monthly temperature in winter is below that necessary for charging of cold accumulator, which is a positive factor. This evidences efficiency of such charging.

The time range of such temperature regime in cold season can be monitored by the map of day number in a year with average air temperature below 0°C. The map illustrates the areas of days with average daily temperature below 0°C. In average for the South of Russia the duration of such period is from 3 to 4 months. For central part of the country it is from 4 to 5 months.

As for low potential cold of ground, it is known that the temperature of Earth surface varies during a year. Mainly it depends on solar activity, beam incidence angle on Earth surface. It can be attributed to top (neutral) layer up to 10 m in depth. At the depth of more than 10 m the ground temperature remains unchanged and corresponds to average yearly temperature in this region, for instance, in Rostov oblast it is +8÷10°C. Thermal potential of ground is sufficient for comfort conditioning of residential buildings but insufficient for deeper cooling of premises, such as storehouses of food products. This dependence is characteristic for southern and central parts of Russia.

It is possible to highlight three main trends among capturing potentials of seasonal cold:

a) circulating systems which pump heat carrier between ground heat exchanger and consumer, capturing potential of cold from ground (passive conditioning);

b) heat exchangers acquiring average potential heat of environment (below +20°C);

c) heat pumps (HP) operating in reverse mode capturing low potential energy of cold from environment and ground.

The first trend implies the following: it is known that the Earth temperature from the depth of 8÷10 m and deeper remains constant all the year round and in static regime equals to +8°C (for Rostov oblast). It is possible to pump heat carrier by circulating pumps via geothermal probes located in ground and to feed this heat carrier to conditioners (fan coil units). Upon pumping the static regime will be disturbed and transferred into dynamic regime when the heat carrier temperature will be +(16÷18)°C. This temperature regime is optimum for soft conditioning of residential area of buildings as well as for cooling of rooms for storage of agricultural products. Such conditioning is known as passive. An advantage of this method is that energy is not used for cooling of heat carrier and consumed only for its circulation in the system. In this case low potential cold is accumulated by ground which stores average yearly temperature potential.

The second trend implies installation of air/water heat exchangers and automatics which will activate circulation pump between heat exchanger and accumulator of cold when the ambient temperature is below the HSM temperature in accumulator of cold. In summer, this approach can operate for short period when air temperature drops. In winter, when free-of-charge natural cold is unlimited, it is reasonable to store it in accumulators of cold and to use when required in summer for comfort conditioning of residential areas. However, it is often the case that deeper cooling of air is required for conditioning of storehouses for food products. Conventionally, the temperature regime in such buildings can be subdivided into two parts. The first regime is that of optimum storage, its operation temperature is from +16°C to -5°C. The second regime is that of freezing. Its temperature is in the range from -5°C to -15°C. In such cases the efficiency can be increased by the use of two HSM with different temperature of phase transition. This can be achieved by means of two-chamber accumulator of cold, its single body will combine two chambers: one of them with higher sizes but with HSM with the temperature of phase transition from +16°C to -5°C, the other one of lower sizes with the temperature of HSM phase transition from -5°C to -15°C. The main chamber used for conditioning of residential areas operates in relatively high temperature regime. Minor chamber, operating in low temperature regime, is intended for freezing of products to the temperature below -15°C. For instance, when the bottom portion of cold accumulator is dischargedat 0°C and the consumer needs the temperature of -15°C, the second chamber is activated which is filled with HSM with lower temperature of phase transition and increases the potential of cold from 0°C to -15°C withdrawing energy from the first relatively high temperature chamber of cold accumulator.

The third trend is based on the use of HP activated in reverse mode in order to increase the potential of cold to required temperature in peak hours. This is so called active conditioning. At present this trend is the most popular and the most energy consuming, it will not be considered in the frames of this work.

DEVELOPED PROCEDURES OF SEASONAL COLD ACCUMULATION IN THE FORM OF HEAT OF PHASE TRANSITION OF VARIOUS SUBSTANCES

The most available working medium for cold accumulating systems is water as well as aqueous solutions of salts, glycols and alcohols. The use of solutions makes it possible to decrease freezing point of cold carrier, thus expanding the application field, however, addition of various components into water can lead not only to decrease in freezing point but also of phase transition heat. Working medium in cold accumulator can exist in one or two aggregate states.

Cooling of water or aqueous solutions for accumulators without phase transition only due to sensible heat is unreasonable since low accumulation density of 5.8 $kW \cdot h/m^3$ stipulates high volume and weight of accumulator and high heat loss.

While accumulating heat by phase transition of heat accumulating medium, the temperature of working medium is maintained constant until phase transformation is completed, herewith, the heat of phase transition is significant (see Table-1), which permits to reduce accumulator dimensions or to increase its heat capacity. The most available substances for use in accumulators

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with the temperatures of phase transition in the range of interest are summarized in Table-1.

On the basis of maximum heat of phase transition and melting point, we select water and ammonium chloride crystal hydrate as HSM for accumulator. The heat of phase transition of these substances is significantly higher than of other substances and the melting points are optimum for consumer needs.

Table-1. Thermophysical properties of substances suitable for application in cold accumulator based on phase transition.

Hydrate	Heat of phase transition, kJ/kg	Density, g/cm^3	Melting point,°C	Specific heat capacity, kJ/(kg·°C)	
				Solid phase	Liquid phase
$C_3H_5(OH)_3$ Glycerol	201.0	1.261	18.0	2.18	2.43
$C_{12}H_{15}N_2O_3PS$ Phoxim	253.0	1.176	5.0	2.31	2.38
$C_6H_{18}N_3OP$ Hexametapol	247.0	1.030	7.0	2.57	2.60
H_2O Water	333.5	0.998	0	2.06	4.19
$C_6H_{14}O_4$ Triethylene glycol	269.0	1.127	-5.0	2.09	2.27
$C_4H_{10}O_3$ Diethylene glycol	271.0	1.118	-10.5	2.11	2.32
$C_2H_6O_2$ Ethylene glycol	264.0	1.113	-12.9	2.13	2.38
NH_4Cl-H_2O Ammonium chloride crystal hydrate	320.0	1.130	-15.0	2.08	3.30
$C_2H_3O_2Na$-H_2O Sodium acetate crystal hydrate	310.0	1.130	-18.0	2.11	3.17
$NaNO_3$-H_2O Sodium nitrite crystal hydrate	280.0	1.120	-18	2.14	3.47
$C_3H_8O_2$ Propylene glycol	257.0	1.040	-60	2.37	2.48
C_2H_5OH Ethyl alcohol	108.0	0.789	-114.5	2.07	2.39

DISCUSSION OF POSSIBILITIES OF SEASONAL COLD ACCUMULATION IN THE FORM OF CHEMICAL BONDS AND SELECTION OF THE MOST OPTIMUM COLD ACCUMULATING SUBSTANCES

Various heat absorbing chemical reactions exist which can be used for cooling. The most available and safe are the reactions where salts are dissolved in water or snow producing cooling mixtures. Dissolution as a means of artificial cold is applied since ancient times. For instance, Romans dissolved saltpeter in water in order to obtain cooling. For deeper cooling, the mixture of snow with saltpeter was applied. Nowadays cooling mixtures are used in everyday life, in laboratories and in the cases not requiring for very intensive and prolonged cooling. Obtaining of cooling mixture by dissolving does not require for complicated and expensive assemblies; the procedure involves rapid mixing of fine salt with water and placement of container with water to be cooled into the solution. Upon cooling by ammonium nitrate solution, which is most often used in ice machines, it is necessary to sue such concentrations which are not related with deposition of salt or ice, since both these cases would lead to heat evolution.

Table-2 summarizes data on decrease in the mixture temperature and amount of absorbed heat which can be expected upon cooling from +20°C, +15°C, +10°C, and +5°C to ultimate temperatures of crystallization and freezing.

As mentioned previously, reactions of this type are relatively short; hence, it is reasonable to accumulate the evolved potential of cold in accumulator.

The most available are ammonium nitrate mixtures. They are widely applied in agriculture as fertilizers [14].

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Table-2. Decrease in mixture temperature and total absorbed heat.

	Decrease in temperature of solution	**Absorbed heat**	**Solution saturation temperature**	**If the temperature of salt and water equals to +20, +15, +10, +5°C, then the heat absorbed upon cooling:**			
1 g salt							
0.75 g water	44.7°C	49.7	+5.0	30.0	38.0	44.1	49.7
0.20 g water	41.3°C	51.6	-2.0	24.1	30.3	36.6	42.8
0.99 g water	39.3°C	52.9	-6.0	17.8	24.5	31.2	37.1
1.14 g water	36.4°C	54.5	-10.0	6.7	14.1	21.6	29.1
1.31 g water	33.9°C	56.2	-17.5	-	2.3	10.6	18.9
				The solution freezes at temperatures:			
1.49 g water	31.5°C	57.6	-16.0	-	0.9	10.1	19.3
2.76 g water	22.1°C	66.0	-10.0	-	-	6.5	21.4
22.50 g water	3.7°C	89.2	-1.5	-	-	-	-

A positive feature of such method of cold production is that one and same salt can be used for cooling several times. This can be aided by vaporization of the salt solutions after their usage; slat is deposited in the form of crystals. Such regeneration can use the heat obtained in solar collector.

The most efficient substances for accumulation of heat of phase transition are water and ammonium chloride crystal hydrate. However, the use of water involves some difficulties:

- water has high phase transition heat, 333.5 kJ/kg, but also relatively high temperature of phase transition, 0°C, so it cannot be used for freezing of products;
- the temperature of phase transition of ammonium chloride crystal hydrate is -15°C, it can be used for freezing of products; however, it has lower temperature of phase transition heat of 320 kJ/kg, in addition it is more expensive than water [15].

Modern available substances which can be applied for cold accumulation upon phase transition are characterized by certain disadvantages and advantages. Therefore, it seemed to be interesting to use their combination so that disadvantages of one substance would be covered by advantages of another one.

This effect is achieved by the fact that major portion of energy is stored at relatively high temperature of water transition, 0°C, and the portion of energy required for freezing to - 15°C (freezing of products) is stored in ammonium chloride crystal hydrate.

The proposed design of cold accumulator will provide temperature regime to -15°C, required for freezing of products. Major portion of energy is accumulated at 0°C in HSM characterized by higher heat of phase transition and minor portion of energy required only for after-cooling in freezing modes, is stored at -15°C in HSM with lower heat of phase transition.

Heat conductance is intensified by developed surface of heat exchange enveloped into Archimedean spiral.

The design of cold accumulator is as follows: the bottom accumulator part is filled with water; spiral heat exchange surface is located here. Heat carrier, cooled to 0°C in the bottom part, can be directed via three-way valve either to conditioning or to deeper cooling to -15°C in upper accumulator part for freezing of products. The upper part is filled with ammonium chloride crystal hydrate and is equipped with similar developed heat exchange surface in the form of Archimedean spiral. The accumulator is thermally insulated. In addition, the isolation separates the upper and bottom parts.

After development of experimental version, the aim of the studies is to confirm its operating properties: heat carrier temperature of conditioning system, heat carrier temperature of freezing system accumulating capacity of each part.

In order to determine optimum heating (cooling) capacity it is necessary to determine its most reasonable dimensions, volumes of HSM and capacities which will reflect the average consumer demands, thus corresponding to the most marketable variant. Such variant should be optimized in terms of minimum payback period.

The energy scheme with all included elements is illustrated in Figure-1.

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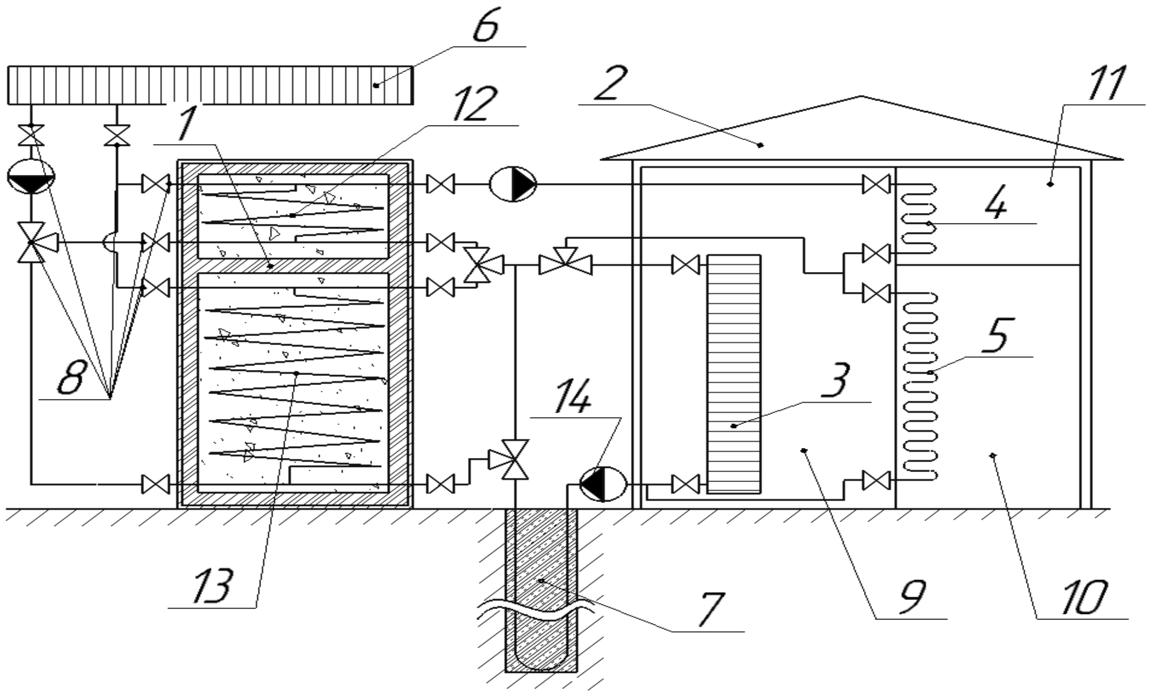

Figure-1. Energy scheme of conditioning system: 1 - high-performance cold accumulator; 2 - residential building; 3 - conditioning devices of residential area; 4 - conditioning devices of freezing area; 5 - conditioning devices of food storage area; 6 - heat exchangers for charging of cold accumulator (air/water heat exchanger); 7 - geothermal probe in well; 8 - shut-off and control valves (ball valves, three-way valves); 9 - residential area; 10 - food storage area; 11 - food freezing area; 12 - cold accumulator top portion; 13 - cold accumulator bottom portion; 14 - circulation pump.

Let us consider possible operation modes of the system for various connection variants. With the aim of convenience all interactions between the units inactive in this mode are excluded. In addition, bypasses on shut-off and control valves closed in this mode are highlighted in black.

Passive (soft) conditioning of residential area. Passive conditioning is carried out by pumping of heat carrier using circulation pump (CP) via the circuit of geothermal probe immersed into well. Schematic view of passive conditioning is illustrated in Figure-2.

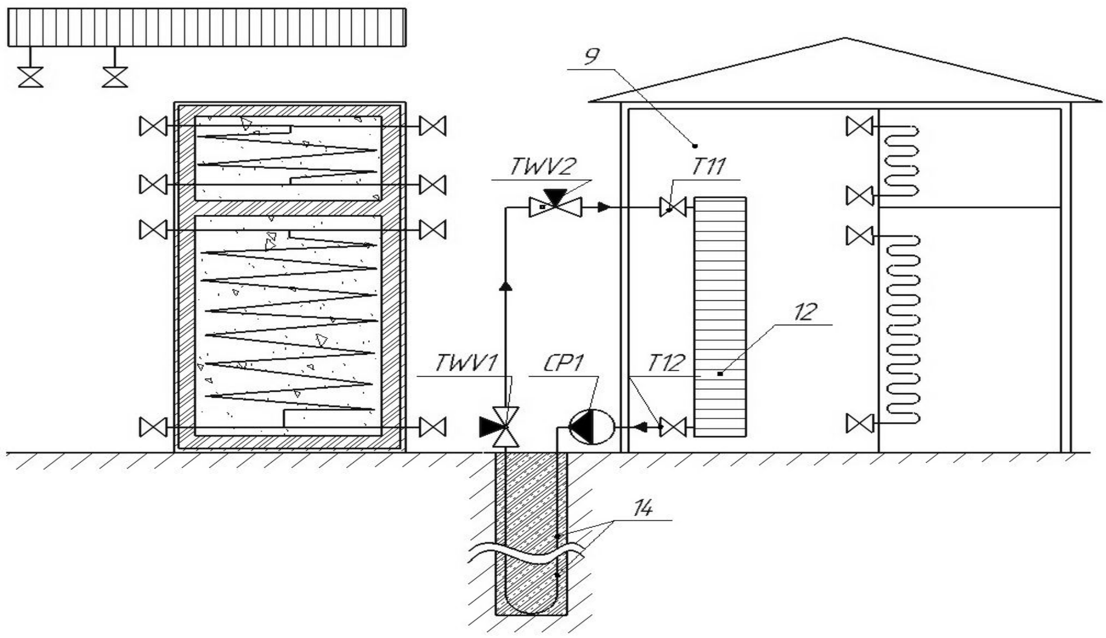

Figure-2. Passive (soft) conditioning.

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Working sequence. The circulating pump CP1 pumps heat carrier with initial temperature via the geothermal probe 14. Here it is cooled by low temperature potential of ground cold to 18°C in dynamic mode. Then, the heat carrier at this temperature is directly fed via three-way valves TWV1 and TWV2 to the conditioning units 12, thus cooling air in the residential area 9. In this case the shut-off valves T11 and T12 are opened.

Normal conditioning of residential area. In the cases when passive conditioning cannot maintain the loads and cannot provide the required temperature mode in building, it is possible to connect the bottom part of cold accumulator. Preliminary charged bottom part of the accumulator will assist in maintaining the required temperature in peak hours. This mode is schematically illustrated in Figure-3.

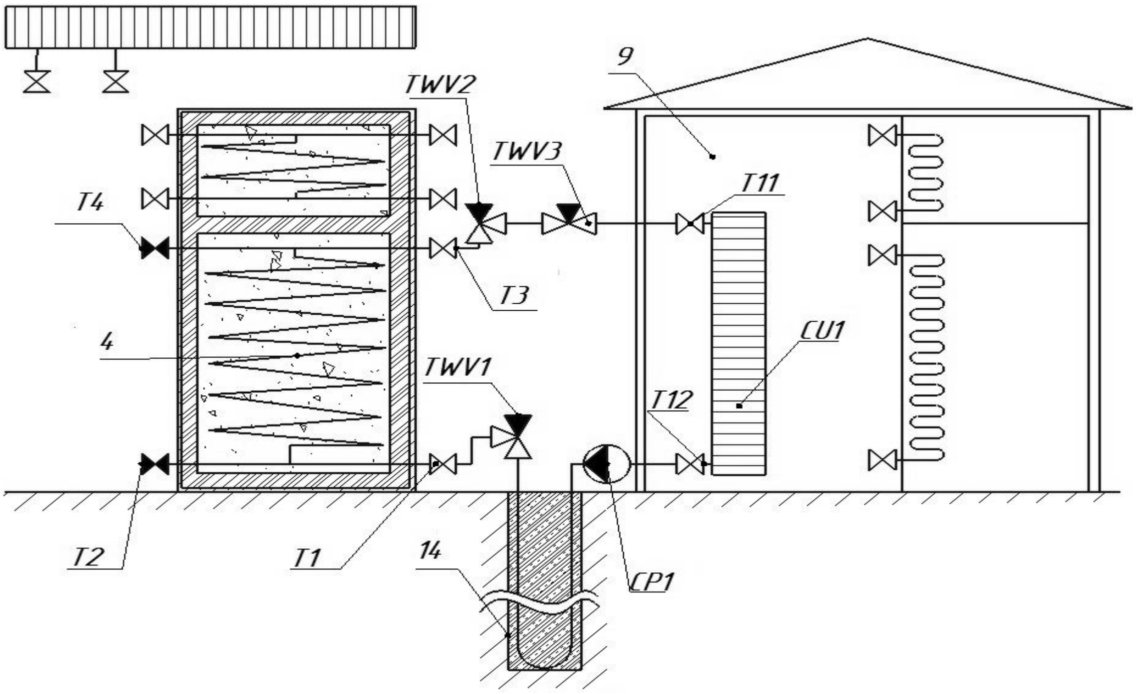

Figure-3. Normal conditioning.

Working sequence. The circulating pump CP1 pumps heat carrier via the geothermal probe 14. Then, via the three-way valve TWV1 the heat carrier is supplied to the heat exchange surface of bottom part of accumulator, where preliminary cooled HSM gives up its heat to the heat carrier. After the bottom part of accumulator, the heat carrier via three-way valves TWV2 and TWV3 is supplied to the conditioning units CU1, where gives up the cold from accumulator to the air of residential area 9. In this case the valves T1, T3, T11, T12 are opened and the valves T2 and T4 are closed.

Food storage conditioning. In food storehouses, it is required to maintain certain temperature regime from +16°C to +1°C. The flowchart of conditioning with these temperatures is illustrated in Figure-4.

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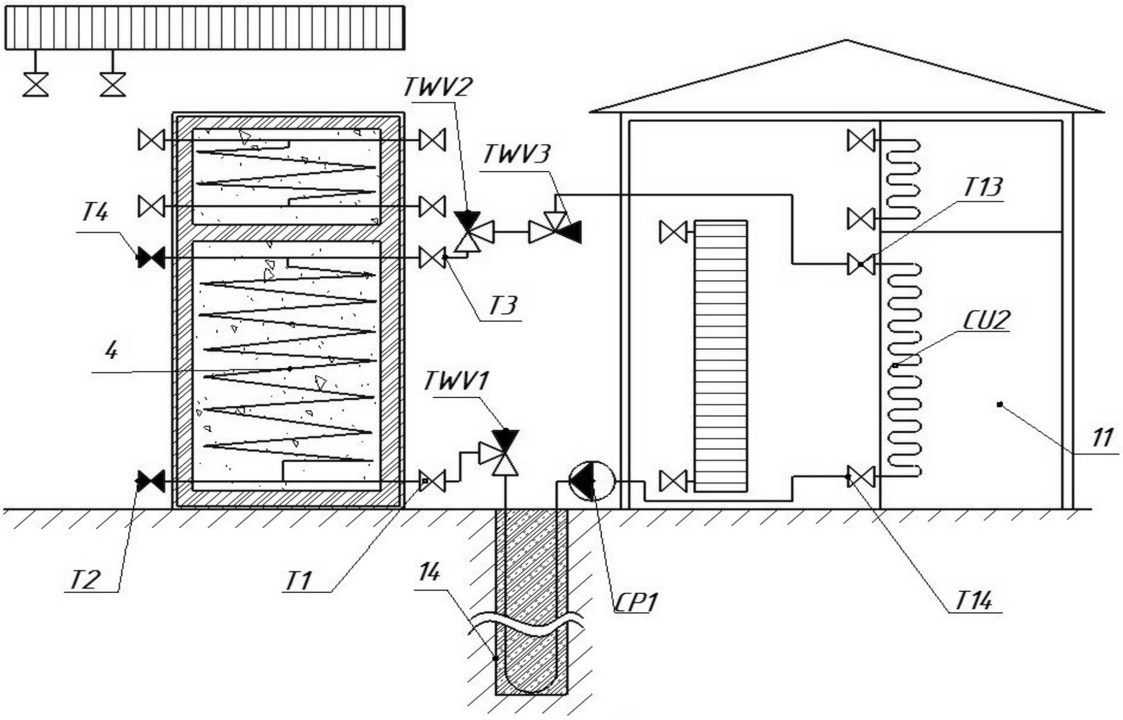

Figure-4. Food storage conditioning.

Working sequence. The circulating pump CP1 pumps heat carrier via the geothermal probe 14. Then, via the three-way valve TWV1 the heat carrier is supplied to the heat exchange surface of bottom part of accumulator 4, where preliminary cooled HSM gives up its heat to the heat carrier. After the bottom part of accumulator, the cooled heat carrier via three-way valves TWV2 and TWV3 is supplied to the conditioning units CU2, where it cools the air in the building 11 to the temperature from +16°C to -1°C. The valves T2 and T2 are closed; T1, T3, T13, T14 are opened.

Food freezing conditions. For freezing and long-term storage of food products it is required to maintain the temperature from 0°C to + 5°C. This temperature regime can be achieved using the upper chamber of cold accumulator. The flowchart of this regime is illustrated in Figure-5.

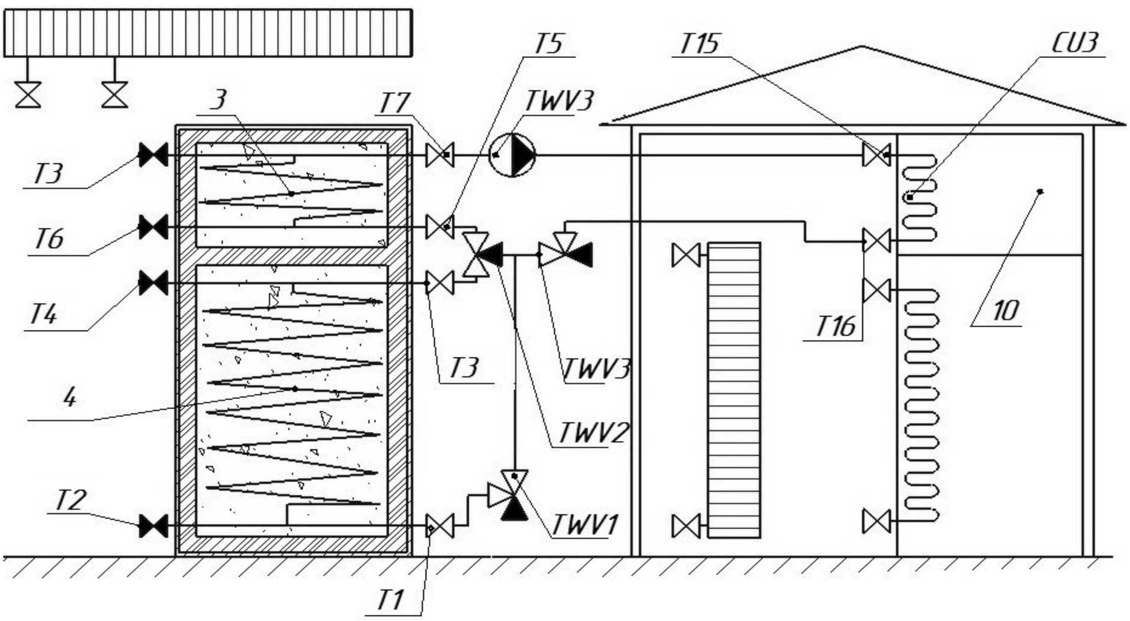

Figure-5. Food freezing conditioning.

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Working sequence. In this case the heat carrier is pumped by the circulation pump CP2 via the heat exchanging surface of the bottom part 4, then, bypassing the three-way valveTWV2, via the heat exchange surface of the upper part 3. After cooling in the upper part, the heat carrier is supplied to the conditioning units CU3 positioned in the room for freezing 10. There the heat carrier gives up cold and repeats the cycle passing via the three-way valves 4 and 14. The valves T1, T3, T5, T7, T15, T16 are opened, the valves T2, T4, T6, T8 are closed.

The combined mode of accumulator charging is available, when it is simultaneously possible to charge the accumulator and to use its upper part for freezing. Such mode is very efficient in winter, when no conditioning is required but it is required to freeze food products. This mode of accumulator operation is illustrated in Figure-6.

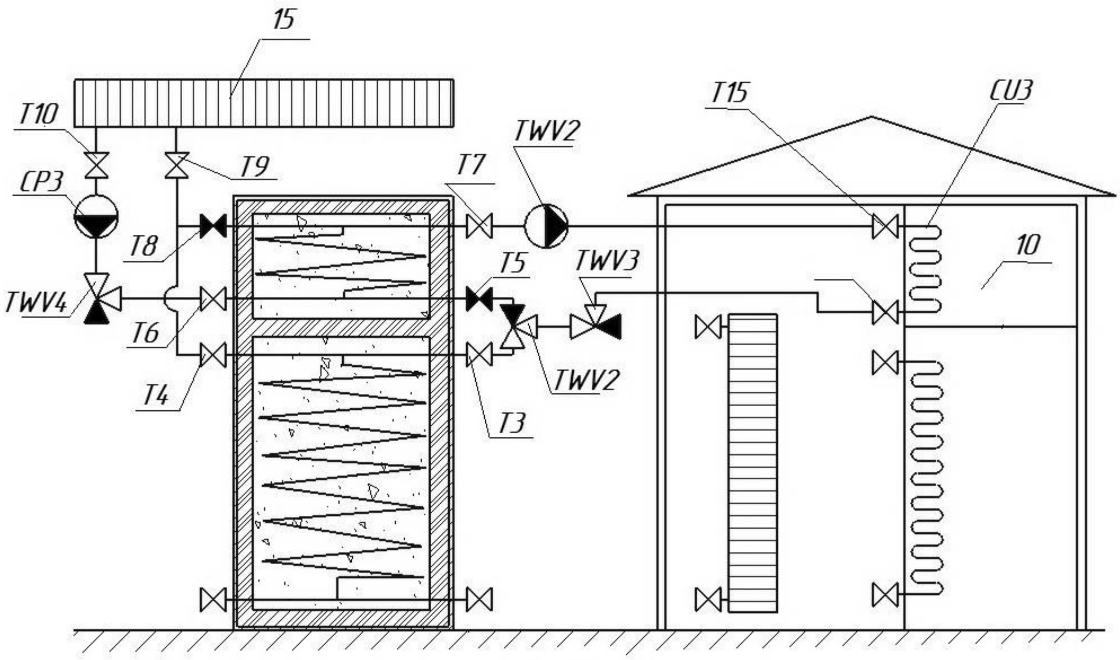

Figure-6. Combined charging/freezing.

Working sequence of combined mode: the heat carrier, cooled outside, from the air/water heat exchanger 15 is pumped by the circulating pump CP3 and, bypassing the three-way valve TWV4, is supplied to the heat exchanging surface of the upper part of accumulator 3, then the heat carrier is supplied to the conditioning units CU3 in the freezing area 10, then, bypassing the three-way valvesTWV2 and TWV 3, is returned back to the heat exchanger 15. For more efficient heat release in this mode, it is possible to increase the flow rate of heat carrier using the second circulating pump CP2. In this operation mode the valves T6, T7, T9, T10, T15, T16 are opened and the valves T5 and T8 are closed.

CONCLUSIONS

The presented overview revealed that in southern regions of Russia it is possible to accumulate seasonal cold. This cold can be captured by HP and environment heat exchangers. In certain northern and eastern regions such capturing is non-demanded due to unnecessary conditioning of residential buildings. In addition, this article analyzes the possibility to accumulate cold both upon heat intensive accumulation and upon phase transition of heat intensive substances. It has been revealed that upon cold accumulation by phase transition of cold accumulating substance the temperature of working medium remains constant until the phase transition is completed, moreover, the heat of phase transition is significant, which permits to reduce dimensions of accumulator or to increase its heat capacity. The most available substances for application in cold accumulators with the temperatures of phase transition in the required range are water and ammonium chloride crystal hydrate.

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