Запропоновано ефективні схемні рішення альтернативної системи гарячого водопостачання. Виконано моделювання теплових процесів в акумуляторах теплоти при різних способах підключення генераторів теплоти та споживачів. Проведено експериментальні дослідження системи гарячого водопостачання на базі теплового насосу при різних температурних режимах

Ключові слова: акумулювання теплоти, геліосистема, тепловий насос, комбіновані системи теплопостачання, фазовий перехід

Предложены перспективные схемные решения альтернативной системы горячего водоснабжения. Выполнено моделирование тепловых процессов в аккумуляторах теплоты при различных способах подключения генераторов теплоты и потребителей. Проведены экспериментальные исследования системы горячего водоснабжения на базе теплового насоса при различных температурных режимах

Ключевые слова: аккумулирование теплоты, гелиосистема, тепловой насос, комбинированные системы теплоснабжения, фазовый переход

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IMPROVING THE OPERATION MODES EFFICIENCY IN HEAT PUMP SYSTEMS OF HOT WATER SUPPLY WITH THE TWO-STAGE HEAT ACCUMULATION

A. Mazurenko
Doctor of Technical Sciences, Professor, Director of Institute
Institute for Energy and Computer-Integrated Management Systems**
E-mail: antmaz@i.ua

A. Denysova
Doctor of Technical Sciences, Professor*
E-mail: alladenysova@gmail.com

G. Balasanian
Doctor of Technical Sciences, Professor*
E-mail: bageal1@rambler.ru

O. Klymchuk
PhD, Associate Professor*
E-mail: aklimchuk74@rambler.ru

K. Borisenko
PhD, Associate Professor
Department of Water Supply
Odessa State Academy of Civil Engineering and Architecture
Didrihsona str., 4, Odesa, Ukraine, 65029
E-mail: nefertichtvo@ukr.net

*Department of Thermal Powel Plants and Energy Saving Technologies**
**Odessa National Polytechnic University
Shevchenko ave., 1, Odesa, Ukraine, 65044

1. Introduction

Application of the combined systems of heat supply with the use of the renewable energy sources is one of the directions to solve a strategic question of reducing the consumption of fossil fuels [1]. Measures that are directed toward the reduction of consuming natural gas are stimulated at present by the government of Ukraine [2].

Pellet boilers and electrical boilers that employ night tariff for electric power have been commonly used by the population and enterprises of small and mid-sized businesses. Applying a night tariff for electric power makes it possible to not only decrease the consumption of traditional fuel but also somewhat balance the load on the energy system of Ukraine [3].

However, the given solutions do not fully utilize the potential of renewable energy sources, first of all, of heat pumps and solar collectors. As is known, effective use of the sources of renewable energy is impossible without heat accumulators, which allow smoothing the nonuniformity of generation and consumption of heat [4]. For example, for heliosystems, the nonuniformity indicated is caused by the mismatch between daily peaks of solar radiation intensity and the need for hot water.

It should be noted that efficient use of renewable energy sources in the combined systems of heat supply with the application of heat accumulators depends on a number of factors. Climatic conditions essentially influence effectiveness of use; however, the circuits of system of heat supply of heat-carriers are also important. Of special interest are the circuit solutions, which make it possible to maximally utilize solar energy and regimes of the heat pump operation in the range of its largest efficiency [5].

Since different renewable sources of low-potential energy for heat pump have limitations on their application, related to the inconstancy of energy potential, which depends on climatic conditions, determining the range of effective work of alternative systems of heat supply with the application of energy accumulators is a relevant task.

2. Literature review and problem statement

Considerable attention is paid to the problem of effective use of renewable sources of heat, including for the preparation of hot water [4–8]. Main attention is paid to the alignment of operational modes of heat generators and consumers, as well as to peculiarities in the application of renewable heat sources along with the traditional systems of heat supply.

It should be noted that the leading manufacturers of thermal-power equipment devised recommendations for circuit solutions of using the renewable sources of heat [9]; however, they are typically aimed at improving the hydraulic performance characteristics of traditional and alternative systems, as well as at aligning the system of automation of the subject of study.

Of all the variety of circuit solutions of the combined systems of heat supply, implemented in practice, the following ones are of the largest interest:

1. Bivalent water heater-accumulator with two sources of heat – from gas boiler and solar collector (Fig. 1).

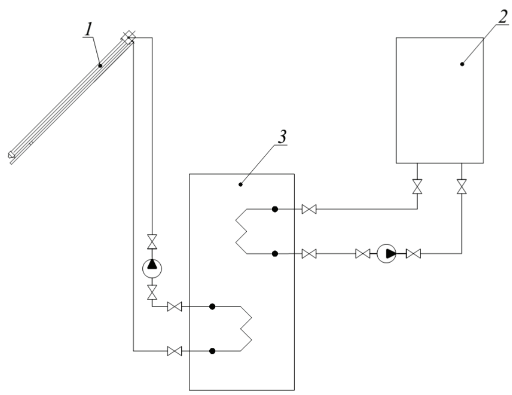

Fig. 1. Combined circuit for the preparation of hot water from two sources of heat with the use of a bivalent water heater-accumulator: 1 – solar collector, 2 – gas boiler, 3 – bivalent water heater-accumulator

Circuit in Fig. 1 makes it possible to prepare hot water in one tank, using heat of the contour of heliosystem in the lower heat exchanger of water heater-accumulator, and then additionally heat it with the aid of gas boiler in the upper heat exchanger.

The drawbacks in the examined circuit are:

– low heat emission due to predominantly free convection in the tank-accumulator [10];

– undeveloped surface of heat-exchange in the coil heat-exchanger of water heater-accumulator leads to a sharp reduction in the heating capacity of heliosystem at low temperatures in the contour of solar collector [11];

– limitation in temperature of heat carrier in the contour of heliosystem, which manifests itself especially vividly during winter period [10].

The intensification of heat exchange between the heat carrier of heliosystem and hot water in the accumulator of heat can be solved by installing a compact external lamellar heat exchanger with the developed surface of heating (Fig. 2).

2. Combined circuit with the intensification of the process of heat exchange due to the installation of external lamellar heat exchanger (Fig. 2).

In the combined circuit for the preparation of hot water, a question of the intensification of heat exchange from the side of heliosystem is solved by applying an external lamellar heat exchanger and a circulating pump. However, a shortcoming of this circuit is again a problem of limitation of temperature of the heat carrier in the contour of solar collectors.

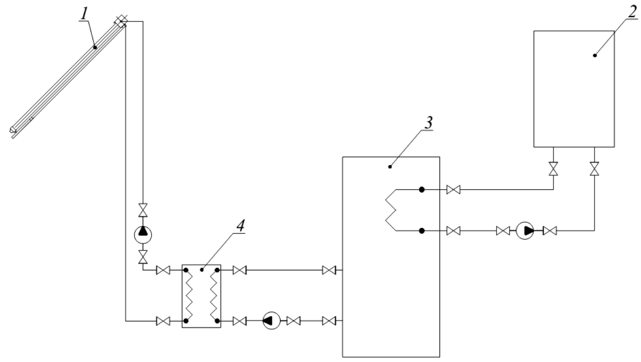

Fig. 2. Combined circuit for the preparation of hot water with the use of a lamellar heat exchanger and monovalent water heater-accumulator: 1 – solar collector, 2 – gas boiler, 3 – monovalent water heater-accumulator, 4 – lamellar heat exchanger

3. Combined circuit for the preparation of hot water with the use of two-step preheating (Fig. 3).

The examined circuit implies the use of two steps for the preparation of hot water, intended for expanding temperature range of work of the contour of heliosystem.

In the represented circuit solution (Fig. 3), the possibility of using low-potential heat from the contour of solar collector for preheating hot water in the first step of tank-accumulator is realized. In this case, temperature of the heat carrier can be lower than 40 °C, which cannot be realized in the circuits, represented earlier (Fig. 1, 2). The use of a reserve energy source is a drawback in this circuit; in this case, the substitution coefficient of organic fuel is less than 50 %.

Additional heating of hot water to the required temperature (not lower than 50 °C) is carried out in a separate contour, which consists of a monovalent water heater-accumulator of the 2nd step and a gas boiler. The deficiencies in the examined circuit (Fig. 3) include a large number of power machinery equipment, and, as a result, an increase in the cost of the system, as well as the need for the excess areas for its arrangement.

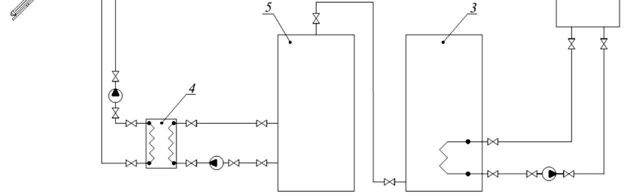

Fig. 3. Combined circuit for the preparation of hot water with the use of two steps for the preparation of hot water: 1 – solar collector, 2 – gas boiler, 3 – monovalent water heater-accumulator (2nd step of heating), 4 – lamellar heat exchanger, 5 – accumulator of hot water (1st step of heating)

4. Combined system with the use of a heat pump and solar collector (Fig. 4), which makes it possible to apply a heat pump in the zone of its largest efficiency and, at the same time, to decrease a number of solar collectors for the purposes of hot water supply [12]. In this case, the base load for preheating hot water is provided by a heat pump (to temperature 35–40 °C) while temperature regime in the feed pipe of the heat pump does not exceed 40–45 °C, which ensures energy efficiency of the circuit.

However, the circuit examined provides for the mean annual coefficient of substituting traditional energy less than 50 % [6], which makes it impossible to do without the backup of power.

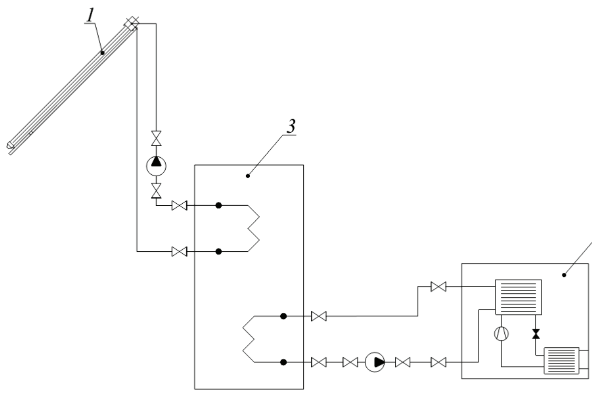

Fig. 4. Combined circuit for the preparation of hot water with the use of heat pump and heliosystem: 1 – solar collector, 2 – heat pump, 3 – bivalent water heater

5. Circuit for the preparation of hot water from the contour of heat recuperation of the refrigeration unit condensation (Fig. 5).

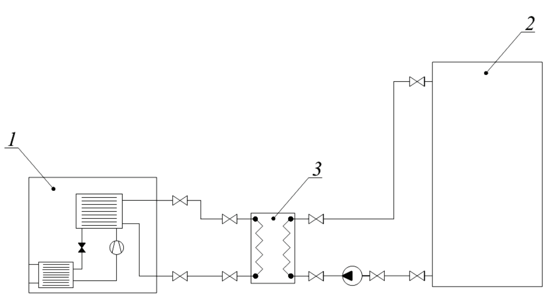

Fig. 5. System for the preparation of hot water from the recuperation contour of condensation heat of refrigeration unit: 1 – refrigeration unit, 2 – accumulator of hot water, 3 – lamellar heat exchanger

One of the varieties of circuit for using heat of refrigeration unit condensation in summer period for the preparation of hot water is a circuit with heat recuperation of condensation in a separate contour [13]. In this case, contemporary systems of conditioning that employ single-stage steam-compression refrigeration units can be equipped with a contour for the recuperation of condensation heat. In this case, by the available heat capacity, the indicated systems are capable of meeting the need for hot water supply to facilities. Condensation temperature of the refrigeration units of conditioning systems may reach 55 °C, which makes it possible to prepare hot water of the required temperature and to do without additional heat sources under summer mode.

However, a drawback of the circuit examined is the fact that refrigeration unit operates beyond the range of energy effectiveness because of the elevated temperature of condensation.

In order to improve effectiveness of the work of system of hot water supply for the preparation of hot water from the recuperation contour of condensation heat of a refrigeration unit, it is possible to use a two-step system.

6. Combined circuit for the preparation of hot water with the use of two sources of renewable energy: a recuperator of condensation heat of refrigeration unit and a heliosystem (Fig. 6).

This is a two-step circuit for the preparation of hot water, in which the first, low-potential, source of heat (along the motion of water) is the recuperation contour of refrigeration unit; the second, high-potential, source of heat is a heliosystem.

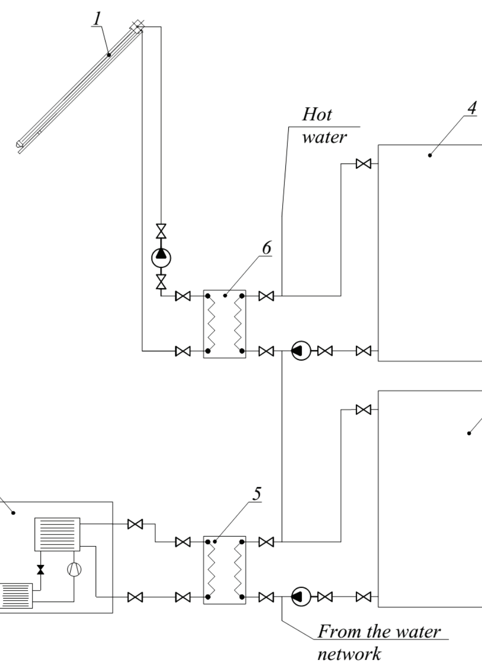

Fig. 6. Combined circuit for the preparation of hot water with the use of two sources of renewable energy: 1 – solar collector, 2 – refrigeration unit, 3 – accumulator of hot water (1st step), 4 – accumulator of hot water (2nd step), 5 – lamellar heat exchanger (1st step), 6 – lamellar heat exchanger (2nd step)

The circuit represented (Fig. 6) makes it possible to maintain energy-effective regime of cooling a refrigeration unit for the systems of conditioning (condensation temperature is not higher than 45 °C). In this case, it is possible to provide for a basic mode of heating water for the needs of HWS, as well as an additional one, for example, for preheating water in the pool.

The application of two tanks for the accumulators of hot water makes it possible to more effectively use the condensation heat of refrigeration unit for preheating hot water during peak load period in the cooling system of a facility and maximum load to heliosystem.

An analysis reveals that the choice of effective circuit solutions for the systems of alternative heat supply depends on a number of external and internal factors, to be conducted through technical and economic substantiation. In this case, one should emphasize that the selection of heat accumulator plays a decisive role that corresponds to the principles of energy-saving technologies. It is worthwhile paying attention to the schemes for connecting heat carriers to the heat accumulator. This circumstance may essentially influence the operation efficiency of combined system of heat supply. The issue of effectiveness in the heat accumulation at different variants of connecting heat carriers has been given insufficient attention.

3. The aim and tasks of the study

The aim of present work is to determine a rational operating mode of the installation that makes it possible to increase the share of using of low-potential energy through a two-step accumulation under different climatic conditions.

To achieve the set aim, the following tasks are to be solved:

– to model the processes for the examined circuits of connecting sources of heat under different regimes of generation and discharge of hot water;

– to visualize the processes in the heat accumulator under different regimes of generation and discharge of hot water;

– to examine experimentally the processes of charging a hot water accumulator from a heat pump under different climatic conditions;

– to determine conditions for the effective operation of alternative systems of heat supply with the application of energy accumulators and heat pumps.

4. Materials and methods of research

An important factor that influences the effectiveness of using hot water accumulators is the technique of connecting the sources of heat. In order to analyze effectiveness of the operation of accumulator, we modeled the processes for the widespread systems of connection under different regimes of generation – heat extraction.

Below (Fig. 7–13) are the results of modeling the thermal processes for three most common schemes of connecting heat carriers to the heat accumulator and two regimes of the system operation: equality of generation and heat consumption and heat accumulation at its low consumption.

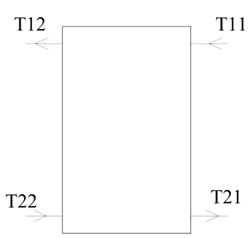

Fig. 7. Estimated parallel circuit of motion of connection flows of heat carriers to the tank-accumulator: T11 – feed line of the heat source, T12 – feed line of the heat consumer, T21 – return line of the heat source, T22 – return line of the heat consumer

For the two considered operation modes of the heat accumulator, with the help of software package Flow Simulation based on the SolidWorks software, we obtained results of numerical CFD-simulation of thermal processes in the heat accumulator with the visualization of temperature field (Fig. 10, 13). The software contains mathematical apparatus that makes it possible by the numerical method of finite elements to solve the equations of heat transfer for determining the estimated parameters, including temperature gradient by the volume of accumulator tank.

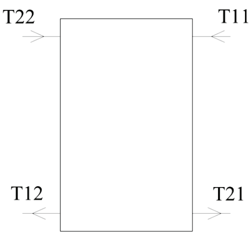

Fig. 8. Estimated cross circuit of motion of connection flows of heat carriers to the tank-accumulator: T11 – feed line of the heat source, T12 – feed line of the heat consumer, T21 – return line of the heat source, T22 – return line of the heat consumer

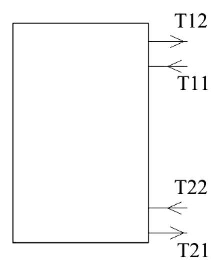

Fig. 9. Estimated circuit of connection of heat carriers to the tank-accumulator combined circuit of the flow motion: T11 – feed line of the heat source, T12 – feed pipe of the heat consumer, T21 – return line of the heat source, T22 – return line of the heat consumer

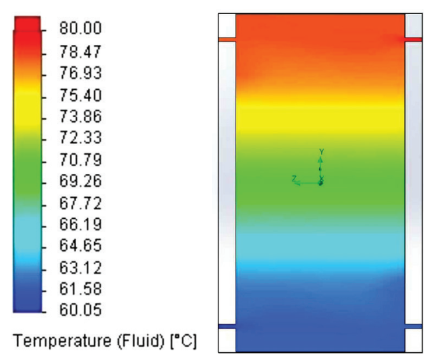

Fig. 10. Visualization of processes in the tank-accumulator during battery charging in the parallel circuit of flow motion

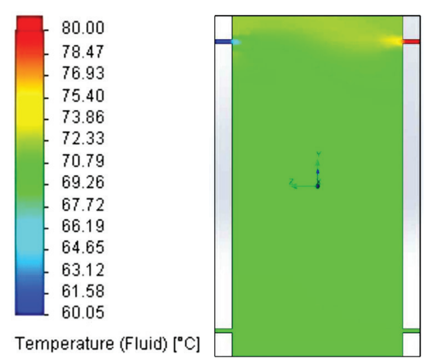

Fig. 11. Visualization of processes in the tan-accumulator during battery charging in the cross circuit of flow motion

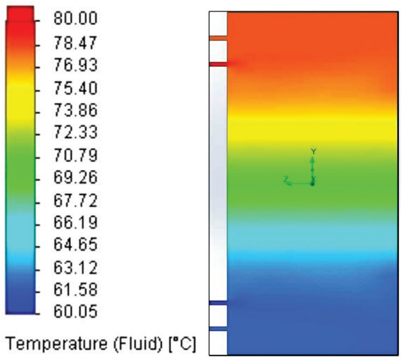

Fig. 12. Visualization of processes in the tank-accumulator during battery charging in the combined circuit of flow motion

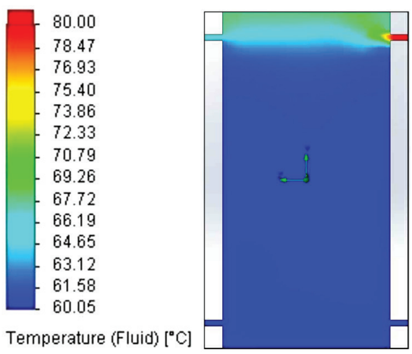

Fig. 13. Visualization of processes in the tank-accumulator during discharging of accumulator in the parallel circuit of flow motion

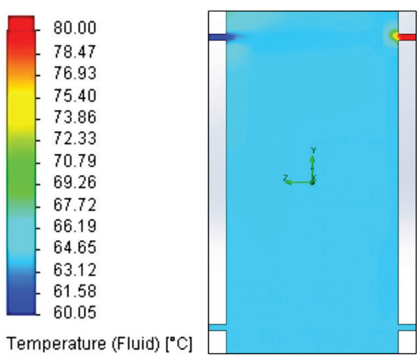

Fig. 14. Visualization of processes in the tank-accumulator during discharging of accumulator in the cross circuit of flow motion

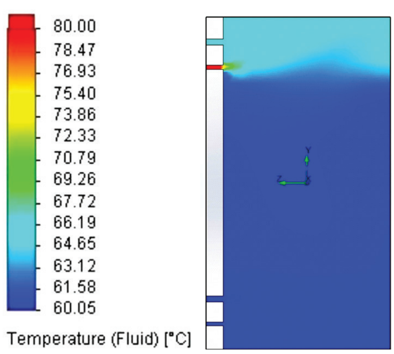

Fig. 15. Visualization of processes in the tank-accumulator during discharging of accumulator in the combined circuit of flow motion

Results of the numerical simulation of thermal processes in the tank accumulator (Fig. 10, 12, 14, 15) demonstrate that the application of traditional connections of heat carriers to the heat accumulator (parallel circuit of flow motion and combined circuit of flow motion) leads to the less effective use of the volume of tank-accumulator (stratification of temperatures in the tank during charging and the larger, not utilized, tank volume at discharging).

When using a cross circuit of flow motion, the distribution of heat by the volume of tank-accumulator is more uniform due to the cross flow of heat carriers and high degree of mixing the flows (Fig. 11, 13). This makes it possible to fully utilize the entire tank volume for the accumulation. However, the application of circuit of cross flow motion leads to the reduction in temperature in the feed pipe of consumer.

5. Experimental studies of effectiveness of heat pump operation under the mode of heat accumulation during summer period for the needs of HWS

One of the facilities (No. 10) at Odessa National Polytechnic University (Ukraine) was used for the implementation of the pilot production-experimental installation of heat accumulation with the use of the heat pump made by Gree, China (Fig. 16) of the split type "air – water" (Fig. 17), the bivalent water heater accumulator AMCOR, Israel (Fig. 18).

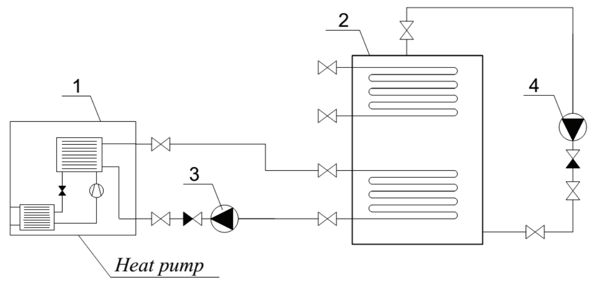

Fig. 16. Schematic of experimental installation: 1 — heat pump of the split type, 2 — bivalent water heater-accumulator, 3, 4 — circulating pumps

In order to analyze effectiveness of using a heat pump under the mode of preparing hot water, we installed a thermal counter and an electric energy measuring device (Fig. 17).

Studies were conducted at different ambient temperatures and varied temperatures of heat carrier. Results of the study are represented in Fig. 18, 19.

Fig. 17. Exterior view of heat pump of the split type "air — water" with heat output 6 kW

Fig. 18. Bivalent water heater-accumulator with capacity 300 l

a *b*

Fig. 19. Measuring devices: *a* – thermal energy; *b* – electrical energy

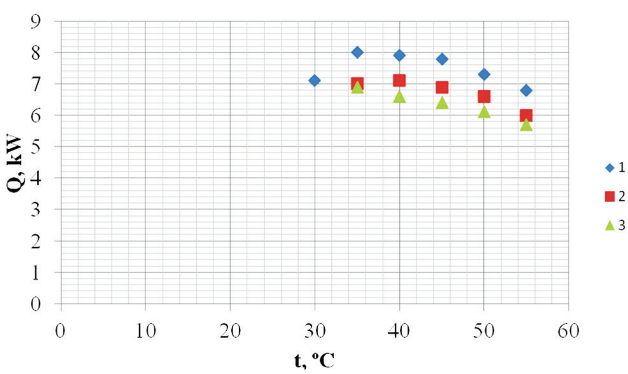

Fig. 20. Chart of dependence of the heat pump capacity on the outdoor air temperature at a change in the temperature of heat carrier: 1 – outdoor air temperature 27 °C; 2 – outdoor air temperature 23 °C; 3 – outdoor air temperature 15 °C

Experimental studies of the processes of charging the tank of accumulator of hot water revealed temperature zones of effective use of the heat pump for the preparation of hot water. As can be seen from chart (Fig. 20), the largest heat transformation ratio (COP) corresponds to the temperature range of heat carrier at 35...45 °C. In this case, increasing the temperature of heat carrier above 45 °C (Fig. 21) leads to a decrease in COP below 4.

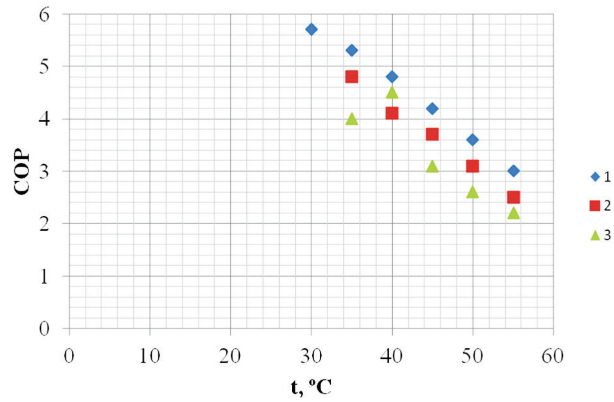

Fig. 21. Chart of dependence of the transformation ratio (COP) of heat pump on the outdoor air temperature at a change in the temperature of heat carrier: 1– outdoor air temperature 27 °C; 2 – outdoor air temperature 23 °C; 3 – outdoor air temperature 15 °C

6. Discussion of results of examining operation modes of heat-pumping systems with the use of heat accumualtors

The studies conducted demonstrated the need for using two-step heat accumulators in the preparation of hot water. In this case, the low-potential source of heat should have its own accumulator as the first stage for the preparation of HWS. The heat accumulators, to increase their effectiveness, should be connected by the cross circuit of heat carrier motion. Such circuit of the heat carrier connection makes it possible to evenly use the volume of accumulator and to maintain uniform temperature in the process of discharging. However, one should take into account that such circuit leads to the reduction in temperature of heat carrier in the feed line.

Experimental research into operational regimes of the production-experimental pilot installation in facility No. 10 at ONPU (Ukraine) confirmed effectiveness of the two-step circuits of accumulation for the preparation of hot water.

Results of present research are relevant for the combined systems of heat supply with the use of heat pump and solar collectors. The solutions proposed will find wide application in the housing and utilities sector, as well as among the enterprises of small and mid-sized businesses.

Present studies are the continuation of work to improve effectiveness of using the renewable energy sources in the combined systems of heat supply and they will continue in the future.

7. Conclusions

As a result of conducted theoretical and experimental research, it was established:

– in order to improve efficiency of using heat from the renewable energy sources, it is necessary to employ a two-step system for the preparation of hot water;

– the application of traditional connection of heat carriers to the tank-accumulator leads to the reduction in effective use of its volume; however, it allows increasing temperature in the feed pipe to the consumer;

– the application of alternative connection of heat carriers to the tank-accumulator (cross circuit of heat carrier motion) leads to an increase in efficiency of utilizing its volume; however, it reduces temperature in the feed pipe to the consumer;

– for the effective heat pump operation (recuperation contour of refrigeration unit), it is necessary for the temperature of heat carrier not to exceed 45 °C.

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