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EFFECTIVENESS OF DECENTRALIZED HEAT SUPPLY BASED ON TRADITIONAL HEAT GENERATORS WITH VAPOR COMPRESSION ENERGY TRANSFORMATION OF LOW-TEMPERATURE SOURCES

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Abstract. The research is devoted to solving the urgent problem of increasing the efficiency of decentralized heat supply of public buildings and industrial enterprises with typical municipal and industrial heat generators on the basis of heat pump energy conversion of pre-cooling of heat flows of the return energy carrier from the heat network, initial cold water and flue gases.

The aim of this work was to analyze and identify conditions that would increase the energy efficiency of the improved system while expanding the total volume of generated heat for decentralized heat supply. Additionally, the work aimed to ensure the environmental friendliness of primary fuel energy use. The proposed approach aims to improve the energy and environmental performance of heat sources by regulating the temperature of the waste energy carrier to its design value, following a standardized temperature schedule.

The most important result of the study of the improved system of decentralized heat supply is the established generalized dependence of determining the actual conversion coefficient in the heat pump operation. It allows qualitative analysis of the dependence of energy efficiency of the heat supply system on the temperature change of the analyzed low-temperature sources, the ratio of the above-mentioned water flow rates and the influence of cold water distribution for municipal and industrial-technological purposes.

The results of the analytical study of the improved heat supply system create a basis for adjusting the temperature schedule of heat supply, taking into account the characteristic conditions of decentralized heat supply and heat consumption modes of municipal and industrial systems.

Keywords: heat-generating plants, heat supply, vapor-compression transformation, integrated heat, conversion coefficient.

Introduction. The aim of the solution to the urgent energy-saving problem is to increase the efficiency of decentralized heat supply to public buildings and industrial enterprises. This will be achieved by using typical municipal and industrial heat generators based on the vapor-compression transformation of integrated energy from low-temperature heat sources. After cooling, the waste energy carrier (WEC) from the heating network, the initial cold water and flue gases can be used to increase the total amount of generated heat, resulting in improved energy and environmental efficiency of primary fuel use.

Analyzing of resent research and publication. The construction and reconstruction of objects must adhere to normative requirements for thermal protection [1]. Modernization of heating systems can provide opportunities to appropriately reduce the design capacity of heat supply systems. European countries such as Germany, Sweden, Holland, Finland, and Denmark have had positive experiences with energy saving. They have developed heat supply technologies that use a reduced temperature schedule, which depends on the outside air temperature. The maximum design temperature in the distribution mains is 90–120°C, and in the return, it is 40–70°C. These values differ significantly from the similar values of domestic standards. Therefore, it is necessary to adjust the water temperature in the existing heat networks, considering their service life, changes in heat load, physical condition, and seasonal variations in outside air temperature and time of day. Improving the regulation of heat supply for subscriber systems can reduce consumption by up to 50% [2], especially during transitional periods. It is also important to stabilize the thermal-hydraulic regime of heat networks during operational and technological changes, as well as during periodic operation of industrial enterprises throughout the day.

Reference [3] highlights that an increase in WEC temperature leads to a decrease in fuel consumption efficiency for heat generators and electricity consumption for circulation pumps, resulting in a further increase in heat consumption in the mains.

Several studies have focused on improving systems [4, 5] that utilize cold water and exhaust gases through recuperative and contact methods. Precooling and stabilization of the temperature of the working fluid can increase the efficiency of heat generating plants and exergy efficiency by expanding the range of operating temperatures.

The utilization of the initial cold water's available potential for industrial, technological, and municipal purposes is becoming increasingly attractive, especially during transitional and inter-heating periods of the year. This is particularly true for the southern regions of Ukraine, where water is supplied from open sources in civil buildings and industrial enterprises. The temperature of the water during this period typically ranges from 10 to 20°C [6].

Industrial enterprises have numerous low-temperature heat sources that can be used to create more efficient combined heat supply systems. Utilizing flue gas aftercooling heat from heat generators is a relevant way to further improve energy-saving and environmental friendliness of heat supply systems.

The heat generating plant has a resource of up to 8–10% in its heat balance. Reducing nitrogen oxide emissions from boiler units is a challenging and pressing ecological issue in heat supply. Previous research [7] has identified deep cooling of flue gases as a promising approach to significantly improve fuel utilization.

In their study [8], the authors investigated a centralized heat supply system with extended heat pump capabilities. The device improves the efficiency of heat supply to remote consumers while reducing the temperature schedule. This increases the economic efficiency of heat network operation by using the energy potential of WEC as a low-temperature source.

The paper [9] presents studies of a new system for utilization of flue gas heat. The system combines recuperative and contact heat extraction using thermal transformer technologies for further utilization in municipal and industrial-technological systems.

Paper [10] analyses the peculiarities of heat pumping units with electric and gas turbine compressor drive.

Based on a critical analysis of pipeline and equipment conditions and known approaches to heat supply system reconstruction, Authors [11] have defined a general indicator for preliminary assessment of conditions to improve the efficiency of modernized centralized and decentralized heat supply systems using heat pump technologies.

In reference [12], a heat supply scheme is proposed that allows for the redistribution of heat flows among individual mains with different inertia loads. This scheme corrects the optimal schedule of daily heat consumption using heat pump technologies.

Therefore, it is clear that the combined use of available low-temperature sources through thermo-transformer technologies offers the prospect of further energy-efficient heat supply improvements. The reduction of primary fuel consumption and harmful impact of exhaust gases on the environment results in an increase in ecological efficiency.

Purpose and Objectives of the Study. The aim of this project is to improve the decentralized heat supply system with steam-compression conversion of the energy potential of WEC, general-purpose cold water and flue gases after the heat generator. In the course of the following theoretical analysis the ways of increasing the energy and environmental efficiency of the system while increasing the total resource of the produced heat will be studied. At the same time, the characteristic operating conditions of the corresponding subsystems in different periods of the year will be taken into account. The set task is solved by analytical substantiation of rational device and possibilities of highly efficient heat pump system of heat supply. Rational operating conditions are determined by adjusting the temperature of the energy carrier after the condenser of the HPU at the inlet to the heat generator, using the integral potential of aftercooling from the given low-temperature sources.

Materials and methods of the research. *The system's design and operation are structured and functional.* The proposed system is shown in Fig. 1. It works in the following way: The spent energy carrier enters the heat exchanger 2 through pipeline 1 for pre-cooling during the regulation of the heat supply system. After passing through the evaporator 3, a portion of the working fluid, controlled by the three-way temperature regulator 4, is directed to the regenerative heat exchanger 10 via branch section 5 and circulation pump 6, while the rest is directed to the recirculation pipeline 8. The recirculation part of the WEC flows through pipeline 9 and into pipeline 1 of the heat network.

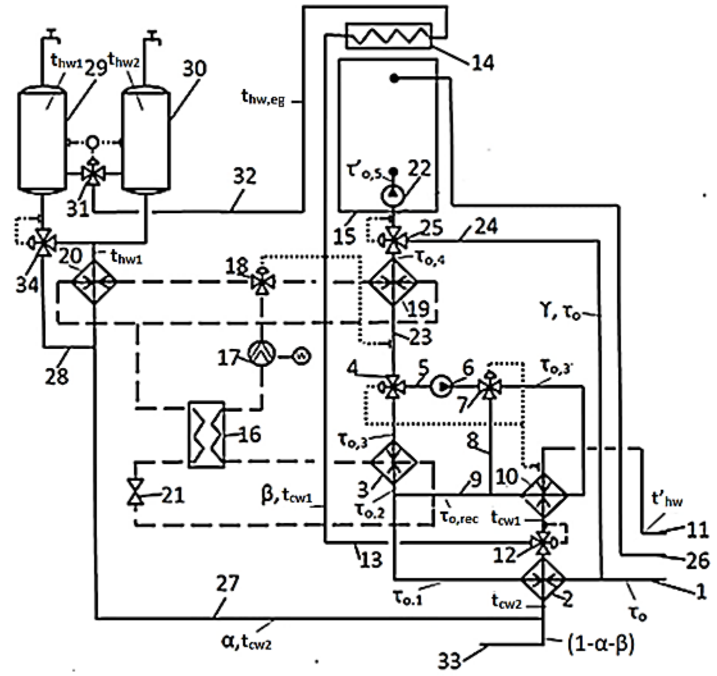

Fig. 1. Schematic diagram of the device of a thermo-transformer system for decentralized heat supply based on integrated WEC aftercooling energy, initial cold water and flue gases after the heat generator: 1 – heat network return pipeline; 2 – recuperative heat exchanger; 3 – heat pump evaporator; 4 – three-way temperature regulator; 5 – recirculation pipeline; 6 – circulation pump; 7 – three-way temperature regulator; 8 – branch section of recirculation pipeline; 9 – general recirculation pipeline; 10 – heat exchanger; 11 – initial cold water pipeline; 12 – three-way temperature regulator; 13 – pipeline to the exhaust gas aftercooling heat exchanger; 14 – exhaust gas heat extraction heat exchanger; 15 – heat generator; 16 – heat pump regenerative heat exchanger; 17 – heat pump compressor with external drive; 18 – three-way temperature regulator; 19, 20 – first and second parts of the condenser connected in parallel; 21 – throttle valve; 22 – circulation pump; 23 – pipeline of the exhaust heat carrier from the network; 24 – bypass pipeline; 25 – three-way temperature regulator; 26 – main pipeline of heat network; 27, 28 – distribution pipelines for two-level hot water supply; 29, 30 – accumulator tanks for two-level hot water supply; 31 – two-way temperature regulator with temperature difference sensor for hot water distribution; 32, 33 – pipelines for hot water supply and heat-technological purposes; 34 – three-way temperature regulator.

Part of the pre-cooled general purpose cold water from the pipeline 11, which has been additionally cooled after passing through the regenerative heat exchanger 10, is directed to the heat exchanger 14 via a pipe branch 13 by means of a three-way temperature controller 12. This is done in order to additionally cool the flue gases after the heat generator 15. The heated water is brought to the appropriate temperature by the heat of the flue gases and is fed through a pipeline 32 to a temperature distribution regulator 31, which includes a temperature difference sensor and a branch line. The water is then distributed to storage tanks 29 and 30 for a two-temperature hot water system.

Analytical study of the conditions required for energy efficient operation of the system. Analysis of the system operation shows that the total flow rate of initial cold water in decentralized heat supply conditions is determined by the needs of industrial-technological and municipal-domestic purposes, providing a two-level hot water supply, i.e. G_{tec}, G_{hw}, because $G_{\text{cw}} = G_{\text{tec}} + G_{\text{hw}}$, and the total water consumption for two-level hot water supply G_{hw} is determined by its respective components: $G_{\text{hw}} = G_{\text{hw1}} + G_{\text{hw2}}$.

Taking into account the reasonable distribution of cold water, its components for hot water supply are defined as:

$$G_{\text{hw1}} = \beta G_{\text{cw}}; \quad G_{\text{hw2}} = \alpha G_{\text{cw}}, \tag{1}$$

where α, β – corresponding parts of the cold water flow rate entering the heat exchangers 14 and 20.

In this case, the temperature of cold water for general purpose t_{cw1} in engineering practice logical to take [11, 18] equal to 5° C for the boundary conditions of countercurrent scheme of modern plate heat exchangers 10 with the highest efficiency of the heat-exchange process. For these conditions, the temperature of the recirculation part WEC after the heat exchanger 10 $\tau_{0,\text{rec}}$ is naturally higher by 5°C. Therefore, based on the above-mentioned engineering approach, after appropriate transformations, dependence t_{cw1} (5) takes the following form:

$$t_{cw1} = t_{cw} - \frac{\rho(1-\gamma)G_{wt}\left(\tau_{o,rec} - \tau_{o,3}\right)}{G_{cw}}, \tag{2}$$

where ρ – the recirculation coefficient of pre-cooled WEC through the heat exchanger 10;

$\tau_{0,3}$ – temperature of WEC in the recirculation circuit after the heat exchanger 3.

Heat of cooling of initial cold water in the process of recuperative heat exchange in heat exchangers 10 and 2 is expressed by the dependence:

$$Q_{\text{hw1}} = c_p \alpha G_{\text{cw}} \left(t'_{\text{cw}} - t_{\text{cw2}}\right). \tag{3}$$

As a result of heat exchange process of initial cold water in heat exchanger 2 with WEC with flow rate $(1-\gamma)G_{\text{wec}}$, its temperature increases to t_{cw2}, respectively:

$$t_{\text{cw2}} = t_{\text{cw1}} + \frac{G_{\text{wec}}}{G_{\text{cw}}} \frac{(1-\gamma)}{(1-\beta)} \left(\tau_0 - \tau_{0,1}\right), \tag{4}$$

where γ – part of the total flow rate WEC G_{wec}, coming through the bypass pipe 24.

From dependence (4), the temperature relationship follows in the following form:

$$\tau_{0,1} = \tau_0 - \frac{(1-\beta)G_{\text{cw}}}{(1-\gamma)G_{\text{wec}}} \left(t_{\text{cw2}} - t_{\text{cw1}}\right). \tag{5}$$

From the equality of heat fluxes of utilized heat of exhaust gases to its generated power for hot water supply, the dependence of the corresponding temperature of water heating $t_{\text{hw,eg}}$ is represented in the following form:

$$t_{\text{hw,eg}} = t_{\text{cw1}} + \frac{c_{\text{p,eg}} G_{\text{eg}} \left(t_{\text{eg,b}} - t_{\text{eg,e}}\right)}{c_{\text{p}} \beta G_{\text{cw}}}. \tag{6}$$

On the basis of the established dependence (6) determine the conditions of heat utilization and rational ratio of heated water and flue gas flow rates $\beta G_{cw}, G_{eg}$ taking into account the balance of the corresponding heat flows.

It is known that the energy efficiency of vapor-compression thermo-transformers is determined by the actual conversion coefficient in the form of the ratio of energy flows [11, 18] in accordance with the dependence:

$$\varphi = \frac{Q_c}{W_c}, \tag{7}$$

where Q_c – thermal power of the condenser with the total heat flux Q_{c1}, Q_{c2} in condensers 19, 20;

W_c – is the thermal equivalent of the external drive power in the heat pump compressor operation, which is given as $W_c = Q_{c1} + Q_{c2} - Q_v$.

In the recuperative heat exchanger 10, the recirculation part WEC takes the heat of cooling of the initial cold water with a common flow rate G_{cw} for municipal and technological purposes. For this process, the following relationship is valid:

$$c_p G_{cw}\left(t'_{cw} - t_{cw1}\right) = c_p \rho (1-\gamma) G_{wec}\left(\tau_{0,rec} - \tau_{0,3}\right), \tag{8}$$

where $\tau_{0,rec}$ – temperature of recirculation coolant after heat exchanger 10, °C;

$\tau_{0,3}$ – temperature WEC in the recirculation circuit after the heat exchanger 3, according to [19] it is recommended to take equal to 5 °C.

From the relation (8) the dependence of the recirculation coefficient of pre-cooled WEC through the heat exchanger 10 is determined as follows:

$$\rho = \bar{G}\frac{\left(t'_{cw} - t_{cw1}\right)}{(1-\gamma)\left(\tau_{0,rec} - \tau_{0,3}\right)}, \tag{9}$$

where $\bar{G} = \frac{G_{cw}}{G_{wec}}$ is the ratio of the total flow rate of cold water and WEC from the heat network.

On the basis of the ratio of heat flows of pre-cooled WEC and its recirculation part respectively with temperatures $\tau_{0,1}$ and $\tau_{0,rec}$ the temperature of their mixture at the inlet to the evaporator 3 of HPU is determined, which after the appropriate simplification takes the form:

$$\tau_{0,2} = \frac{\left(\tau_{0,1} + \rho\tau_{0,rec}\right)}{1+\rho}. \tag{10}$$

The heat of cooling of WEC and its recirculation part in evaporator 3 is determined according to the dependence:

$$Q_v = c_p(1+\rho)(1-\gamma)G_{wec}\left(\tau_{0,2} - \tau_{0,3}\right). \tag{11}$$

The cooling temperature WEC after the evaporator 3 is determined, taking into account the dependence Q_v, (11), as:

$$\tau_{0,3} = \tau_{0,2} - \frac{Q_v}{c_p(1-\gamma)(1+\rho)G_{wec}}. \tag{12}$$

In practice of development [19] of such systems, the temperature $\tau_{0,3}$ is limited to its minimum value <5°C.

Note that WEC with the flow rate $(1-\gamma)G_{wec}$ with the set temperature $\tau_{0,3}$ enters the condenser 19. As a result, the temperature dependence $\tau_{0,4}$ of WEC after condenser 19, taking into account dependence $\tau_{0,3}$, (12), takes the following form:

$$\tau_{0,4} = \tau_{0,2} - \frac{Q_{v}}{c_{p}(1-\gamma)(1+\rho)G_{wec}} + \frac{Q_{c2}}{c_{p}(1-\gamma)G_{wec}}. \quad (13)$$

Consequently, WEC with the temperature after the condenser 19 with bypass flow γG_{wec} and the temperature τ_0, at the inlet to the heat generator 15 $\tau_{0,5}$, is determined according to the relation:

$$\tau_{0,5} = \gamma\tau_0 + (1-\gamma)\tau_{0,4}. \quad (14)$$

Dependences Q_{c1} and Q_{c2}, taking into account the regime parameters α, γ, β, $\bar{G}$ and temperature t_{cw2} according to (4), take the following form:

$$Q_{c1} = c_{p}\alpha G_{cw}\left(t_{hw} - t_{cw1} - \bar{G}\frac{(1-\gamma)}{(1-\beta)}(\tau_0 - \tau_{0,1})\right). \quad (15)$$

$$Q_{c2} = c_{p}(1-\gamma)G_{wec}(\tau_{0,4} - \tau_{0,3}). \quad (16)$$

Taking into account the above equations of heat flows Q_v, Q_{c1}, Q_{c2} and temperature of pre-cooling of initial cold water t_{cw1} after the heat exchanger 10, the dependence of the actual conversion factor φ in the operation of the improved decentralized heat supply system based on the transformation of energy flows of pre-cooling WEC, initial cold water of general purpose and flue gases, after appropriate transformations, takes the final form:

$$\varphi = \left[1 - \frac{(1-\gamma)(1+\rho)(\tau_{0,2} - \tau_{0,3})}{A+B}\right]^{-1}, \quad (17)$$

where $A = \alpha\bar{G}\left(t_{hw} - t_{cw} + \frac{\rho(1-\gamma)G_{wt}(\tau_{o,rec} - \tau_{o,3})}{G_{cw}} - \frac{1}{\bar{G}}\frac{(1-\gamma)}{(1-\beta)}(\tau_0 - \tau_{0,1})\right)$;

$B = (1-\gamma)(\tau_{0,3} - \tau_{0,4})$.

Results of the research. The initial cold water temperature t'_{cw} for general use is determined based on the corresponding period of the year's outdoor air temperature. The current temperature τ_0 is determined according to the operational control schedule for decentralized heat supply systems, using its calculated values $(\tau_r - \tau_0) =$ (95 – 70 ºC).

Operating conditions were determined based on reasonable parameter values: $\bar{G} = 0.1 \div 1.5$, $\alpha = 0.1 \div 0.15$, $\beta = 0.05$, $\gamma = 0.0$.

Fig. 2 illustrates the dependence of the actual conversion coefficient φ on the ratio $\bar{G}$ of the initial cold water and WEC flow rates in the range of limiting values of its temperatures τ_0 in the heating period, taking into account insignificant changes in the cold water temperature t'_{cw}. From the graphical dependencies is evident the area of rational values of conversion coefficient of energy flows in HPU on the whole range of possible ratio of the total flow rate of cold water and WEC. From the analysis of the graphs also follows a significant increase in its increase when the temperature of WEC to the design value in extreme conditions of the heating period. It is obvious that the change in the conversion coefficient φ is significantly affected by the selected value of the intermediate temperature WEC after the condenser 19 $\tau_{0,4}$. In particular, in the range of the real ratio of the indicated flow rates $\bar{G} = 0{,}5...1{,}0$, the conversion coefficient φ increases significantly at a lower temperature $\tau_{0,4} = 45°C$ compared to its value $\tau_{0,4} = 55°C$.

The specified result indicates the essential influence of the intermediate temperature $\tau_{0,4}$ on the efficiency of the system, and accordingly the importance of substantiation of its necessary value after the condenser 19 at the inlet to the heat generator 15 for the analyzed system of decentralized heat supply. It should be noted that the obtained result of increasing the energy efficiency of the improved system of municipal and industrial-technological heat supply is in positive agreement with the increase in cold water consumption in transitional conditions of the heating period with its characteristic growth at the enterprises, in particular, industrial-technological and processing industry.

The results of the analysis of graphical dependencies also indicate the inexpediency of additional heating of WEC after the condenser HPU at the inlet to the heat generator to high temperatures, in particular to the design value $\tau_{0,4} = 70°C$ over the entire range of the analyzed ratio of flow rates.

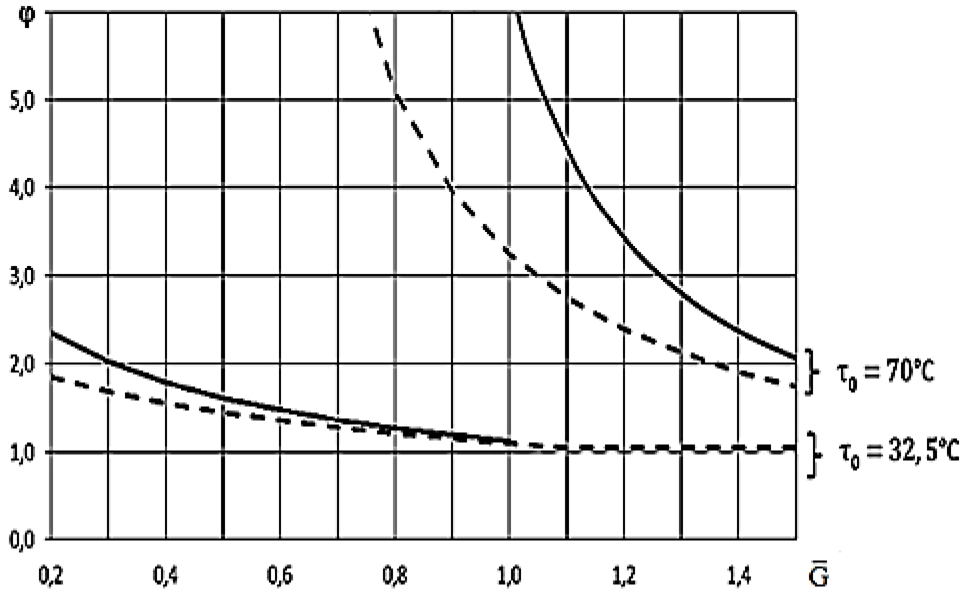

Fig. 2. Dependence of the actual conversion coefficient on the ratio of flow rates of initial cold water and waste heat carrier from the heating network in the operation of the system under design conditions and at the final stage of the heating period. For conditions $\beta = 0.1$ and $\gamma=0.0$:

——— – at $\tau_{0,4} = 45°C$, $\alpha = 0.1$; – – – – – at $\tau_{0,4} = 55°C$, $\alpha = 0.1$

Additional calculation-analytical study established the dependence of the actual conversion coefficient φ on the intermediate temperature $\tau_{0,4}$ WEC according to the generally accepted schedule of operational regulation of decentralized heat supply systems when the ambient temperature $t_a^{'}$ changes during the heating period. The results confirm the possibility of providing a sufficiently high-energy efficiency of the improved heat supply system, as well as the positive effect of reducing the ratio $\bar{G}$ of the above-mentioned water flows in a wide range of changes, typical for most industrial-technological enterprises.

Conclusions:

1. For the improved decentralized heat supply system, a generalized dependence is established to determine the actual conversion coefficient of the HPU based on the integrated sub-cooling potential of the WEC, initial cold water and flue gases. This allows a qualitative analysis of the energy efficiency of the heat supply system. For this purpose, the temperature changes of the analyzed low-temperature sources, the ratio of reduced water consumption and the influence of the regime distribution of cold water for municipal and industrial-technological purposes are investigated.

2. For the proposed system it is established that the change of the actual conversion coefficient is significantly influenced by the value of the intermediate temperature WEC after the condenser at the inlet to the heat generator. From the results of the analytical study it follows that the ra-

tional value of the temperature of steam compression heating WEC after the condenser at the inlet to the heat generator should be based on the thermo-economic optimization of the calculated difference of the temperature of condensation during heating of the subscriber coolant and boiling of the working body in the HPU evaporator.

3. The results of the analytical study of the improved system of decentralized heat supply create the basis for its technical development with justification of the rational intermediate temperature of the cooling medium in the sequential process of heat generation according to the two-stage scheme in a traditional heat generator with HPU for its consumption at municipal and industrial-technological enterprises.

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ЕФЕКТИВНІСТЬ ДЕЦЕНТРАЛІЗОВАНОГО ТЕПЛОПОСТАЧАННЯ НА ОСНОВІ ТРАДИЦІЙНИХ ГЕНЕРАТОРІВ ТЕПЛОТИ З ПАРОКОМПРЕСІЙНОЮ ТРАНСФОРМАЦІЄЮ ЕНЕРГІЇ НИЗЬКОТЕМПЕРАТУРНИХ ДЖЕРЕЛ

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Анотація. Дослідження присвячене вирішенню актуальної задачі підвищення ефективності децентралізованого теплопостачання громадських будівель та промислових підприємств з типовими комунально-побутовими і промисловими теплогенераторами на основі парокомпресійної трансформації енергії доохолодження теплових потоків відпрацьованого енергоносія з теплової мережі, початкової холодної води димових газів. Метою роботи стало аналітичне обґрунтування умов розширення загального обсягу генерованої теплоти та підвищення ефективності удосконаленої системи децентралізованого теплопостачання, а також екологічності використання енергії первинного палива. Запропонований підхід передбачає підвищення енергетичних та екологічних показників джерел теплоти з регулюванням обґрунтованої температури відпрацьованого енергоносія відносно її розрахункового значення відповідно нормованого температурного графіка. Важливим результатом дослідження є встановлена узагальнена залежність для визначення дійсного коефіцієнта перетворення в роботі теплонасосної системи. Вона дає змогу проводити якісний аналіз залежності енергетичної ефективності системи теплопостачання від зміни температури аналізованих низькотемпературних джерел, співвідношення вищезазначених витрат водних потоків та режимів розподілу холодної води для комунально-побутового та промислово-технологічного спрямування. Встановлено, що значення дійсного коефіцієнта перетворення суттєво залежить від обраної температури підігріву відпрацьованого енергоносія з теплової мережі на вході в теплогенератор. Значне зростання дійсного коефіцієнта перетворення відмічається при збільшенні складової витрати води на гаряче водопостачання технологічного призначення. Встановлено, що підтримка раціональної температури підігріву відпрацьованого енергоносія має базуватись на термоекономічній оптимізації розрахункової різниці температур абонентського теплоносія та кипіння робочого тіла в випарнику ТНУ. Результати дослідження вдосконаленої системи теплопостачання створюють основу для коригування раціональної температури відпуску теплоти з врахуванням характерних умов децентралізованого теплопостачання та режимів споживання теплоти системами комунально-побутового та промислового призначення.

Ключові слова: теплогенеруючі установки, теплопостачання, парокомпресійна трансформація, інтегрована теплота, коефіцієнт перетворення.

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