



Shaharning qozonxona sxemasiga issiqlik nasoslarini optimal ulash imkoniyatlarini tahlil qilish

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Dolzarbli: energetik xavfsizlikni oshirish, qazilma yoqilg'ilarga bo'lgan qaramlikni kamaytirish va atrof-muhitga salbiy ta'sirni qisqartirish markazlashtirilgan issiqlik ta'minoti tizimlariga energiya samarador texnologiyalarni joriy etishni talab etadi. Toshkent shahridagi issiqlik manbalari uchun tabiiy gaz va zaxira yoqilg'isi sifatida ishlatiladigan mazutga bo'lgan qaramlikni kamaytirish dolzarb vazifalardan biridir. Mazutdan foydalanish yuqori ekspluatatsion xarajatlar hamda atmosferaga ifloslantiruvchi moddalar chiqarilishi bilan bog'liq.

Maqsad: "Toshkent Issiqlik Markazi" MChJning amaldagi Issiqlik Markazi IM-3 texnologik sxemasiga issiqlik nasoslarini integratsiya qilish samaradorligini baholash hamda zaxira mazut yoqilg'isi sarfini kamaytirish va issiqlik ta'minoti ishonchligini oshirish maqsadida ularni ulashning optimal variantlarini aniqlash.

Usullari: tadqiqotda analitik va qiyosiy usullar, issiqlik nasosining transformatsiya koeffitsientini (COP) baholash, shuningdek, ekologik samaradorlikni aniqlash usullaridan foydalanildi.

Natijalar: issiqlik nasoslarini ulashning uchta varianti ko'rib chiqildi: qo'shimcha suvni isitish, chiqindi tutun gazlari issiqligini utilizatsiya qilish hamda issiqlik tarmog'ining qaytish quvuriga ulash. Tahlil Toshkent shahrining issiqlik ta'minoti tizimida issiqlik nasoslaridan foydalanishning texnik jihatdan mumkin va iqtisodiy jihatdan maqsadga muvofiq ekanligini tasdiqladi. Issiqlik nasoslarini integratsiya qilish zaxira rejimida mazut yoqishdan voz kechish, ekspluatatsion xarajatlarni kamaytirish, issiqlik manbai ish samaradorligini 7–10% ga oshirish va hisobiy 4–6 yillik qoplash muddatini ta'minlash imkonini beradi. Bundan tashqari, zaxira yoqilg'isida ishlash jarayonida hosil bo'ladigan qurum va oltingugurt oksidlari chiqindilarining bartaraf etilishi qo'shimcha ekologik samara beradi.

Kalit so'zlar: issiqlik nasosi, issiqlik markazi, qozonxona, markazlashtirilgan issiqlik ta'minoti, past potentsialli issiqlik manbai, transformatsiya koeffitsienti, mazut, energiya samaradorligi, dekarbonizatsiya.

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Анализ возможностей оптимального подключения тепловых насосов к технологической схеме городской котельной

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Актуальность: повышение энергетической безопасности, снижение зависимости от ископаемого топлива и сокращение негативного воздействия на окружающую среду требуют внедрения энергоэффективных технологий в системы централизованного теплоснабжения. Для теплоисточников Ташкента актуальной задачей является снижение зависимости от природного газа и резервного мазутного топлива, использование которого сопровождается высокими эксплуатационными затратами и выбросами загрязняющих веществ.

Цель: оценка эффективности интеграции тепловых насосов в технологическую схему действующей теплоцентрали ТЦ-3 ООО «Toshkent Issiqlik Markazi» и определение оптимальных вариантов их подключения для снижения потребления резервного мазутного топлива и повышения надежности теплоснабжения.

Методы: в работе использованы аналитический и сравнительный методы, оценка коэффициента преобразования теплового насоса (COP), а также экологического эффекта.

Результаты: рассмотрены три варианта подключения тепловых насосов: для нагрева подпиточной воды, для утилизации теплоты уходящих дымовых газов и к обратному трубопроводу тепловой сети. Анализ подтверждает техническую осуществимость и экономическую целесообразность применения тепловых насосов в системе теплоснабжения Ташкента. Интеграция тепловых насосов позволяет отказаться от сжигания мазута в резервном режиме, снизить эксплуатационные затраты, повысить эффективность работы теплоисточника на 7–10% и обеспечить расчетный срок окупаемости 4–6 лет, а также дополнительным эффектом является устранение выбросов сажи и оксидов серы при работе на резервном топливе.

Ключевые слова: тепловой насос, теплоцентр, котельная, централизованное теплоснабжение, низкопотенциальный источник теплоты, коэффициент преобразования, мазут, энергоэффективность, декарбонизация.



Analysis of the possibilities of optimal connection of heat pumps to the city's boiler house scheme

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Relevance: improving energy security, reducing dependence on fossil fuels, and mitigating adverse environmental impacts require the implementation of energy-efficient technologies in district heating systems. For heat sources in Tashkent, reducing dependence on natural gas and heavy fuel oil used as a reserve fuel is an important task. The use of heavy fuel oil is associated with high operating costs and emissions of pollutants into the atmosphere.

Aim: to evaluate the effectiveness of integrating heat pumps into the technological scheme of the existing Heat Center No. 3 (HC-3) operated by "Toshkent Issiqlik Markazi" LLC and to determine the optimal connection options for reducing reserve heavy fuel oil consumption and improving the reliability of heat supply.

Methods: the study employed analytical and comparative methods, evaluation of the heat pump coefficient of performance (COP), and assessment of the environmental effect.

Results: three heat pump connection options were considered: heating makeup water, recovering heat from exhaust flue gases, and connecting the heat pump to the return pipeline of the district heating network. The analysis confirms the technical feasibility and economic viability of applying heat pumps in Tashkent's district heating system. The integration of heat pumps makes it possible to eliminate heavy fuel oil combustion in the reserve operating mode, reduce operating costs, increase the efficiency of the heat source by 7–10%, and achieve an estimated payback period of 4–6 years. An additional environmental benefit is the elimination of soot and sulfur oxide emissions associated with operation on reserve fuel.

Keywords: heat pump, heat center, boiler house, district heating, low-potential heat source, coefficient of performance, heavy fuel oil, energy efficiency, decarbonization.

1. Introduction

The Republic of Uzbekistan is an actively developing country and one of the most important conditions for the development of modern Uzbekistan is the economic stability of the country, which largely depends on achieving energy security and independence. Currently, the republic is implementing a large-scale transformation of its energy system, which is dictated by the need to ensure sustainable economic growth and fulfillment of international climate commitments, according to the 2015 Paris Agreement.

The relevance of studying the possibilities of integrating HP into the technological scheme of heat sources is provided by the following acts:

- Resolution of the President of the Republic of Uzbekistan No. RP-436 dated December 2, 2022 "On measures to improve the effectiveness of reforms aimed at the transition of the Republic of Uzbekistan to a "green" economy by 2030". This resolution aims to reduce specific greenhouse gas emissions per unit of GDP by 35% from the 2010 level.

- Resolution of the President of the Republic of Uzbekistan No. RP-100 of March 11, 2025, "On measures to radically reform the provision of heat to residential buildings, structures, and structures, as well as to improve the energy efficiency of buildings". One of the objectives of this resolution is to upgrade 103 outdated boilers and 1,600 kilometers of heating networks.

The republic's energy balance remains highly dependent on fossil fuels: approximately 85–90% of electricity and heat generation is provided by thermal power plants, which operate primarily on natural gas. The centralized heating system of Tashkent, the key link of which is Toshkent Issiqlik Markazi LLC, requires the implementation of innovative technologies that can reduce dependence on fossil fuels (natural gas, fuel oil). According to the Ministry of Energy of the Republic of Uzbekistan, the annual consumption of natural gas in the country is approximately 45 billion cubic meters, of which a significant share is spent on heating and HWS. During seasonal gas shortages, especially during abnormally cold periods (such as in January 2023), the boiler houses operated on fuel oil, which negatively impacted boiler operation and the city's ecology. Therefore, the issue of diversifying heat sources has become a matter of national energy security. Considering that by 2030, electricity consumption in the republic will grow to 120.8 billion kW·h, and the share of renewable energy sources in generation should reach 40%, the introduction of powerful absorption and compression heat pumps are becoming strategically important.

Currently, there is a significant body of research worldwide on the application of alternative energy sources to heat sources. The integration of heat pumps (HPs) into existing heat sources, such as combined heat and power plants (CHPs) and large boiler houses, is currently one of the key trends in the global energy sector. This enables the use of low-grade waste heat, improves overall energy efficiency, and integrates the heat and electricity supply sectors (sector coupling). International studies emphasize the need for large-scale implementation of heat pump systems in centralized heat sources.

In the work by David A., et al. (2017) [1] the current status and potential of integrating large-scale electric heat pumps into district heating systems (including large boiler houses and CHP plants) were assessed within the framework of the European energy strategy until 2050. As a result, the authors calculated that in order to achieve decarbonization goals, the integration of large-scale HPs at heat sources should cover 25–30% (about 520 TWh/year) of total heat production in Europe by 2050 with an average coefficient of performance (COP) of 3. It was proven that the use of HPs at CHP plants allows for balancing electricity grids by using surplus renewable electricity for heat production.

Alberto Vannoni et al. (2023) [2] from the University of Genoa conducted a study on the technical and economic feasibility of implementing high-temperature heat pumps (HTHP) for the recovery of industrial waste heat (with a source temperature of 70 °C and heating the coolant to 120 °C). The study revealed that, although the compressor accounts for 30–60% of all capital costs, the main element for HP optimization is the evaporator: increasing its area increases the COP and reduces the required compressor volume, reducing its cost. HTHPs are most economically feasible with large thermal capacity and operation in base mode with the maximum number of loading hours per year.

The efficiency of integrating heat pumps into urban boiler and central heating systems critically depends on the selected connection topology and hydraulic parameters. Capone et al. (2023) [3] modeled heat pump placement options in large heating networks and found that incorrectly selecting the connection point relative to the return network water flow can reduce heat pump efficiency by up to 63%.

A separate scientific field is devoted to the utilization of low-potential heat (condenser waste water, flue gases, blowdown water) using lithium bromide absorption heat pumps (LBAHP). Professor Sven Werner, in his paper (2017) [4] and related works, demonstrated that large-scale heat pumps using heat from treated wastewater or recycled water can cover up to 10–15% of the base heat load of large cities without the use of fossil fuels.

S.K. Abildinova et al. (2019) [5] presented the results of a study on the performance of staged compression heat pumps and formulated concepts for using a heat pump with two-stage compression of the working fluid. Various thermodynamic cycle implementation schemes for single- and two-stage heat pumps were considered. As a result, they demonstrated the efficiency of two-stage heat pumps implementing a thermodynamic cycle with condensate subcooling and heat recovery from the working fluid vapor.

Comparing the options of centralized and decentralized installations, Ochs et al. (2022) [6] substantiated that in dense urban development conditions, the placement of large HPs directly at central boiler houses or thermal power plants has an advantage over individual installations at consumers due to the absence of spatial restrictions, reduced noise levels, and high maneuverability in the electricity market.

Today, the use of heat pump technologies (in particular, absorption and vapor compression high-temperature heat pumps) is considered by the global scientific community as one of the most promising areas for decarbonization and increasing the energy efficiency of centralized heating systems. Modern research covers in detail the issues of thermodynamic optimization of cycles, the selection of efficient refrigerants, the integration of heat pumps into low-temperature heating networks, as well as the replacement of natural gas through the utilization of waste and low-potential heat. However, in modern scientific literature there is a virtual absence of scientifically substantiated technical, economic and technological solutions aimed at the targeted replacement of reserve or peak fuel oil heating capacity of boiler houses with heat pump units. The issue of abandoning expensive and environmentally unfriendly liquid fuel (fuel oil) through the introduction of alternative heat-generating systems based on HPs remains virtually unexplored. Methods for hybridizing and adapting the design of heat sources equipped with Soviet-designed PTVM series hot water boilers (PTVM-30, PTVM-50, PTVM-100, PTVM-180) are not presented.

The heat pumps make it possible to obtain a high-potential heat from a low-potential heat source for heating and hot water supply, providing significant savings on primary fuel. Low-potential heat sources include natural sources - ground, water, air and artificial sources - secondary energy resources, waste heat. The heat pump converts 1 kW of electrical energy into 3–4 kW of heat, whereas burning fuel oil or inefficiently burning gas at low pressure produces huge losses. Analysis of the optimal connection scheme for the heat pump unit in the existing boiler house system is necessary to achieve the maximum Coefficient of Performance (COP) and ensure system stability.

The aim of the study: Technical modernization of the boiler house with the installation of the heat pump to reduce dependence on gas limits and eliminate risks when switching to backup fuel, as well as the selection of a low- potential heat transfer fluid for Tashkent conditions.

The object of the study is the boiler house of heat center HC-3, of “Toshkent Issiqlik Markazi” LLC, which provides thermal energy to the Shaykhantakhur and Almazar districts in Tashkent city. HC-3 is a typical centralized heating unit, where natural gas is used as the primary fuel and fuel oil is the backup fuel.

The tasks of the study:

- Hydraulic integration

Provide the heat pump connection to the return line before the boilers to preheat the coolant, which will allow the boilers to operate in a stable mode even with a gas shortage;

- Base load coverage

Switch the heat pump to the main energy source mode to cover background heat losses, leaving the gas-oil boilers as peak capacities;

- Optimization of the fuel balance

Minimize the consumption of gas and expensive fuel oil by replacing part of the thermal power with electrical energy with a high COP;

- Emissions reduction

Completely eliminate soot and sulfur oxide emissions that occur when running on reserve fuel.

The integration of high-capacity heat pumps is seen as a key tool for changing the fuel balance and increasing the energy security of the capital region. Using fuel oil as a backup fuel is the most expensive and environmentally “dirty” part of boiler operation. The primary equipment used at HC-3 consists of two hot water boilers PTVM-50 tower-type once-through hot-water boiler (with a capacity of 50 Gcal/h) and three boilers PTVM-100 (100 Gcal/h). Two hot water boilers have 4 fuel oil burners each. Fuel oil consumption per burner is 600 kg/hour. Fuel oil is used in sub-zero ambient temperatures, as well as when natural gas is supplied at low pressure. The implementation of the heat pump will reduce the cost of thermal energy by 50-60% compared to backup fuel oil and ensure uninterrupted operation of the system during seasonal gas supply restrictions.

2. Methods and materials

The introduction of the heat pumps directly impacts the reduction of energy costs and greenhouse gas emissions.

The economic efficiency of using heat pump heating systems is determined by the choice of heat source and the operating characteristics of the system. Following the laws of thermodynamics, we calculate the heat conversion coefficient using the formula [7]:

$$COP = 0,5 \cdot \frac{t_h}{t_h - t_l}; \quad (1)$$

where t_h – high temperature (condensation temperature - temperature in the heating system), °C; t_l – low temperature (evaporation temperature of a low- potential heat source), °C.

To justify the decommissioning of the heavy fuel oil facilities, a comparative analysis method was applied to the boiler plant's auxiliary energy balance. The total thermal energy expenditure required to maintain the HFO handling system (Q_{sn}^{HFO} , kW) was modeled as the sum of three key components:

$$Q_{sn}^{HFO} = Q_{store} + Q_{pipe} + Q_{preheat}; \quad (2)$$

where Q_{store} is the heat consumed to continuously maintain the HFO temperature in the storage tanks ($t = 50-60^\circ\text{C}$) to prevent solidification and paraffin crystallization. The calculation was based on heat transfer equations through the tank enclosure structures to the ambient environment, taking into account seasonal temperature fluctuations;

Q_{pipe} represents the heat losses in the circulation heating circuits and steam tracing of the fuel oil pipelines within the pumping station;

$Q_{preheat}$ is the energy required for the final preheating of the HFO before the atomizers ($t = 110-130^\circ\text{C}$) to ensure the required standard kinematic viscosity.

To estimate the volume of displaced fossil fuel, a method comparing the boiler plant's thermal load profiles is utilized. The annual savings of standard reference fuel (ΔB , t/year) upon transitioning to heat pump generation is calculated using the following formula:

$$\Delta B = \left(\frac{Q_h \cdot \tau}{\eta_{boiler} \cdot q_{HFO}} \right) - \left(\frac{Q_g \cdot \tau}{\eta_{source} \cdot q_{alternative}} \right); \quad (3)$$

where τ – is the annual operating hours of the HP, h;

η_{boiler} – is the operational efficiency of the HFO boiler, accounting for incomplete combustion and the degradation of heating surfaces due to sulfur deposits ($\eta = 0.78-0.82$);

q_{HFO} – is the lower heating value of the HFO (39.8 MJ/kg);

$\eta_{source}, q_{alternative}$ – are the parameters of the energy source supplying the HP generator (in the case of using natural gas or district heating steam from a CHP plant).



The environmental effect can be determined using a calculation-analytical method for assessing gross pollutant emissions into the atmosphere before and after modernization. The calculation of emission volumes for sulfur dioxide and fuel oil ash particulate matter expressed as vanadium is carried out in accordance with the regulatory document IESH 34-301-778:2020 "Calculation and determination of maximum allowable specific emissions of pollutants for boiler plants of thermal power stations", by JSC "Thermal Power Plant":

Maximum specific emissions for sulfur dioxide (SO₂):

- Per unit of thermal energy input into the furnace, g/MJ:

$$n_{SO_2} = \frac{C_{SO_2} \cdot V_{cr} \cdot k_n}{Q_w^l}; \quad (4)$$

where: C_{SO_2} is the mass concentration of sulfur oxides in dry flue gases;

V_{cr} is the volume of dry flue gases generated during the complete combustion of 1 kg of fuel;

k_n is the conversion factor (when determining emissions in grams per second, $k_n = 0.278 \cdot 10^{-3}$; in tons, $k_n = 10^{-6}$;

Q_w^l is the lower heating value (LHV) of the fuel.

- Per 1 ton of reference fuel, kg/t_{ref.fuel}:

$$m_{SO_2} = n_{SO_2} \cdot Q_{ref.fuel}; \quad (5)$$

where $Q_{ref.fuel}$ is the calorific value of the reference fuel, equal to 29.3 MJ/kg_{ref.fuel}.

- Maximum concentration of pollutants in flue gases discharged into the atmosphere (mg/m³), corresponding to the specific indicator n_{SO_2} :

$$\mu_{SO_2} = n_{SO_2} \cdot \frac{Q_w^l}{V_g} \cdot 10^3. \quad (6)$$

Maximum specific emissions of heavy fuel oil ash particulate matter in terms of vanadium:

- The calculation of the mass quantity of vanadium oxides, g/s (t/year), is performed according to the formula:

$$M_{V_2O_5} = 3,57 \cdot 10^{-6} G_V B. \quad (7)$$

Or expressed as vanadium pentoxide:

$$M_{V_2O_5} = 10^{-6} G_{V_2O_5} B; \quad (8)$$

where: G_V is the vanadium content (or $G_{V_2O_5}$ expressed as vanadium pentoxide) in the liquid fuel, g/t, calculated by the formula:

$$G_{V_2O_5} = 95,4S^p - 31,6. \quad (9)$$

- Per unit of thermal energy introduced into the boiler furnace, mg/MJ:

$$n_{HFO} = \frac{M_{V_2O_5}}{B \cdot Q_w^l}; \quad (10)$$

where B is the mass flow rate of the as-fired fuel, g/s (t/year).

- Per 1 ton of reference fuel, kg/t_{ref.fuel}:

$$m_{HFO} = n_{HFO} \cdot Q_{ref.fuel}. \quad (11)$$

- Maximum concentration of pollutants in flue gases discharged into the atmosphere (mg/m³), corresponding to the specific indicator n_{HFO} :

$$\mu_{HFO} = n_{HFO} \cdot \frac{Q_w^l}{V_g} \cdot 10^3; \quad (12)$$

where V_g is the volume of flue gases during the combustion of 1 kg (1 m³) of fuel under normal conditions and at an excess air ratio $\alpha = 1.5$.

2.1. Options of Heat Pump Connection

• Connecting the heat pump to heat make-up water

A large volume of makeup water is required to supply hot water and replenish losses in heating networks. During the non-heating period, it is advisable to use vapor compression heat pumps. The heat pump takes low-potential heat (from the return network water pipeline or the ground) and transfers it to chemically treated water, which must be heated from 10–15°C to 35–40°C before it enters the deaerator or storage tanks.

Thermal power of the heat pump for heating makeup water:

$$Q_h = G_w \cdot c_p \cdot (t_h - t_l); \quad (13)$$

where Q_h is the amount of heat transferred to a high-temperature reservoir, kW; G_w — coolant consumption (kg/s); c_p — specific heat capacity of water (4.187 kJ/(kg °C)).

The coefficient of performance is a measure of the efficiency of the heat pump. It is a measure of how much heating or cooling is produced per unit of energy input, and is defined as the ratio of the amount of heat transferred to a hot reservoir compared to the amount of work input required to transfer that heat. For a heating application, the COP is given by [8]:

$$COP = \frac{Q_h}{W_{el}}; \quad (14)$$

where W_{el} is the amount of power input required to transfer that heat, kW.

The COP for this connection option is the highest and is usually 4-5.

• Connecting the absorption heat pump to utilization the heat of flue gases

This is the most efficient option for modern boiler houses. Lithium bromide absorption heat pumps are used for deep flue gas cooling. Since fuel oil is used at HC-3 during low gas pressure or peak cold periods, connecting the LBAHP will make it possible to replenish the missing power from the heat of exhaust gases, essentially replacing the need to burn fuel oil. The connection of the LBAHP to the technological scheme of the HC-3 can be performed as follows: the heat exchanger-utilizer is installed at the tail of the boiler. Flue gases with a temperature of 120–150°C are cooled to 30–40°C. In this process, the latent heat of vaporization of the combustion products is released. Return water from the city network (45–55°C) passes through the LBAHP and is heated to 70–80°C before entering the main boilers.

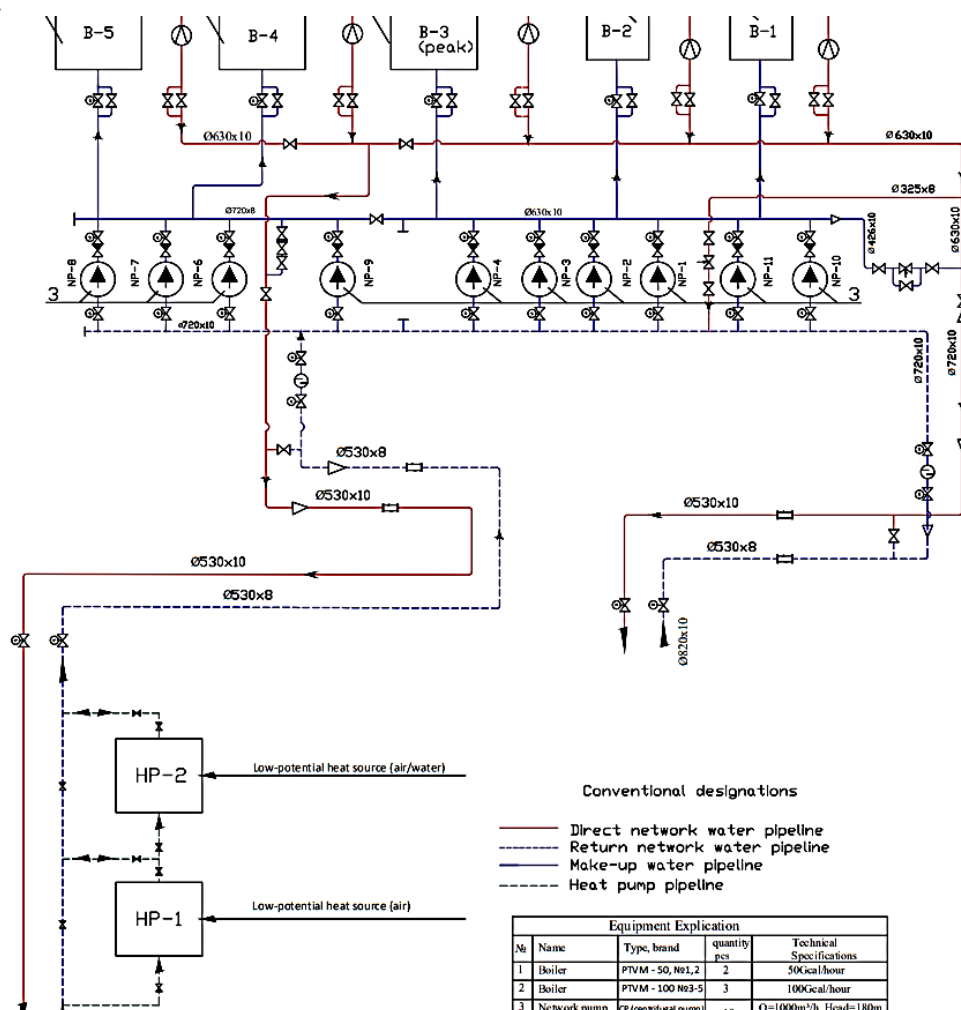


Fig. 1. Thermal scheme of HC-3 with heat pumps

The efficiency of the LBAHP is characterized by the coefficient of transformation [9]:

$$\mu = \frac{Q_h}{Q_g}; \quad (15)$$

where Q_h – amount of heat produced; Q_g – the amount of high-temperature heat supplied to the HP generator.

In LBAHP, the μ value is lower than COP of compression HP, because the transformation of thermal energy is estimated, and $\mu = 1.2-2$.

• Connecting the heat pump to the return pipeline of a heating network

During the non-heating period, the heat pump can provide for needs of hot water supply using the heat from the return pipeline. The option for connecting heat pumps to the heating circuit of HC-3 on the return pipeline line of the heating network is shown in Figure 1. This scheme shows 5 hot water boilers, 10 network pumps, 2 heat pumps (air-to-water and air/water-to-water). They are connected to the network water return line using a cascade method.

The evaporator of the heat pump takes heat from the source (air, ground), and the condenser of the heat pump is connected to the return pipeline before the network pumps and boilers, thus reducing the load on the gas burners or completely covering the heat demand at low gas pressure. This circuit uses

a bypass circuit with shut-off valves, allowing the coolant flow to be switched through the heat pump or directly to the boiler.

Increasing the return water temperature increases the system's efficiency, as the boiler requires less gas to reach operating temperature. The heat pump takes on the brunt of the heating load during peak cold spells or emergency situations.

The ground-water heat pump is the most efficient and stable, as the ground temperature is always $+8...+10^{\circ}\text{C}$, unlike air, which makes the heat pump ineffective at sub-zero temperatures.

Since the return water temperature is high ($45\text{--}70^{\circ}\text{C}$), the COP will be around 2.8–3.5.

3. Results

The use of a heat pump to eliminate the operation of boilers on fuel oil, which causes increased corrosion and fouling of heating surfaces, is the key objective of this study. The HC-3 operates two boilers with four fuel oil burners each. Fuel oil consumption per burner is 600 kg/hour. The transition to a heat pump unit allows for the complete elimination of fuel oil combustion, a reduction in operating costs by more than 50%, and the fulfillment of the requirements of state programs for the decarbonization of the Uzbek economy. Moreover, the integration of the heat pump unit into the HC-3 scheme ensures a payback period of 4-6 years, which is an attractive indicator for the energy sector.

The estimated results of the analysis of the possibilities for optimal connection of the heat pumps to the boiler house HC-3 are presented in the table 1:

Table 1. Comparison table of the heat pump connection options

Parameter	Makeup water	Flue gases	Return line of network water
Heat source	Return water/Ground	Flue gases	Air/Ground
COP	4 -5	1,2-2	2,8-3,5
Installation complexity	Low	High	Average
Effect	Stable hot water supply	Increase in boiler efficiency by 7-10%	Peak coverage

It is known that more than 60-70% of sulfur in the oil refining process is converted into fuel oil, which is used as boiler fuel in energy plants [10]. When fuel oil is burned, a huge amount of sulfur dioxide, nitrogen oxides, and particulate matter (soot) is released per hour. Switching to a fuel oil heater makes the HC-3 completely "clean" in this mode. Furthermore, using fuel oil requires preheating it to $90\text{--}110^{\circ}\text{C}$ before feeding it to the burners, which requires additional energy consumption.

4. Discussion

Unlike gas, coal, or electricity, heavy fuel oil cannot simply be fed into a burner directly from storage. Heavy fuel oil infrastructure is an energy-intensive complex that consumes a significant portion of the generated heat for its own operation. To prevent highly viscous grades of heavy fuel oil (e.g., the widely used M-100) from solidifying into a monolith, it is necessary to maintain a constant temperature of at least $50\text{--}60^{\circ}\text{C}$ in the storage tanks, depending on the grade. Immediately prior to being fed into the boiler atomizers, the fuel oil is heated to $110\text{--}130^{\circ}\text{C}$ to reduce its viscosity and ensure proper atomization. Receiving railway tank cars during winter requires prolonged "steaming" (heating with live steam) to enable discharging. Ultimately, the operation of the heavy fuel oil infrastructure (steam tracers, circulation heating, high-pressure pumps) consumes up to 10–12% of the total thermal energy generated by the boiler plant.

The implementation of HPs completely eliminates this expense category, as HPs do not require "fuel" preparation and directly deliver heat to the network with a high coefficient of performance.

Heavy fuel oil is an unstable multicomponent system whose characteristics deteriorate with each month of storage in tanks. Heating heavy fuel oil with open steam (in tank cars or storage tanks) inevitably leads to its moisture contamination. Water accumulates at the bottom of the tanks or forms stable emulsions. The combustion of water-contaminated fuel oil decreases the boiler's efficiency, leads to flame pulsation, and can cause an emergency shutdown. Over time, heavy fractions (asphaltenes, resins) settle to the bottom of the tanks, forming a dense, hard-to-remove sludge. The useful volume of the tanks decreases, forcing the enterprise to regularly incur the costs of expensive and hazardous manual tank cleaning, followed by the complex disposal of petroleum sludge. Furthermore, the presence of sulfur in heavy fuel oil (up to 3.5% in high-sulfur grades), combined with moisture, leads to the formation of sulfuric acid. This causes intense internal corrosion of the tank walls and heater coils.

A comparison of the efficiency of heavy fuel oil combustion and energy transformation by a heat pump clearly demonstrates the technological superiority of the latter. During heavy fuel oil combus-

tion, the actual efficiency of the boiler — accounting for flue gas heat losses, incomplete combustion, and auxiliary energy consumption (own needs) — rarely exceeds 75–82%. This means that out of 1 Gcal of fuel energy, the consumer receives at best 0.8 Gcal. Heat pumps operate on the principle of the reverse Carnot cycle. Their efficiency is measured by the Coefficient of Performance. Assuming that the boiler plant is equipped with an industrial absorption lithium-bromide heat pump or vapor compression machines that recover low-grade heat (industrial wastewater, circulating water supply heat, ventilation exhausts), the COP will range from 3.5 to 5.0. In other words, while a fuel oil boiler consumes 1.2 kW of fuel energy to produce 1 kW of heat, a heat pump consumes only 0.2–0.3 kW of electrical or thermal energy (depending on the type of HP) to transfer and deliver the same 1 kW of heat to the consumer.

Heavy fuel oil is considered one of the "dirtiest" types of fossil fuels. Its combustion releases the following pollutants into the atmosphere: sulfur dioxide (SO_2) — the primary cause of acid rain; nitrogen oxides (NO_x) — toxic gases that contribute to smog formation; particulate matter (fly ash, soot) — containing vanadium compounds, which are potent carcinogens.

Vanadium oxides formed during the combustion of heavy fuel oil and emitted into the environment through the chimney are highly toxic substances that cause severe environmental damage. Pollution of the atmosphere and water resources by these oxides triggers processes destructive to nature. Inhalation of vanadium oxide emissions can lead to pathological changes in the body [11].

Modernizing the boiler plant by installing HPs transitions the system into the category of environmentally clean solutions. Local emissions of harmful substances into the atmosphere are reduced to absolute zero. This relieves the enterprise from regular payments for negative environmental impact, eliminates the risk of facing environmental regulatory sanctions, and reduces the costs associated with maintaining a sanitary protection zone. The results of the study confirm the high efficiency of using HP in Uzbekistan. The choice of a low-potential heat source and working fluid is a determining factor. Modern industrial heat pumps are designed for 20–25 years of operation [12,13], which will provide HC-3 with more than 15 years of net profit after reaching payback.

Unlike hot water boilers, heat pumps are not dependent on gas pressure in the main line. If the gas pressure drops to critical levels, the heat pump continues to provide baseline heat, preventing the system from freezing. However, implementing a heat pump in the existing boiler house at HC-3 requires upgrading the boiler house's electrical infrastructure to ensure the required capacity.

Fuel oil systems require constant heating, nozzle cleaning, and emissions fees. The heat pump operates automatically and without personnel. Moreover, the cost of heat from a heat pump in Uzbekistan will be at least 2–2.5 times lower than fuel oil.

5. Conclusion

The analysis shows that the introduction of the heat pumps into the system of "Toshkent Issiqlik Markazi" LLC in Tashkent is a technically feasible and effective solution.

- The energy situation in the republic requires not just replacing old equipment with new, but a qualitative change in the approach to energy production.
- Integration of the heat pumps at boiler houses allows to increase the efficiency by 7–10% and to reduce fuel consumption.
- Three options for optimal connection of the heat pump to the boiler house's scheme were considered: makeup water, exhaust flue gases and return pipeline of the network water.
- The highest COP (4 – 5) is for the option of connecting the heat pump for heating makeup water.
- The introduction of the HP will allow HC-3 to stop depending on the supply of fuel oil and its complex logistics (storage, heating, draining/filling).
- Integration of the heat pump unit into the HC-3 scheme ensures payback within 4–6 years.
- The environmental benefit consists of a significant reduction in thermal pollution of the atmosphere. In particular, the complete elimination of soot and sulfur oxide emissions when operating on reserve fuel.

Analysis of the implementation of the heat pumps at existing facilities in the capital is a relevant scientific and practical area capable of ensuring energy security and sustainable development of the republic's cities.

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