

Chapter 7

Physical Principles of Wastewater Heat Utilization Using High-Temperature Solar Installations



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Abstract In world practice, the use of renewable energy sources and heat pump devices in creating modern energy and resource-saving systems for managing traditional fuel and energy resources is increasing. Experimental research, technical measurements, and heat and technical calculation methods were used to assess the efficiency of obtaining technical clean water by utilizing the low-potential heat of wastewater at the “Shurtan Gas-Chemical Complex” enterprise. Analysis of wastewater’s physical and thermal properties from “Shurtan Gas-Chemical Complex” enterprise. Empirical equations were obtained that determine the physical properties of wastewater formed from the addition of oily, chemically contaminated, and domestic wastewater generated in the technological processes of “Shurtan Gas-Chemical Complex” enterprise. As a result, it was determined that the density of wastewater is $\rho = 920.2 \text{ kg/m}^3$, and the coefficient of dynamic viscosity is $\mu = 0.00496 \text{ m}^2/\text{s}$. A technological scheme was developed that allows obtaining technical water by utilizing the heat of wastewater from “Shurtan Gas-Chemical Complex” enterprise using parabolic cylindrical solar concentrator, and equations were obtained that allow calculating its energy efficiency. For the technological process, 6 Eurotrough-150 solar concentrators are connected in series, with a reflector surface area of 408.75 m^2 and a length of 74.25 m . According to the technical parameters of the Eurotrough-150 solar concentrator, experimental studies and calculation results, it was determined that the Eurotrough-150 solar concentrator in the natural climatic conditions of the city of Karshi has an average solar radiation of $700\text{--}800 \text{ W/m}^2$, $\eta_{PCSC} = 19.54\%$, when the Re number of wastewater is 10,000, $\eta_{PCSC} = 39.08\%$ when $\text{Re} = 20,000$ and $\eta_{PCSC} = 97\%$ when $\text{Re} = 50,000$.

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7.1 Introduction

As a result of the significant reduction in the amount of natural fuel and energy resources in the world and the increase in emissions of toxic emissions into the environment, the conservation of traditional energy sources and their use in energy-resource-efficient devices is very urgent [1]. Today, the problem of energy resources has become global in all countries, and the restructuring of the energy base, the use of environmentally friendly, renewable, and alternative energy sources, and low-potential secondary energy resources for heat recovery processes is rapidly developing [2, 3].

Secondary energy resources (SER) in industrial and manufacturing enterprises are low-potential SER, such as the heat of combustion products generated during the combustion of fuel and energy resources, the heat of wastewater and air generated after the cooling process in technological devices, the heat of ventilation air, the secondary heat of water vapor in technological processes, the heat of chemically contaminated wastewater and sewage, etc. [4].

7.1.1 *Statement of the Problem*

In oil and gas processing plants, a large amount of low-potential heat is released into the environment with wastewater and causes environmental damage.

Technical clean water used in oil and gas processing plants is contaminated with various hydrocarbon compounds (oils, petroleum oils), various types of salts, coarse, colloid, and particles, as well as mechanical impurities, and in most cases such chemically contaminated water is technically treated and discharged as wastewater [5, 6].

The consumption of water used during technological processes at enterprises, its chemical composition, quality indicators, and the composition of the resulting chemically contaminated water depend on the current state of production technologies, the type of product being produced, the level of technical equipment, and automation of the enterprise.

Wastewater is rarely used as a coolant, and the main focus in the design of energy-efficient systems is on data on the temperature in wastewater collection collectors, water flow rate, and physicochemical properties [7, 8].

7.2 Materials and Methods

The wastewater of the “Shurtan GChC” LLC enterprise is a liquid mixture of waste generated during the production and domestic activities of the enterprise. It represents water containing a mixture of dissolved and undissolved liquid, solid, and gaseous substances.

All methods used in wastewater treatment are classified into 3 types according to their essence and content, namely:

- Mechanical—settling, centrifugation, and filtration.
- Chemical—combining various wastewaters and carrying out chemical reactions, for example, neutralization reactions, to remove harmful substances.
- Biological—with microorganisms, mycobacteria, and aquatic plants.

At the “Shurtan GChC” LLC enterprise, oily wastewater is 10–36 m³ per hour, 864 m³ per day, chemical wastewater is 18 m³ per hour, 432 m³ per day, domestic wastewater is 40 m³ per hour, 960 m³ per day, and their composition, physical and chemical properties are presented in Tables 7.1 and 7.2.

Chemically contaminated wastewater consists of various organic and inorganic compounds and must be technically treated depending on technological properties before being reused and discharged as wastewater.

Mechanical methods of wastewater treatment.

Table 7.1 “Shurtan GChC” LLC results of wastewater analysis for 11.06.2024 [4]

Component name (requirements)	Identified component cost (requirements)	
	According to the regulatory document	Fact
I	II	III
pH	6.5–8.5	8.16
Suspended solids, mg/l	30	30
Ammonium nitrogen, mg/l	2.0	1.8
Nitrite ion, mg/l	3.3	0.066
Nitrate ion, mg/l	45	8.3
Chlorides, mg/l	350	329
Petroleum product, mg/l	0.3	0.22
Phosphate ion, mg/l	1.0	0.36
Sulfate ion, mg/l	500	472
Dry residue, mg/l	1000	976
Ferric ion (+3), mg/l	0.3	0.12
Dissolved oxygen, mg/l	4–6	5.42
BOD, mg/l	6.0	–
CDP, mg/l	40	36.0

Table 7.2 “Shurtan GChC” LLC results of wastewater analysis for 11.12.2024

Date	Sampling point	Standard	pH	Dissolved oxygen	Mg/l									
					Suspended articles	Dry residue	Petroleum product	Iron	Ammonium nitrogen	CPC	Residual chlorine			
11.12.2024	Oily wastewater Outlet from GA-6401/S pump	Standard	6.5–8.15		63	1747	1.5	0.13	16.4	134.4				
		Fact	6.71		38	976	1.1	0.3	4.6	84				
	Chemical wastewater	Standard	7.5–8.9		44	1982			24					
		Fact	8.47		42	1966			6.4					
	Domestic wastewater	Standard	6.5–8.5		31	997			15.5					
		Fact	7.14		18	780			7.42					
	Contact chlorination pool outlet	Standard	6.5–8.5	4.0	23.14	1500	0.3	0.3	2.0		0.3–0.5			
		Fact	7.38	3.8	20	1850	0.24	0.25	2.88		0.33			

Mechanical wastewater treatment is used to remove undissolved mineral and organic impurities from the water being treated.

The implementation of mechanical treatment usually involves the preparation of industrial wastewater to achieve a high level of purification using one of the physicochemical, chemical and biological, as well as thermal methods.

Such treatment provides for the removal of suspended solids from wastewater by 90–95% and a reduction in organic pollution (total BOD) by 20–25%.

More complete clarification of wastewater, the process of cleaning it from suspended particles, is carried out by filtering, that is, passing water through various granular materials (quartz sand, granite gravel, slag formed in cast iron foundries, etc.).

7.2.1 Calculation Methods

Taking into account the thermal and physical properties of oily, chemical and domestic wastewater generated in the technological processes of “Shurtan GChC” LLC, we express the movement of wastewater based on the mass conservation equation as follows [4]:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \cdot v) = 0 \quad (7.1)$$

where, ρ —wastewater density, $\frac{kg}{m^3}$; v —velocity vector, $\frac{m}{sek}$.

Based on the Navier-Stoke equation, we express it as follows:

$$\rho \left(\frac{\partial v}{\partial t} + (\nabla \cdot v)v \right) = -\nabla P + \nabla \cdot (\mu \nabla v) + F \quad (7.2)$$

where, P —pressure, Pa; μ —coefficient of dynamic viscosity of wastewater, $\frac{m^2}{sek}$; F —external forces.

We apply the advection–diffusion equation for each component of wastewater (petroleum oils, chemicals, organics):

$$\frac{\partial C_i}{\partial t} + \nabla \cdot (C_i \cdot v) = D_i \cdot \nabla^2 \cdot r_i + R_i, \quad (7.3)$$

where, r_i —i-concentration of the component; D_i —diffusion coefficient; R_i —source of the substance (substance deposition).

We write the temperature equation of wastewater as follows:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p v \cdot \nabla T = \lambda \cdot \nabla^2 T + Q, \quad (7.4)$$

T —wastewater temperature, K; C_p —specific heat capacity of wastewater, $\frac{Dj}{(kg \cdot K)}$; λ —thermal conductivity coefficient, $\frac{W}{(m \cdot K)}$; Q —thermal power of wastewater, W.

The thermal and physical properties of wastewater are calculated by the volume fractions of the components that make up the wastewater. Therefore, we calculate the density of wastewater based on the following equation:

$$\rho = \sum_i r_i \cdot \rho_i \quad (7.5)$$

where, $r_i = \frac{V_i}{\sum_i V_i}$ —volume fraction of the component, %.

We calculate the dynamic viscosity coefficient of wastewater based on the following equation:

$$\mu = \sum_i r_i \cdot \mu_i \quad (7.6)$$

μ_i —dynamic viscosity coefficient of the component, $\frac{m^2}{sek}$.

We calculate the specific heat capacity of wastewater based on the following equation:

$$C_p = \sum_i r_i \cdot C_{pi} \quad (7.7)$$

We calculate the thermal conductivity of wastewater based on the following equation (Table 7.3):

$$\lambda = \sum_i r_i \cdot \lambda_i \quad (7.8)$$

We calculate the total wastewater consumption using the following equation [5]:

$$G_{ww} = G_{o.w.} + G_{ch.w.} + G_{d.w.} \quad (7.9)$$

We find the average pollution concentration of wastewater.

$$G_{ww} C_{ww} = G_{o.w.} C_{o.w.} + G_{ch.w.} C_{ch.w.} + G_{d.w.} C_{d.w.} \quad (7.10)$$

We write the equation in differential form, taking into account the change in concentration with time:

$$\frac{d(C_{ww} \cdot V)}{dt} = G_{o.w.} \cdot C_{o.w.} + G_{ch.w.} \cdot C_{ch.w.} + G_{d.w.} \cdot C_{d.w.} - G_{out.} \cdot C_{ww} \quad (7.11)$$

where, $C_{o.w.}$, $C_{ch.w.}$, $C_{d.w.}$ —concentration of pollutants in wastewater, mg/l; V —working volume of the wastewater treatment plant PCSC, m^3 .

Table 7.3 The results of calculations of the thermal and physical parameters of wastewater from “Shurtan GChC” LLC

Water type	Consumption, G, m ³ /h	Consumption, G, m ³ /day	Density, ρ kg/m ³	Volume fraction of the component, r _i , %	Dynamic viscosity coefficient, μ, $\frac{m^2}{sek}$
Oily waste water, G _{o.w.}	10–36	864	800	0.36	0.01
Chemical waste water, G _{ch.w.}	18	432	1000	0.18	0.002
Domestic waste water, G _{d.w.}	40	960	990	0.46	0.001
Mixed waste water, G _{ww}	68–94	2256	920.2	1.0	0.00496

The temperature of the wastewater mixture is determined by the following formula:

$$G_{ww}T_{ww} = G_{o.w.} \cdot T_{o.w.} + G_{ch.w.} \cdot T_{ch.w.} + G_{d.w.} \cdot T_{d.w.} \tag{7.12}$$

We write the equation in differential form, taking into account the change in temperature with time:

$$\frac{d(T_{ww} \cdot \rho \cdot V \cdot C_p)}{dt} = G_{o.w.} \cdot T_{o.w.} \cdot \rho \cdot C_p + G_{ch.o.} \cdot T_{ch.o.} \cdot \rho \cdot C_p + G_{d.o.} \cdot T_{d.o.} \cdot \rho \cdot C_p - G_{out} \cdot T_{ww} \cdot \rho \cdot C_p \tag{7.13}$$

where, C_p—specific heat capacity of wastewater, $\frac{Dj}{(kg \cdot K)}$.

Dividing both sides by ρ · V · C_p, we get the following simplified equation

$$\frac{d(T_{ww})}{dt} = \frac{1}{V} (G_{o.w.} \cdot T_{o.w.} + G_{ch.w.} \cdot T_{ch.w.} + G_{d.w.} \cdot T_{d.w.} - G_{out} \cdot T_{ww}) \tag{7.14}$$

In practice, the utilization of low-potential heat of wastewater is carried out using various methods. The utilization of wastewater heat in enterprises based on PCSC, that is, its reuse as SER, is of significant scientific and technical importance. The most important feature of the use of this type of equipment is its multifunctionality of low-potential energy. This allows you to optimize the use of fuel and energy resources.

Our country also has various sources of low-potential secondary energy resources, and currently, the utilization of SERs has not been effectively used in power supply

systems. In particular, the annual amount of secondary energy sources (wastewater) of “Shurtan Gas-Chemical Complex” LLC is 0.9–1.0 million tons, the hourly consumption is 115 m³/h, and the average temperature is 20–35 °C.

Utilization of secondary heat of low-potential wastewater using PCSC and obtaining technically purified water is one of the main methods of energy resource saving.

Analytical, heat-technological, heliotechnical, and thermodynamic calculation methods were used to determine the efficiency of utilizing secondary heat of low-potential wastewater generated at the “Shurtan GChC” LLC enterprise and the possibility of obtaining technical water. Based on the conducted experimental studies, measurement, and control works, the main sources of SER of the “Shurtan GChC” LLC enterprise and their heat-technical parameters are presented in Table 7.4.

From the data in Table 7.4, it can be seen that the technical potential of the wastewater of the “Shurtan GChC” LLC enterprise is 3346 kW, and by utilizing this high-power SER based on a parabolic cylindrical solar concentrator, it is possible to achieve energy and resource savings by using technically purified water for the needs of the enterprise and autonomous energy supply systems of the enterprise’s facilities.

The proposed scheme of wastewater heat utilization of the “Shurtan GChC” LLC enterprise based on a parabolic cylindrical solar concentrator, shown in Fig. 7.1, allows obtaining technically clean water for the needs of the enterprise by increasing the temperature of wastewater to 150–450 °C (see Fig. 7.1).

Table 7.4 Main thermal and technical parameters of wastewater of the enterprise “Shurtan GChC” LLC

Wastewater (SER) parameters	Marking	Unit of measurement	Quantity
Consumption	G _h	m ³ /h	115
Annual quantity	G _y	m ³ /year	900,000–1 000,000
Pressure	p	MPa	0.05–0.25
Temperature	t	°C	22.4–35
Heat capacity	Q	kW	3346

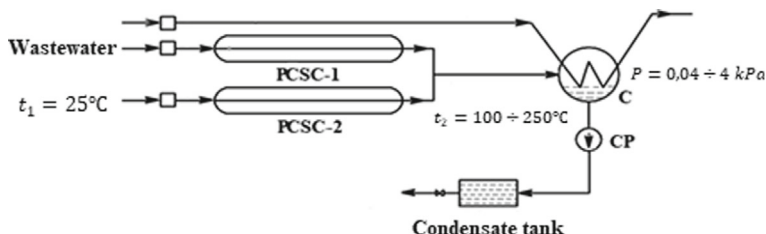


Fig. 7.1 Scheme of wastewater heat utilization based on a parabolic-cylindrical solar concentrator at the “Shurtan GChC” LLC enterprise

F_1, F_2, F_3 —filters, PCSC—parabolic cylindrical solar concentrator, C—condenser (heat exchanger), CP—condensate pump.

The solar concentrator reflects the energy of solar radiation and concentrates it on the surface of the absorber tube located in the focal line of the parabolic cylindrical reflector [9, 10]. Due to the geometric shape of the solar concentrator, the parabolic cylindrical reflector collects the direct solar radiation falling on the surface into the absorber tube passing along the focal line. To reflect solar radiation, films made of glass, aluminum or silver are placed on the surface of the parabolic cylindrical surface. The absorber tube is one of the main elements of the solar concentrator, and the efficiency of the device largely depends on it.

To calculate the energy parameters of the PCSC, we use the following calculation methods.

The date (month and day) and time of the design point are selected; solar energy resources are determined for the given coordinates (date and time).

The angle of incidence of direct solar radiation is determined:

The angle of declination (δ) of the sun for a given day n is determined by the following formula [12]:

$$\delta = 23,45 \sin\left(360 \frac{284 + n}{365}\right) \quad (7.15)$$

The hour angle ω of the sun at point A (φ° and ψ°) at a given time of day local time is calculated by the following formula:

$$\omega = \frac{15^\circ}{hour} (12 - t_h) \quad (7.16)$$

where, t_h —sunny time.

Radiation power on the active surface.

Taking into account the amount of direct solar radiation, the solar energy power on the active surface of the PCSC is determined by the following formula [12]:

$$Q_{PCSC} = F_{PCSC} \cdot q^\Sigma \cdot \cos(\theta) \quad (7.17)$$

F_{PCSC} —PCSC reflector surface area, m^2 ; q^Σ —amount of solar radiation, W/m^2 ; θ —angle of incidence, $^\circ$.

The energy efficiency of a PCSC, taking into account all losses in the PCSC (optical, geometric, and thermal), can be written in the following form [13]:

$$\eta_{PCSC} = \eta_{opt,0^\circ} \cdot K(\theta) \cdot t_{h.s.} \quad (7.18)$$

or,

$$\eta_{PCSC} = \frac{Q_{PCSC}^{usef}}{Q_{PCSC}} \quad (7.19)$$

For the case where the PCSC incidence is zero ($\theta = 0^\circ$), the resulting optical losses are expressed as:

$$\eta_{opt,0^\circ} = \vartheta \cdot \tau \cdot \alpha \cdot \gamma \quad (7.20)$$

For the case where the PCSC incidence angle is greater than zero ($\theta > 0^\circ$), the resulting geometric and optical losses are determined according to the following expression:

$$K = f(\theta) \quad (7.21)$$

The heat losses of the PCSC are determined according to the following expression:

$$Q_{h.l.}^{PCSC} = \Delta q_{h.l.} \cdot L_{PCSC} \quad (7.22)$$

$\Delta q_{h.l.}$ —is the specific heat loss (W/m), which is calculated as follows:

$$\Delta q_{h.l.} = \left[(0.00036 \cdot \Delta T^2 + 0.2029 \cdot \Delta T + 24.899) \cdot \left(\frac{q^\Sigma}{900} \right) \cdot \cos(\theta) \right] + 0.00154 \cdot \Delta T^2 + 0.2021 \cdot \Delta T - 24.899 \quad (7.23)$$

where, L_{PCSC} -PCSC is the length, m; ΔT -PCSC is the difference between the maximum temperature of the wastewater in the absorber pipe and the ambient temperature, K; $\cos(\theta)$ -cosine of the angle of incidence, $^\circ$.

The useful thermal capacity of PCSC depends on solar radiation and the energy parameters of PCSC and is calculated based on the following equation [11].

$$Q_{PCSC}^{usef} = Q_{PCSC} \cdot \eta_{PCSC} \quad (7.24)$$

or

$$Q_{PCSC}^{usef} = F_{PCSC} \cdot q^\Sigma \cdot \cos(\theta) \cdot \eta_{opt,0^\circ} \cdot K(\theta) \cdot t_{h.l.} \cdot k_{dust} \quad (7.25)$$

k_{dust} —dusting coefficient of the reflector surface of the PCSC, ($0 < k_{dust} < 1$).

If we replace the expression for thermal efficiency in the equation for useful thermal power with the expression for heat losses, then the equation for calculating the useful thermal power of a PCSC will look like this:

$$Q_{PCSC}^{usef} = F_{PCSC} \cdot q^\Sigma \cdot \cos(\theta) \cdot \eta_{opt,0^\circ} \cdot K(\theta) \cdot k_{dust} - Q_{h.l.}^{PCSC} \quad (7.26)$$

Since the daily wastewater consumption of “Shurtan GChC” LLC is high, the number of PCSCs required in the process of technical water extraction using PCSCs is also greater. Therefore, the serially connected PCSC is calculated based on the following equation:

$$N_{PCSC} = \frac{\Delta T_T}{\Delta T_C} \quad (7.27)$$

ΔT_T —maximum temperature of wastewater in the focal area of the PCSC, K;
 ΔT_C —temperature of wastewater in one PCSC, K.

It is known from the operating mode of the PCSC that the flow regime of the wastewater inside the absorber tube is characterized by the Reynolds number, which prevents the tube from deforming and the PCSC from being damaged when it is overheated [13].

For different Re, the wastewater velocity can be calculated by the following formula:

$$v = \frac{Re \cdot \mu}{\rho \cdot d} \quad (7.28)$$

Here, d is the inner diameter of the absorber pipe, m; ρ is the density of the wastewater, kg/m^3 ; μ is the coefficient of dynamic viscosity of the wastewater, m^2/s .

After determining the wastewater velocity, the mass flow rate q_m can be determined based on the cross-sectional area S of the PCSC absorber pipe and the density ρ of the liquid:

$$q_m = v \cdot S \cdot \rho \quad (7.29)$$

We also determine the useful thermal capacity of the PCSC through the enthalpies of the PCSC wastewater:

$$Q_{PCSC}^{usef} = q_m \cdot \Delta h = q_m \cdot (h_{out} - h_{in}) = q_m \cdot \int_{T_i}^{T_0} C_p dT \quad (7.30)$$

h_{in} , h_{out} —input and output enthalpy of wastewater at the inlet to the PCSC, Dj/kg ;
 C_p —specific heat capacity of wastewater, $\text{Dj}/(\text{kg} \cdot ^\circ\text{C})$; T_i , T_0 —wastewater inlet and outlet temperatures of the PCSC, K.

To obtain technical water through the utilization of “Shurtan GChC” LLC wastewater, a Eurotrough-150 PCSC was selected, its main characteristics are given in Table 7.5 and Fig. 7.2, and a technological scheme of the PCSC utilization process of “Shurtan GChC” LLC wastewater is given.

The calculation results presented in Figs. 7.3, 7.4 and 7.5. For example, Fig. 7.3 shows the results of the dependence of Q_{PCSC}^{usef} on the Reynolds number, that is, as the Reynolds number of the wastewater flowing through the absorber tube of the PCSC changes, the Q_{PCSC}^{usef} also changes, Fig. 7.4 shows the results of the dependence of PCSC thermal power on solar radiation and Fig. 7.5 shows the results of the effect of the useful energy of PCSC on the useful work of the device.

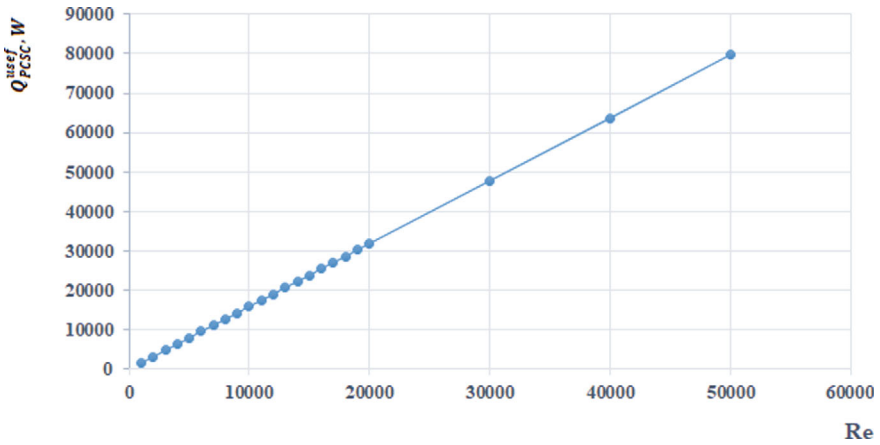


Fig. 7.3 Diagram of the dependence of the useful thermal power of the PCSC on the Re number

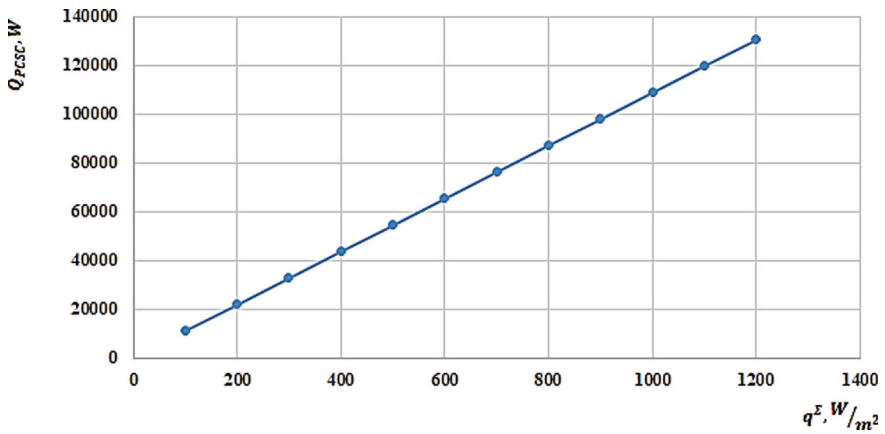


Fig. 7.4 Diagram of the dependence of the thermal power of the PCSC on changes in the amount of solar radiation

7.3 Conclusions

The temperature at the PCSC outlet should be slightly lower than the maximum operating temperature (450 °C) that the oil mixture in the wastewater can reach. In this case, the temperature is set to 430–440 °C.

Rainwater from the complex’s technological devices to the oily wastewater treatment device 6401 of the wastewater treatment plant receives 864 m³ of oily wastewater per hour from 10 to 36 m³ per hour.

The flue gas is treated using the Oily Wastewater Treatment Plant (Unit 6401) of the chemical complex. The treated wastewater is directed to the PCSC.

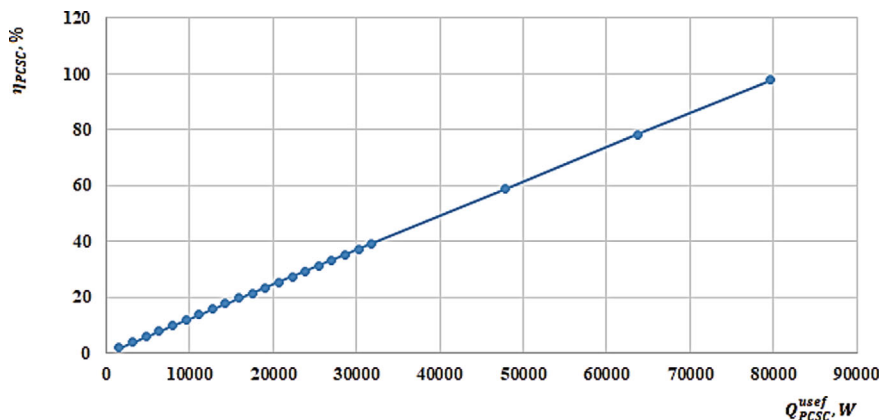


Fig. 7.5 Energy efficiency index of the PCSC

The calculation results were calculated based on the thermal and physical parameters of “Shurtan GChC” LLC wastewater and the main characteristics of the Eurotrough-150 PCSC given in Table 7.3, and the calculation results are presented in Figs. 7.3, 7.4 and 7.5.

As a result, it was determined that the density of the wastewater of the enterprise “Shurtan GChC” LLC is $\rho = 920.2 \text{ kg/m}^3$, and the dynamic viscosity coefficient $\mu = 0.00496 \text{ m}^2/\text{s}$.

A scheme for utilizing the heat of wastewater at the “Shurtan GChC” LLC enterprise based on a parabolic cylindrical solar concentrator was developed, and a Eurotrough-150 PCSC was selected, and its technical parameters were presented.

A technological scheme for utilizing the heat of wastewater at the “Shurtan GChC” LLC enterprise using PCSC to obtain technical water was developed, and equations were presented that allow calculating its energy efficiency.

6 Eurotrough-150 PCSCs are connected in series to utilize the heat of wastewater at the “Shurtan GChC” LLC enterprise, which allows obtaining technical clean water by increasing the temperature of wastewater to 150–450 °C.

According to the technical parameters of the Eurotrough-150 PCSC, experimental studies and calculation results, it was determined that the Eurotrough-150 PCSC in the natural climatic conditions of the city of Karshi, when the average solar radiation is 700–800 W/m², the wastewater Re number is 10,000, $\eta_{PCSC} = 19.54\%$, when Re = 20,000, $\eta_{PCSC} = 39.08\%$, and when Re = 50,000, $\eta_{PCSC} = 97\%$.

According to the technological scheme, the average temperature of the wastewater of the “Shurtan GChC” LLC enterprise is 20–35 °C, and as a result of the conversion of steam into condensate in the condenser, its temperature rises to 70–85 °C and is directed to the PCSC. As a result, this affects the energy efficiency of the PCSC.

The technical clean water obtained as a result of the utilization of wastewater of the “Shurtan GChC” LLC enterprise using the Eurotrough-150 brand PCSC will be used for technological processes at the enterprise.

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