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PARABOLASILINDRIK KONSENTRATORLI ISSIQLIK TA'MINOTI TIZIMIDA ISSIQLIK ALMASHINUVI JARAYONLARINI MATEMATIK MODELLASHTIRISH

Sherqulov Bahrom G'ulomovich
Qarshi davlat texnika universiteti katta o'qituvchi

Annotatsiya. Quyosh energiyasidan foydalanishga asoslangan issiqlik tizimlari, xususan parabola silindrik konsentratorlar yordamida issiq suv olish texnologiyalari bugungi kunda global energetika tizimining muhim yo'nalishlaridan biriga aylanmoqda. Bunga asosiy sabab — dunyo miqyosida issiq suvga bo'lgan talabning keskin ortib borayotgani va an'anaviy yoqilg'ilar hisobiga ishlab chiqariladigan issiqlik energiyasining ekologik va iqtisodiy jihatdan tobora qimmatlashib borayotganidir. So'nggi yillarda olib borilgan tahlillar shuni ko'rsatadiki, global miqyosda suvni isitish uchun har yili trillionlab kilovatt-soat energiya sarflanadi[1]. Masalan, Xalqaro qayta tiklanuvchi energiya agentligi hisobotlariga ko'ra, faqatgina maishiy issiq suv ta'minoti uchun sarflanadigan energiya hajmi yiliga 4000–5000 TWh atrofida baholanadi. Bu ko'rsatkich ayrim rivojlangan davlatlarda umumiy elektr energiyasi iste'molining 15–25% ini tashkil etadi. Shu bilan birga, issiq suvga bo'lgan talab aholi sonining o'sishi, urbanizatsiya jarayonlari va sanoatning kengayishi natijasida yiliga o'rtacha 2–3% ga ortib bormoqda. Quyosh energiyasidan issiqlik olish texnologiyalari, xususan parabola silindrik konsentratorlar bu muammoning samarali yechimlaridan biri hisoblanadi. Ushbu qurilmalar quyosh nurlarini fokus chizig'iga jamlash orqali yuqori issiqlik zichligini hosil qiladi va natijada issiqlik tashuvchi muhit (masalan, transformator moyi) orqali katta miqdordagi issiqlik energiyasini olish imkonini beradi. Tadqiqotlar shuni ko'rsatadiki, bunday tizimlar yordamida issiqlik tashuvchi moy haroratini 200–250°C gacha, suv haroratini esa 80–100°C gacha yetkazish mumkin[1-3-4]. Bu ko'rsatkichlar issiq suv ta'minoti va texnologik jarayonlar uchun yetarli darajada hisoblanadi.

Kalit so'zlar: Parabola silindrik konsentrator (PTC), Quyosh issiqlik energiyasi, Issiq suv ta'minoti, Issiqlik tashuvchi suyuqlik (HTF), Qayta tiklanuvchi energiya, Energiya samaradorligi, Sanoat issiqlik jarayonlari.

Abstract. Solar-driven thermal systems, particularly hot water production technologies utilizing parabolic trough collectors (PTCs), are emerging as a pivotal component of the global energy landscape. This shift is primarily driven by the escalating global demand for domestic hot water and the increasing environmental and economic burdens associated with heat generation from conventional fossil fuels. Current longitudinal analyses indicate that water heating accounts for trillions of kilowatt-hours of energy consumption annually on a global scale. Specifically, according to the International Renewable Energy Agency (IRENA),

energy consumption for domestic hot water (DHW) is estimated at approximately 4,000–5,000 TWh per annum. In several developed economies, this figure represents 15–25% of the total residential electricity load. Furthermore, driven by demographic growth, rapid urbanization, and industrial intensification, the demand for hot water is projected to grow at an average annual rate of 2–3%. Concentrating solar power (CSP) technologies, specifically parabolic trough collectors, offer a highly efficient solution to mitigate these challenges. By concentrating direct normal irradiance (DNI) onto a focal line, these systems achieve high flux density, facilitating the transfer of significant thermal energy to a heat transfer fluid (HTF), such as transformer oil. Empirical research demonstrates that such configurations can elevate HTF temperatures to 200–250°C, subsequently yielding water temperatures in the range of 80–100°C. These thermal performance indicators are highly suitable for both large-scale hot water supply and diverse industrial process heat (IPH) applications.

Keywords: Parabolic trough collector (PTC), solar thermal energy, hot water supply, heat transfer fluid (HTF), renewable energy, energy efficiency, industrial process heat (IPH).

Аннотация. Тепловые системы на основе использования солнечной энергии, в частности технологии получения горячей воды с применением параболоцилиндрических концентраторов (ПЦК), становятся одним из важнейших направлений современной глобальной энергетической системы. Основными факторами этого процесса являются резкий рост мирового спроса на горячее водоснабжение, а также возрастающие экологические и экономические издержки производства тепловой энергии на базе традиционных видов топлива. Анализ последних лет показывает, что в глобальном масштабе на нагрев воды ежегодно затрачиваются триллионы киловатт-часов энергии. В частности, согласно отчетам Международного агентства по возобновляемым источникам энергии (IRENA), объем энергопотребления исключительно для нужд бытового горячего водоснабжения оценивается в пределах 4000–5000 ТВтч в год. В ряде развитых стран данный показатель составляет 15–25% от общего потребления электроэнергии. Параллельно с этим, вследствие роста численности населения, процессов урбанизации и расширения промышленного сектора, спрос на горячую воду увеличивается в среднем на 2–3% в год. Технологии гелиотермальной генерации, в особенности параболоцилиндрические концентраторы, рассматриваются как одно из эффективных решений данной проблемы. Эти устройства обеспечивают высокую плотность теплового потока за счет фокусировки солнечного излучения на фокальной линии, что позволяет получать значительное

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количество тепловой энергии через теплоноситель (например, трансформаторное масло). Исследования демонстрируют, что при использовании таких систем температура теплоносителя может достигать 200–250°C, а температура воды — 80–100°C. Данные показатели являются достаточными как для систем горячего водоснабжения, так и для различных технологических процессов.

Ключевые слова: параболоцилиндрический концентратор (ПЦК), гелиотермальная энергия, горячее водоснабжение, теплоноситель, возобновляемые источники энергии, энергоэффективность, промышленное тепло.

KIRISH.

Mazkur ishda parabola silindrik konsentrator asosida ishlaydigan issiqlik tizimining matematik modeli ishlab chiqildi va uning asosiy parametrlarining tizim samaradorligiga ta’siri o‘rganildi. Modelda issiqlik qabul qilgich, transformator moyi va suvli akkumulyator o‘rtasidagi issiqlik almashinuvi differensial tenglamalar tizimi orqali ifodalandi.

Issiqlik qabul qilgich metall bo‘lganligi uchun, uning issiqlik-fizikaviy hossalari asosida issiqlik balansini quyidagicha yoza olamiz:

$$m_m \cdot c_m \cdot \frac{dt_m}{dt} = Q_{nur} - Q_{d-moy} - Q_{yo'q} \qquad (1)$$

bu yerda, Q_{nur} – Quyosh konsentratori yordamida fokusga jamlangan issiqlik nurlanishi, Vt; Q_{d-moy} – issiqlik qabul qilgichidan moyga uzatiladigan issiqlik quvvati, Vt; $Q_{yo'q}$ – issiqlik qabul qilgich devoridan atrof muhitga yo‘qotiladigan issiqlik oqimi, Vt; m_m – issiqlik qabul qilgich metall massasi, kg; c_m – issiqlik qabul qilgich (metal) ning solishtirma issiqlik sig‘imi, $J/kg \cdot ℃$; $\frac{dt_m}{d\tau}$ – issiqlik qabul qilgich haroratining vaqt bo‘yicha o‘zgarishi. (1) ifodaning chap tomondagi hadi devorda vaqt birligida to‘planayotgan yoki kamayayotgan issiqlik miqdorini bildiradi.

Quyosh konsentratori yordamida issiqlik qabul qilgichga nurlanish orqali beriladigan issiqlik oqimini quyidagicha yozamiz:

$$Q_{nur} = I(\tau) \cdot A_k \cdot \eta_{opt} \qquad (1a)$$

bu yerda, $I(\tau)$ – yuza birligiga tushadigan quyosh radiatsiyasi, $\frac{Vt}{m^2}$; A_k – konsentrator maydoni, m^2; η_{opt} – konsentratorning optik samaradorligi.

Issiqlik qabul qilgich devori bilan moy orasidagi issiqlik almashinuvini quyidagi ifoda orqali hisoblaymiz

$$Q_{d-moy} = U_{d-moy} \cdot A_{d-mo} \cdot \left(t_d - t_{moy}\right), \qquad \frac{1}{U_{d-moy}} = \frac{1}{h_{moy}} + \frac{\delta_d}{\lambda_d} \qquad (2)$$

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bu yerda, U_{d-moy} – devordan moyga issiqlik uzatish koeffitsienti, $(Vt/m^2 \cdot ℃)$; h_{moy} – devor-moy orasidagi konvektiv issiqlik uzatish koeffitsienti, $(Vt/m^2 \cdot ℃)$; δ_d, λ_d – mos ravishda metalning qalinligi (m) va issiqlik o‘tkazuvchanlik koeffitsienti, $Vt/m^2 \cdot ℃$; A_{d-mo} – devor va moy tutashgan issiqlik almashinuv yuzasi, m^2; t_d – devor harorati, ℃; t_{moy}- moy harorati ℃;

Issiqlik qabul qilgich devoridan atrof-muhitga yo‘qotiladigan issiqlikni quyidagicha yoza olamiz

$$Q_{yo'q} = U_{yo'q} \cdot A_m \cdot (t_d - t_{a-m}) \quad (3)$$

bu yerda, A_m – devorning tashqi issiqlik almashinuv yuzasi (m^2) bo‘lib, amaliy hisoblashlarda ichki issiqlik almashinuv yuzasiga $(A_m = A_{d-moy})$ deb qabul qilish mumkin; t_{a-m} – atrof-muhit harorati, ℃; $U_{yo'q}$ – issiqlik qabul qilgichdan atrof-muhitga issiqlik yo‘qotish koeffitsienti bo‘lib, uni quyidagicha hisoblash mumkin.

$$U_{yo'q} = h_{kon} + h_{nur}\,, \quad h_{kon} = 5.7 + 3.8 \cdot v\,, \quad h_{nur} = \varepsilon \cdot \sigma \cdot (T_d^2 - T_{a-m}^2)(T_d - T_{a-m}) \quad (3a)$$

bu yerda, h_{kon} – issiqlik qabul qilgichdan atrof-muhitga konveksiya orqali (konvektiv) issiqlik berish koeffitsienti, $Vt/m^2 \cdot ℃$; h_{nur} – sirtdan atrof-muhitga nurlanish orqali issiqlik yo‘qotish koeffitsienti, $Vt/m^2 \cdot ℃$; v – shamol tezligi, $\frac{m}{s}$; ε – sirtning nurlanish qobiliyati; $\sigma = 5.67 \cdot 10^{-8}$ $\frac{Vt}{m^2K^4}$ – Stefan-Boltsman doimiysi; T_d, T_{a-m} – devor va atrof-muhit haroratlarining absolyut haroratlari, K.

Moy quvur yoki kvadrat shakldagi profilda harakatlanganda haroratining uzunlik bo‘yicha yoki vaqt bo‘yicha o‘zgarishini quyidagicha ifodalashimiz mumkin:

$$m_{moy} \cdot c_{moy} \frac{dt_{moy}}{dx} = U_{d-moy} \cdot p_d\left(t_d - t_{moy}\right),$$

$$m_{moy} \cdot c_{moy} \frac{dt_{moy}}{d\tau} = U_{d-moy} \cdot A_{d-moy}\left(t_d - t_{moy}\right) - U_{moy-s} \cdot A_{moy-suv} \cdot \left(t_{moy} - t_{suv}\right) \quad (4)$$

bu yerda, m_{moy} , c_{moy} – mos ravishda issiqlik qabul qilgich ichida harakatlanadigan moyning massasi (kg) va solishtirma issiqlik sig‘imi $j/kg \cdot ℃$; A_{moy-s} – Bak-akkumulyator ichida joylashgan issiqlik almashtirgich (zmeyvik) yuzasi, m^2 ; t_{moy} – moyning o‘rtacha harorati, ℃; t_{suv} – suvning harorati, ℃; $U_{moy-suv}$ – maydon suvga issiqlik uzatish koeffitsienti $(Vt/m^2 \cdot ℃)$ bo‘lib, uni quyidagi ifoda orqali hisoblash mumkin:

$$\frac{1}{U_{moy \cdot suv}} = \frac{1}{h_{moy}} + \frac{\delta_q}{\lambda_q} + \frac{1}{h_{suv}},\ \frac{\delta_q}{\lambda_q} \ll \frac{1}{h_{moy}},\ \frac{1}{h_{suv}},\ U_{moy-suv} \approx \left(\frac{1}{h_{moy}} + \frac{1}{h_{suv}}\right)^{-1}$$

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bu yerda, h_{moy} – maydon issiqlik almashinuv quvuriga issiqlik berish koeffitsienti, $\frac{Vt}{m^{2}\cdot ℃}$; h_{suv} – issiqlik amashinuv quvuridan suvga issiqlik berish koeffitsienti, $\frac{Vt}{m^{2}\cdot ℃}$; δ_q , λ_q – mos ravishda issiqlik almashinuv quvurining qalinligi (m) va issiqlik o‘tkazuvchanlik koeffitsienti (4) ifodani moyning o‘rtacha harorati bilan ishlasak ikkinchi tenglama orqali ifodalasak bo‘ladi.

Suvli bak issiqlik akkumulyator uchun energiya balansini quyidagicha yozishimiz mumkin.

$$m_{suv}\cdot c_{suv}\frac{dt_{suv}}{d\tau}=U_{moy-suv}\cdot A_{moy-suv}\left(t_{moy}-t_{suv}\right)-U_{d.bak}\cdot A_{d.bak}\cdot \left(t_{suv}-t_{a-m}\right) \qquad (5)$$

bu yerda, m_{suv} , c_{suv} – mos ravishda bak akkumulyatordagi suvning massasi (kg) va solishtirma issiqlik sig‘imi, $j/kg\cdot ℃$; t_{suv} – suv harorati, ℃ ; $A_{d.bak}$ – suvli bakning tashqi devor sirtining yuzasi, m^2; $U_{d.bak}$ – suvli bakning tashqi yuzasidan atrof-muhitga issiqlik uzatish (yo‘qotish) koeffitsienti ($\frac{Vt}{m^{2}\cdot ℃}$) bo‘lib quyidagi ifoda orqali hisoblanadi[1-2-5-7-12].

$$\frac{1}{U_{d.bak}}=\frac{\delta_d}{\lambda_d}+\frac{\delta_{i2}}{\lambda_{i2}}+\frac{1}{h_{a-m}} \qquad (5a)$$

bu yerda, δ_d, δ_{i2}, va λ_d, λ_{i2} – mos ravishda bak akkumulyator materialining va izolyatsiya qatlamining qalinliklari (m) hamda o‘tkazuvchanlik koeffitsientlari $\frac{Vt}{m\cdot ℃}$; h_{a-m} – bak akkumulyator tashqi devoridan atrof muhitga issiqlik berish koeffitsienti ($\frac{Vt}{m^{2}\cdot ℃}$) bo‘lib, amaliy hisoblashlarda (3a) ifodadagi konvektiv issiqlik berish koeffitsientiga teng ($h_{kon}=h_{a-m}$) deb qabul qilish mumkin[1-9-15-18].

Yuqoridagilarni hisobga olib, (1), (4), (5) differensial tenglamalarni (2), (3) ifodalarni hisobga olib tizimli ko‘rinishda quyidagicha yoza olamiz

$$\begin{cases} m_m\cdot c_m\frac{dt_d}{d\tau}=I(\tau)\cdot A_k\cdot\eta_{opt}-U_{d-moy}\cdot A_{d-moy}\cdot\left(t_d-t_{moy}\right)-U_{yo'q}\cdot A_{d-moy}\cdot\left(t_d-t_{a-m}\right) \\ m_{mo}\cdot c_{moy}\frac{dt_{mo}}{d\tau}=U_{d-mo}\cdot A_{d-moy}\cdot\left(t_d-t_{moy}\right)-U_{moy-suv}\cdot A_{moy-suv}\cdot\left(t_{moy}-t_{suv}\right) \\ m_{suv}\cdot c_{suv}\frac{dt_{suv}}{d\tau}=U_{moy-suv}\cdot A_{moy-suv}\cdot\left(t_{moy}-t_{suv}\right)-U_{d.bak}\cdot A_{d.bak}\cdot\left(t_{suv}-t_{a-m}\right) \end{cases} \qquad (6)$$

(6) tenglamalar sistemasini[1-3-11-17-20] yechishdan oldin kanonik ko‘rinishga keltiramiz va quyidagicha yozamiz.

$$\begin{cases} \frac{dt_d}{d\tau}=-\frac{A_{d-moy}\left(U_{d-moy}+U_{yo'q}\right)}{m_m\cdot c_m}\cdot t_m+\frac{U_{d-mo}\cdot A_{d-moy}}{m_m\cdot c_m}\cdot t_{moy}+\frac{U_{yo'q}\cdot A_{d-moy}}{m_m\cdot c_m}\cdot t_{a-m}+\frac{I(\tau)\cdot A_k\cdot\eta_{opt}}{m_m\cdot c_m} \\ \frac{dt_{moy}}{d\tau}=\frac{U_{d-moy}\cdot A_{d-moy}}{m_{moy}\cdot c_{moy}}\cdot t_d-\frac{U_{d-moy}\cdot A_{d-moy}+U_{moy-suv}\cdot A_{moy-suv}}{m_{moy}\cdot c_{moy}}\cdot t_{moy}+\frac{U_{moy-suv}\cdot A_{moy-suv}}{m_{moy}\cdot c_{moy}}\cdot t_{suv} \\ \frac{dt_{suv}}{d\tau}=\frac{U_{moy-suv}\cdot A_{moy-suv}}{m_{suv}\cdot c_{suv}}\cdot t_{moy}-\frac{U_{moy-suv}\cdot A_{moy-suv}+U_{d-bak}\cdot A_{d-bak}}{m_{suv}\cdot c_{suv}}\cdot t_{suv}+\frac{U_{d-bak}\cdot A_{d-bak}}{m_{suv}\cdot c_{suv}}\cdot t_{a-m} \end{cases} \qquad (7)$$

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(7) tenglamalar sistemasini matritsa ko‘rinishida yozib olishdan oldin, sistemadagi haroratlar vektorini A va B koeffitsientlarini belgilab olamiz.

$$T(\tau) = \begin{bmatrix} t_d \\ t_{moy} \\ t_{suv} \end{bmatrix}, \quad \frac{dt}{d\tau} = At + B \qquad (8)$$

$$A\begin{bmatrix} -\frac{A_{d-moy}\left(U_{d-moy} + U_{yo'q}\right)}{m_m \cdot c_m}, & \frac{U_{d-moy} \cdot A_{d-moy}}{m_m \cdot c_m}, & 0 \\ \frac{U_{d-moy} \cdot A_{d-moy}}{m_{moy} \cdot c_{moy}}, & -\frac{U_{d-moy} \cdot A_{d-moy} + U_{moy-suv} \cdot A_{moy-suv}}{m_{moy} \cdot c_{moy}}, & \frac{U_{moy-suv} \cdot A_{moy-suv}}{m_{moy} \cdot c_{moy}} \\ 0, & \frac{U_{moy-suv} \cdot A_{moy-suv}}{m_{suv} \cdot c_{suv}}, & -\frac{U_{moy-suv} \cdot A_{moy-suv} + U_{d-bak} \cdot A_{d-bak}}{m_{suv} \cdot c_{suv}} \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{I(\tau) \cdot A_k \cdot \eta_{opt} + U_{yo'q} \cdot A_{d-moy} \cdot t_{a-m}}{m_m \cdot c_m} \\ 0 \\ \frac{U_{d.bak} \cdot A_{d.bak} \cdot t_{a-m}}{m_{suv} \cdot c_{suv}} \end{bmatrix}$$

Yuqoridagi tenglamalar sistemasidagi o‘zgarmas qiymatlarni 1- jadvalda keltiramiz [1-21-23-25].

1-jadval

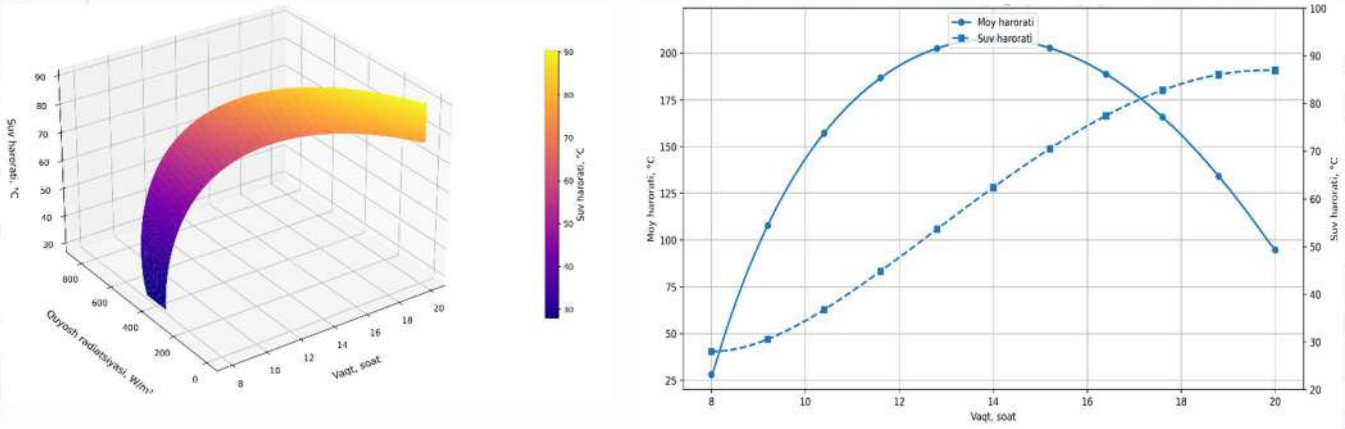
Parametrlar jadvali

№	Parametr nomi	Belgilanishi	Birligi	Qiymati
1.	Konsentrator maydoni	A_k	m²	1
2.	Optik samaradorlik	η_{opt}	-	0,82
3.	Devor va moy tutashgan issiqlik almashinuv yuzasi	A_{d-moy}	m²	0,15
4.	Bak-akkumulyator ichida joylashgan issiqlik almashtirgich (zmeyvik) yuzasi	$A_{moy-suv}$	m²	0,1
5.	Suvli bakning tashqi devor sirtining yuzasi	$A_{d.bak}$	m²	1,8
6.	Issiqlik qabul qilgich metal massasi	m_m	kg	3,9
7.	Metall (po‘lat) solishtirma issiqlik sig‘imi	c_m	$J/kg \cdot ℃$	460
8.	Moy massasi	m_{moy}	kg	8
9.	Moy solishtirma issiqlik sig‘imi	c_{moy}	$J/kg \cdot ℃$	5500
10.	Suv massasi	m_{suv}	kg	80
11.	Suvning solishtirma issiqlik sig‘imi	c_{suv}	$J/kg \cdot ℃$	4180

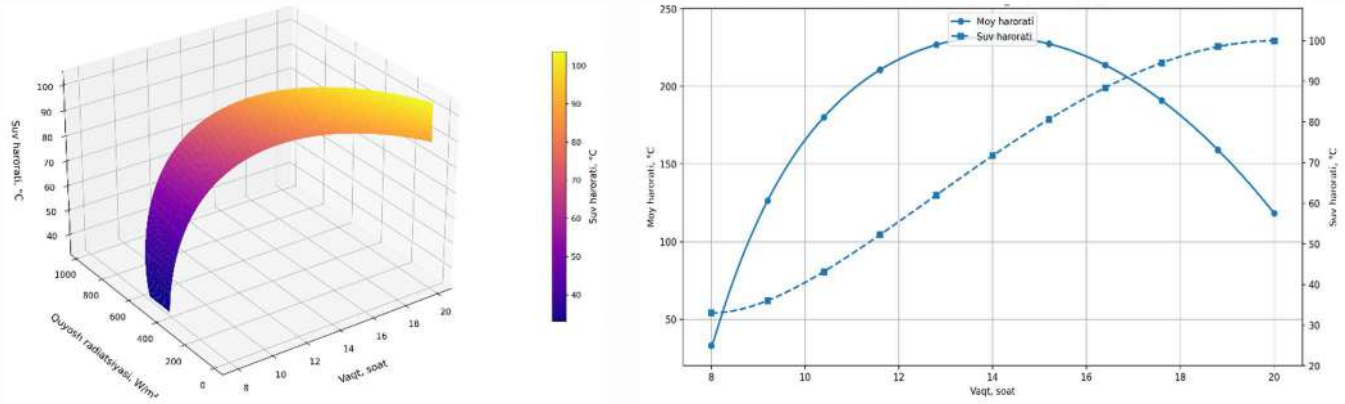
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12.	Stefan-Boltsman doimiysi	σ	$\frac{Vt}{m^2K^4}$	$5{,}67 \cdot 10^{-8}$
13.	Sirtning nurlanish qobiliyati	ε	-	0,78

Tashqi havo harorati va quyosh raditasiyasini Qarshi shahri sharoiti uchun 2025 yil 15-may, 15-iyun, 15-iyul, 15-avgust sanalaridagi ma’lumotlari asosida (7), (8) ifodalarning hisoblash natijalarini 1-4 rasmlarda keltiramiz.

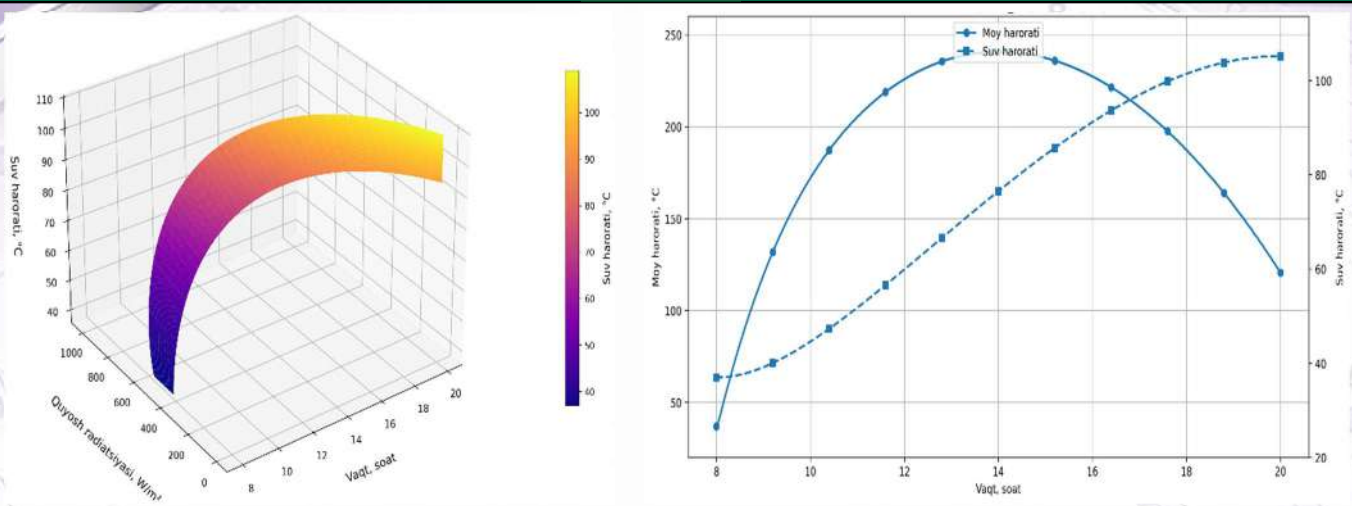


1-rasm. Qarshi shahri sharoti uchun (15.05.2025) parabolasilindrik konsentrator issiqlik qabul qilgichidagi moy hamda bak-akkumulyatordagi suv haroratining sutkalik vaqt davomida o‘zgarishi

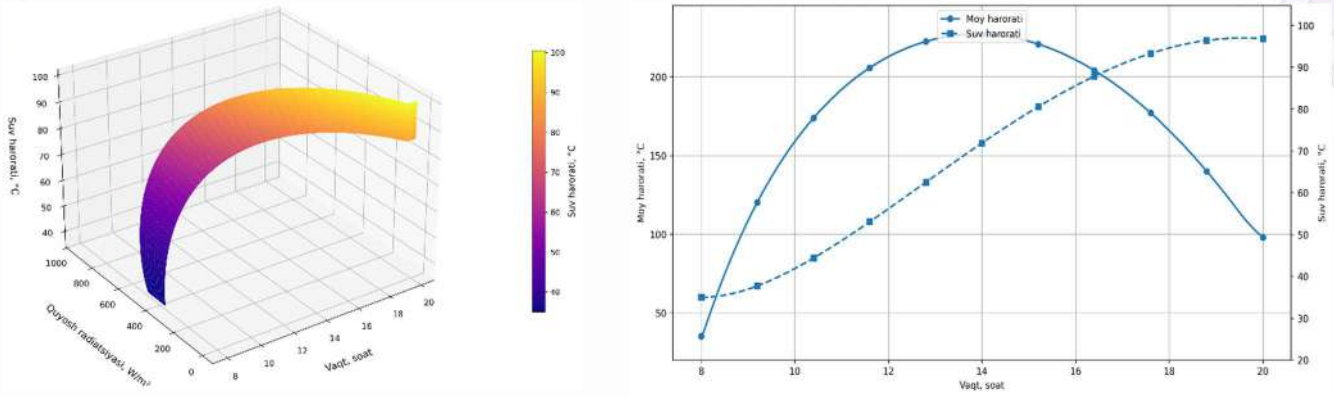


2-rasm. Qarshi shahri sharoti uchun (15.06.2025) parabolasilindrik konsentrator issiqlik qabul qilgichidagi moy hamda bak-akkumulyatordagi suv haroratining sutkalik vaqt davomida o‘zgarishi

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3-rasm. Qarshi shahri sharoti uchun (15.07.2025) parabolasilindrik konsentrator issiqlik qabul qilgichidagi moy hamda bak-akkumulyatordagi suv haroratining sutkalik vaqt davomida o‘zgarishi



4-rasm. Qarshi shahri sharoti uchun (15.08.2025) parabolasilindrik konsentrator issiqlik qabul qilgichidagi moy hamda bak-akkumulyatordagi suv haroratining sutkalik vaqt davomida o‘zgarishi

1-rasmdan ko‘rish mumkinki, moyning harorati 200 °C dan yuqori qiymatlarga ko‘tariladi. Suv haroratining o‘zgarishi esa nisbatan inertroq xarakterga ega bo‘lib kun davomida asta-sekin ortib boradi va maksimal qiymati 85–90 °C atrofida ko‘tariladi. 2-rasmda esa moy haroratining 230 °C ga yaqin, suv harorati esa 90–100 °C oralig‘ida, 3-rasmda moy harorati 240 °C dan yuqori, suv harorati esa 100 °C dan oshishini, 4-rasmda moy harorati 225–230 °C, suv harorati esa 90–98 °C oralig‘ida shakllanishi nazariy hisoblashlar natijasida aniqlandi.

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