Modeling the heat balance of a solar concentrator heliopyrolysis device reactor

G N Uzakov[1*], *X A* Almardanov[1], *I N* Kodirov[1], and *L A* Aliyarova[1]

[1]Karshi Engineering Economics Institute, 225, Mustakillik avenue, Karshi, 180100, Uzbekistan

Abstract. The article presents the principle scheme of the heliopyrolysis device with a solar concentrator and the mathematical model of the equations representing the heat balance of the heliopyrolysis reactor. Based on the mathematical modeling method, the energy balance of the heliopyrolysis reactor was theoretically studied, and graphs representing the temperature change of the reactor surface were obtained when the solar radiation falling on the concentrator was Ir=600÷900 W/m^2 in the climatic conditions of the region of Karshi (Uzbekistan). Based on modeling in the SOLTRACE program, the graphs of the temperature field at different points of the solar parabolic concentrator are determined to change depending on the energy of the incident solar radiation. In the experimental device, it was determined that an average temperature of 200-300 ℃ can be generated in the reactor within one hour. Experiments show that in the conditions of the city of Karshi, it is possible to create a regime of 200÷500℃ sufficient for biomass pyrolysis through a parabolic solar concentrator in the daytime mode.

1 Introduction

Currently, rational use of natural fuel resources and ensuring energy efficiency are important tasks. Effective use of renewable energy sources is important in saving energy resources. The energy potential of solar and biomass energy from renewable energy sources is great, and their practical use is highly effective in terms of energy, ecology and economy [1]. The increase in the population and the development of the utility service system lead to an increase in energy consumption. With the increase in the population, there are problems such as saving food and energy resources without harming the environment. To solve these problems, organic fuels (coal, oil, natural gas) use should be radically reduced [2-3].

In the world, the use of renewable energy sources such as wind, solar, water and biomass is considered a priority, and special scientific research is required for the effective use of these energy sources and the creation of technological devices based on them. For this, it will be necessary to create energy-efficient technologies, reduce harmful gases released from them, optimize the share of extracted organic fuel, and increase the efficiency of renewable energy sources. It is planned to increase the share of energy produced by renewable energy sources in the world from 8.5% in 2005 to 25% in 2025 [4].

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* Corresponding author: hamid_8191@mail.ru

Pyrolysis is a modern effective method of obtaining solid (coal), gaseous (biogas) and liquid (tar and oil) biofuels from biomass and various organic wastes. Pyrolysis is a method of turning organic waste and biomass into steam-gas by heating them in an airless environment, and then cooling them to produce gas, liquid, and solid hydrocarbon products. liquid, gaseous and solid alternative fuels are obtained from organic waste within hours. In a pyrolysis device, it is possible to generate three different types of alternative fuels and heat energy (hot water) at the same time, which dramatically reduces the amount of "greenhouse" gases released into the environment [5].

The process of biomass pyrolysis is a high-temperature thermochemical process, in which the average temperature regime is 500÷700 ℃. Biomass is one of the classic renewable energy sources, which can be processed into solid, gaseous and liquid alternative fuels. By processing biomass, it is possible to firstly dispose of agricultural and local organic waste, secondly to obtain cheap fuel, and thirdly to reduce the amount of toxic gases released into the atmosphere. Possibilities of using biomass for energy purposes provide energy, environmental and economic benefits at the same time [6].

Currently, it is important to use solar concentrators to use solar energy in technological processes that require high temperatures. In recent years, in the world and in Uzbekistan, scientific research on the use of solar energy in various technological processes has been conducted and practical results have been achieved. The analysis of devices for obtaining energy from biomass shows that it is necessary to solve problems such as reducing the energy capacity of the raw material processing process, optimizing the energy balance of the device, and increasing its energy efficiency [7-19].

The purpose of the study is to model the heat balance of the reactor of the heliopyrolysis device with a solar concentrator and justify the thermal technical parameters.

2 Materials and methods

Reducing the energy used for self-extraction in pyrolysis devices is one of the main problems. Because in order to ensure the required (350-500 ℃) temperature regime in the reactor, energy (heat) must be spent initially. It is usually done by using coal, natural gas or electricity as an energy source for the processes carried out in the pyrolysis device. The reason is that it takes a lot of heat energy to break down biomass waste. Additional heating of biomass requires excessive energy consumption. This problem can be solved by fully covering the required energy with solar energy during daytime operation.

The method of effective use of solar concentrators for biomass heliopyrolysis is considered in this research work. Taking into account the solar energy potential of the region, the principle scheme of the pyrolysis device for the thermal processing of biomass was created (Figure 1).

Production of biofuel from biomass in a heliopyrolysis device includes the following technological processes. The heliopyrolysis device consists of the main reactor 1, the moving pipe 2 of the gas mixture separated from the biomass, the heat exchanger 3 and the parabolic concentrator 12. The heliopyrolysis device is mainly designed for obtaining biofuels from biomass. Sunlight is concentrated in the parabolic concentrator 12 and heats the biomass inside the reactor. When the temperature inside the reactor rises above 300-350 ℃, biogas is released from the biomass. As biogas moves through pipe 2 and passes through the center of parabolic cylindrical concentrator 13, the speed of movement increases and its pressure is measured by manometer 17. Biogas goes to condenser 3. Incoming 10 and outgoing water pipes 11 are connected to the heliopyrolysis condenser, where the biofuel separated from the biomass is condensed. The part of biofuel separated into gas is first passed through the water filter 7, then through the activated carbon filter 8 and collected in the gas holder 9. The liquefied part of the fuel passes through the screw 14-

15-16 and is collected in the tank. The use of the heliopyrolysis device in Kashkadarya, Surkhondarya, Bukhara and Samarkand regions of our Republic with hot climate conditions gives effective results and allows saving fuel and energy resources.
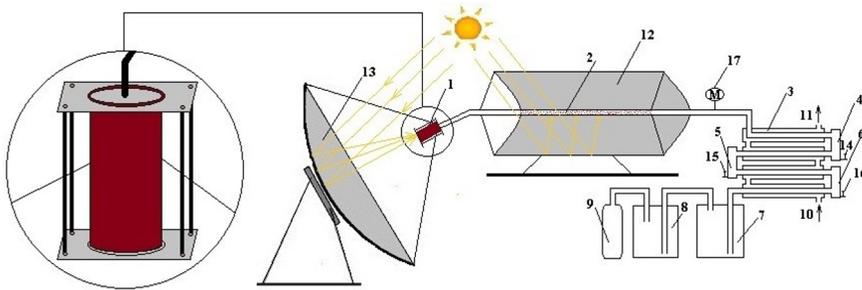
1-helipyrolysis reactor; 2- gas mixture movement pipe; 3- heat exchange device (condenser); 4- 1st condensing unit; 5- 2nd condensing unit; 6- 3rd condensing unit; 7- water filter; 8-active carbon filter; 9- gas holder; 10- cold water inlet; 11-hot water outlet; 12-parabolic cylindrical concentrator; 13-parabolic concentrator; 14, 15, 16-screw; 17-manometer.

Fig. 1. The principle scheme of the helipyrolysis device.

In this research work, the theory of heat-mass exchange of thermal engineering and solar devices and methods of calculating heat balance equations were used.
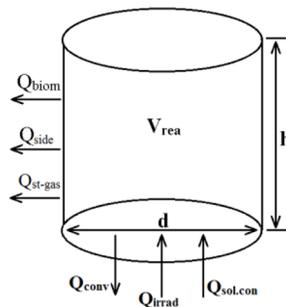
We can construct a mathematical model of the heat balance equation for a heliopyrolysis reactor as follows:

$$Q_{\text{sup}} = Q_{consum} \tag{1}$$

$$Q_{\text{sup}} = Q_{reac} + Q_{irrad} \tag{2}$$

$$Q_{con} = Q_{biom} + Q_{side} + Q_{convec} \tag{3}$$

Here, Q_{sup} − the heat supplied to the heliopyrolysis reactor, kW; Q_{consum} − heat consumed in the reactor, kW.

Fig. 2. Heat balance scheme of the heliopyrolysis reactor.

The energy supplied to the heliopyrolysis reactor is determined as follows:

$$Q_{reac} = \eta_{opt} \cdot Q_{sol.con} \tag{4}$$

The energy generated due to solar energy entering the aperture of the parabolic solar concentrator is determined as follows:

$$Q_{sol.con} = I_{irrad} \cdot F_{sol.con}$$
(5)

Here, I_{irrad} − solar radiation falling on the surface of the concentrator, W/m^2.

The aperture of a parabolic solar concentrator is determined using the following expression:

$$F_{sol.con.} = \frac{\pi d_{sol.con.}^2}{4}$$
(6)

Here, $d_{sol.con.}$ − parabolic solar concentrator diameter, m .

The optical efficiency coefficient of the concentrator is determined as follows:

$$\eta_{opt} = R_g \cdot \varepsilon_g \cdot \cos\varphi$$
(7)

Here, R_g − reflection coefficient of concentrator glass surface; ε_g − light absorption coefficient of concentrator glass surface; $\cos\varphi$ − the angle of incidence of sunlight on the surface of the concentrator.

The solar energy falling on the side surfaces of the heliopyrolysis reactor is determined as follows:

$$Q_{irrad} = F_{reac} \cdot I_{irrad}$$
(8)

Here, F_{reac} − the surface of the side surfaces of the reactor, m^2 .

The amount of heat used to increase the biomass loaded into the heliopyrolysis reactor to the temperature of the pyrolysis process is determined using the following expression:

$$Q_{biom} = \frac{c_b \cdot \rho_b \cdot V_b \cdot (t_{pyr} - t_b)}{d\tau}$$
(9)

Here, c_b − biomass heat capacity, $\frac{J}{kg \cdot {}^\circ C}$; ρ_b − biomass density, $\frac{kg}{m^3}$; V_b − volume of biomass, m^3; t_{pyr} − temperature of the pyrolysis process, °C; t_b − biomass temperature, °C.

The heat lost from the external side surfaces of the heliopyrolysis reactor is determined as follows:

$$Q_{side} = \frac{2 \cdot \pi \cdot l_r \cdot \lambda_r}{\ln\frac{d_2}{d_1}} (t_{pyr} - t_b)$$
(10)

Here, l_r − reactor length, m ; λ_r − coefficient of thermal conductivity of the reactor material, $\frac{W}{m \cdot {}^oC}$; d_2 − outer diameter of the reactor, m ; d_1 − inner diameter of the reactor, m .

Chamber of heat lost from the interior of the heliopyrolysis reactor to the environment:

$$Q_{convec} = k \cdot F_{reac} \cdot (t_{pyr} - t_{amb}) \cdot d\tau \tag{11}$$

Here, t_{amb} − ambient temperature, °C; $d\tau$ − heat exchange time.

The heat transfer coefficient for a heliopyrolysis reactor is calculated using the following equation:

$$k = \frac{1}{\frac{1}{\alpha_n} + \frac{\delta_r}{\lambda_r} + \frac{1}{\alpha_c}} \tag{12}$$

When calculating the heat lost from the glass surface in the radiation method, it is determined by the following equation:

$$\alpha_n = \frac{\sigma \cdot \varepsilon_g \cdot 10^{-8} \cdot (T_{pyr}^4 - T_{amb}^4)}{T_{pyr} - T_{amb}} \tag{13}$$

When calculating the heat lost from the reactor to the air in the convective method, it is determined by the following equation:

$$Nu = \frac{\alpha_c \cdot l_{reac}}{\lambda_{air}} \tag{14}$$

$$\alpha_c = Nu \cdot \frac{\lambda_{air}}{l_{reac}} \tag{15}$$

It is important to determine the Nu number in the process of heat exchange between the reactor devoir and the environment, and it is calculated using the following expression [20]:

$$Nu = 0,4 + 0,54 \cdot Re^{0,52} \tag{16}$$

If we take into account the wind speed in the process of heat exchange, then it is necessary to determine the Re number:

$$Re = \frac{\omega_{wind} \cdot d_{reac}}{v_{air}} \tag{17}$$

The efficiency of the heliopyrolysis device is determined as follows:

$$\eta_{reac} = \frac{Q_{reac}}{Q_{sol.con}} \tag{18}$$

If we combine equations (4), (8), (9), (10), (11) in the heat balance equations, the following equation is formed:

$$\frac{c_b \cdot \rho_b \cdot V_b \cdot (t_{pyr} - t_b)}{d\tau} = \eta_{opt} \cdot I_{irrad} \cdot \frac{\pi d_{sol.con}^2}{4} - k \cdot \frac{\pi d_{reac}^2}{4} \cdot (dt_{pyr} - t_{amb}) \tag{19}$$

From this, the equation of time dependence of the temperature formed during biomass pyrolysis is derived:

$$t_{pyr}(\tau) = \left[(2 \cdot \exp(-\frac{\pi d_{reac}^2}{4 \cdot c_b \cdot m_b} \cdot \tau) - 1) \cdot t_{amb} + \frac{I_{irrad} \cdot (\eta_{opt} \cdot d_{sol.con}^2 + d_{reac}^2)}{d_{reac}^2 \cdot k} \cdot (1 - \exp(-\frac{\pi d_{reac}^2}{4 \cdot c_b \cdot m_b} \cdot \tau)) \right] \tag{20}$$

Table 1. Paraboloid solar concentrator parameters.

Parameters	Designation	Value	Unit
Concentrator diameter	d_{cons}	1.8	m
Focus distance	f	0.7	m
Surface reflection coefficient	R_g	0.9	-
The degree of blackness of the surface	ε_g	0.1	-
Concentrator aperture	$F_{sol.con}$	1.13	m^2
Solar radiation	I_{irrad}	600-900	W/m^2
Optical efficiency coefficient of the concentrator	η_{opt}	0.7	-
Angle of incidence of light	$\cos\varphi$	45º	-
Stefan-Boltsman constant	σ	$5.67 \cdot 10^{-8}$	$W/m^2 \cdot K$

Table 2. Parameters of heliopyrolysis reactor.

Parameters	Designation	Value	Unit
Reactor volume	V_{reac}	0.003	m^3
The surface of the side surfaces of the reactor	F_{reac}	0.25	m^2
Reactor length	l_{reac}	0.2	m
Heat transfer coefficient of the reactor material	λ_r	45-50	$\frac{W}{m \cdot {}^{\circ}C}$
Reactor wall thickness	δ_r	2	mm
Inner surface temperature of the reactor wall	t_{in}	350÷500	°C
The outer surface temperature of the reactor wall	t_{out}	400	°C
Inner diameter of the reactor	d_2	158	mm
The outer diameter of the reactor	d_1	160	mm

Table 3. Parameters of biomass loaded into the heliopyrolysis reactor (wood shavings).

Parameters	Designation	Value	Unit
Biomass density	ρ_b	200÷300	kg/m^3
Mass of biomass	m_b	1.0÷2.0	kg
Biomass moisture	φ_b	20÷30	$\%$
Biomass size	d_b	2÷4	mm
Biomass temperature	t_b	18÷20	℃
Heat capacity of biomass	c_b	0.08÷0.1	$\frac{J}{kg \cdot {}^oC}$
Heat transfer coefficient of biomass	λ_b	0.45÷0.56	$\frac{W}{m \cdot {}^oC}$

Table 4. External environment parameters.

| Parameters	Designation	Value	Unit
Ambient temperature	t_{amb}	20	℃
Average wind speed	ω_{air}	2.0÷3.0	m/sek
Relative air humidity	φ_h	30÷40	$\%$
Dynamic viscosity of air	μ_{air}	18.1·10⁻⁶	$N \cdot s/m^2$
Kinematic viscosity of air	ν_{air}	15.06·10⁻⁶	m^2/sec
Heat transfer coefficient of air	λ_{air}	0.0257	$\frac{W}{m \cdot {}^oC}$

3 Results and Discussion

Heliopyrolysis method of biomass processing has a number of advantages over other methods, it is an energy efficient and environmentally friendly method. In this case, the intensity of sunlight depends on the climatic conditions of the region and the position of the sun, so it is possible to ensure uniform heating of the surface of the heliopyrolysis reactor using stationary solar concentrators. The latitude angle for the city of Karshi is 39°. As a result of meteorological measurements in the city of Karshi, the amount of solar energy falling on 1 m² of surface is 600-900 W/m². Measurement results were made during sunny hours of the day (08:00 - 17:00). The calculation results are presented in table 5.

The results of the study were taken at the GLOBAL SOLAR ATLAS site in monthly sections of the average annual solar radiation in a 24-hour time interval. The maximum average direct solar energy was 5,563 kW in August, and the minimum average value was 2,517 kW in December [21].

Table 5. Heat-technical parameters of heliopyrolysis process.

Parameters	Designation	Value	Unit
Energy absorbed in a heliopyrolysis reactor	Q_{reac}	0.84	kW
Solar energy entering the aperture of a parabolic solar concentrator	$Q_{sol.con}$	1.114	kW
Solar energy falling on the side surfaces of the reactor	Q_{side}	0.225	kW
Energy used to heat biomass	Q_{biom}	0.8	kW
Heat lost from the side surfaces of the reactor	Q_{sur}	0.071	kW
Convective heat loss from the reactor	Q_{conv}	0.08	kW
The energy lost to the steam-gas mixture released from the biomass is energy	$Q_{stem-gas}$	0.163	kW
Useful efficiency of the heliopyrolysis device	η_{reac}	0.7	$-$
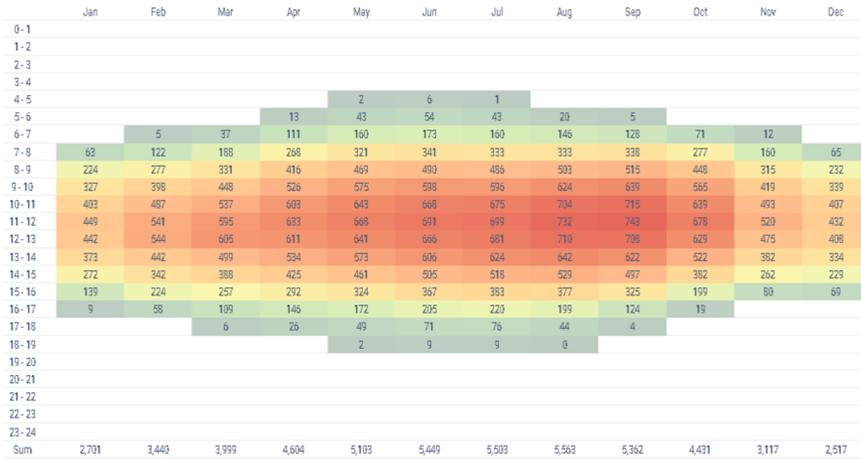
Fig. 3. Values of solar radiation in different months for the city of Karshi.
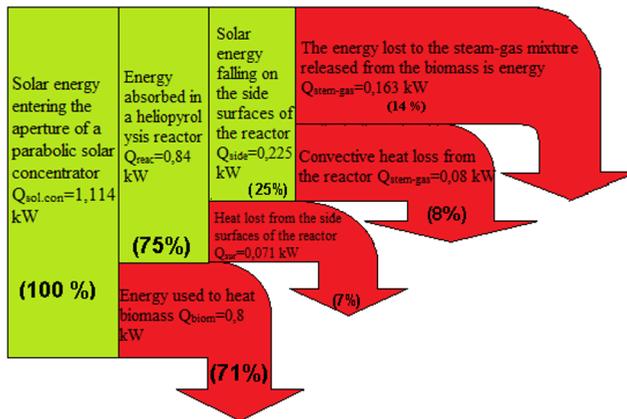
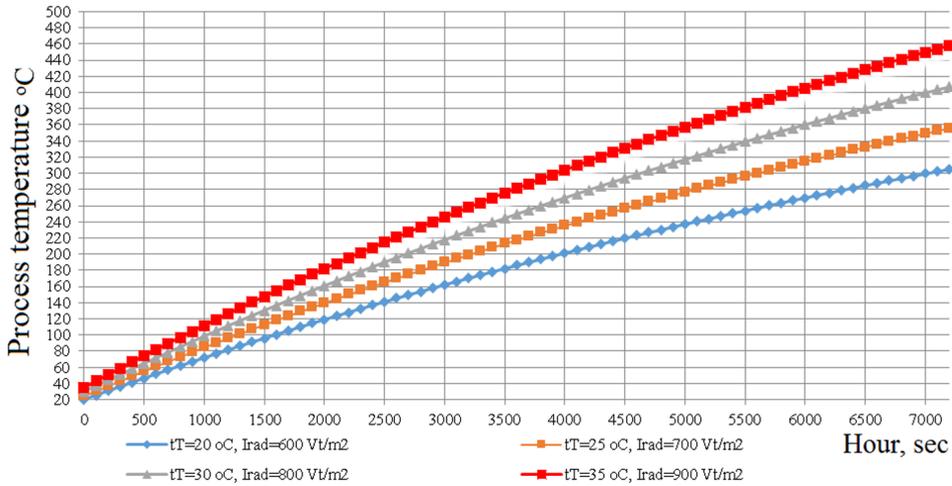**Fig. 4.** Energy balance of the heliopyrolysis plant.

Fig. 5. Graph of dependence of heliopyrolysis process on time and solar radiation.
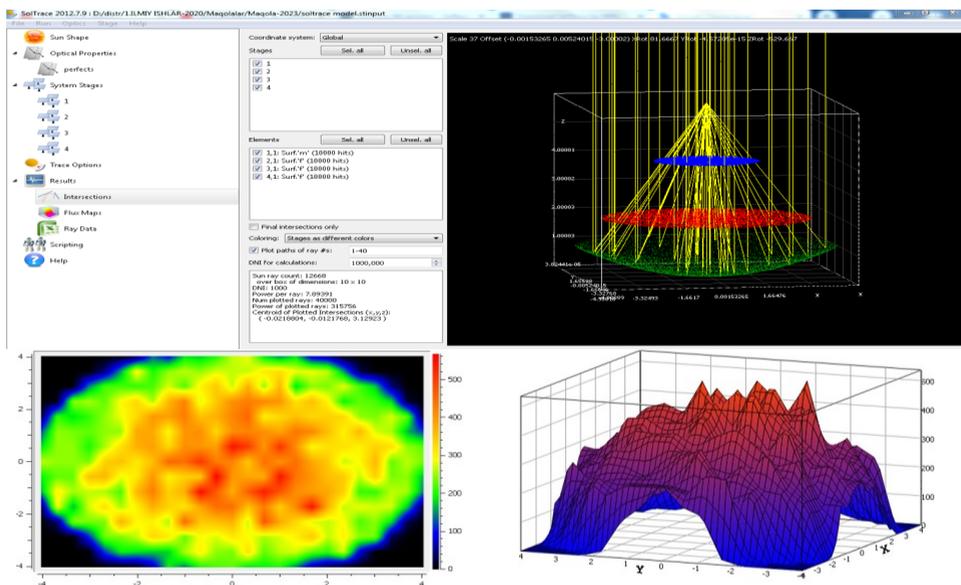

Fig. 6. A solar concentrator modeled using the SOLTRACE program and its graphs at different values.

4 Conclusion

The efficiency of biofuel production varies mainly depending on the operating temperature of the pyrolysis reactor, the type of biomass and the duration of operation. The experiments carried out in the heliopyrolysis device showed that the optical efficiency coefficient was 0,7 for raising the internal temperature of the reactor to 400 ℃ for the pyrolysis process of 2 kg of biomass with a moisture content of 20% and an aperture surface of 3 m^2 used a parabolic solar concentrator. As a result, 0,9 kW of energy was generated from biomass, which can be used for alternative fuels. By using solar concentrators in biomass pyrolysis, the amount of fuel used for the process was fully covered by the sun. The results obtained

through the experiment can be used in the design and calculation of the heliopyrolysis device.

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