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Heat and Material Balance of Heliopyrolysis Device

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Abstract. The article proposes a technological scheme for the process of obtaining alternative fuels from local biomass by the method of heliopyrolysis. Besides, the temperature regime in the reactor of the pyrolysis device and the thermal energy savings consumed for the specific needs of the device, as well as the thermal performance of the device are analyzed. It is known that reducing energy consumption in pyrolysis technology is a major challenge-because energy (heat) must first be supplied to maintain the reactor temperature regime. Typically, the processes carried out in a pyrolysis unit are carried out at the expense of coal, natural gas or electricity consumption. For the operation very large amount of thermal energy is required to decompose biomass waste, and additional heating of biomass requires excessive energy consumption. To prevent these technological problems, the article proposes a solar concentrator's heliopyrolysis system to heat the pyrolysis reactor. Applying a solar concentrator to this type of pyrolysis device can achieve a temperature of 400–700 °C. A schematic diagram of the experimental pyrolysis unit of the solar concentrator was developed, and samples of alternative fuels (pyrogas, liquid, solid fuels) were obtained as a result of thermal processing of biomass. Based on the analysis of the material balance of a heliopyrolysis plant with a parabolic-cylindrical solar concentrator, it was found that about 20 % pyrogas, 60 % liquid fuel, 8–20 % solid alternative fuel were obtained during the pyrolysis of cotton stalks with an initial biomass load of 3.76 kg. In order to determine the consumption of thermal energy in the pyrolysis process, as well as for the replaced solar energy, an analysis of the heat balance of the proposed installation was carried out. It is shown that the use of a solar concentrator makes it possible to reduce the specific energy consumption for the pyrolysis process by up to 30 %. The proposed heliopyrolysis device makes it possible to reduce the consumption of thermal energy for own needs, increase the overall efficiency of the installation and ensure a stable temperature regime for pyrolysis.

Keywords: heliopyrolysis, concentrator, pyrolysis reactor, biomass, amount of heat, enthalpy, solar radiation, thermal efficiency, alternative fuel, temperature, heat transfer coefficient, time

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Тепловой и материальный баланс гелиопиролизного устройства

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Реферат. Предложена технологическая схема процесса получения альтернативного топлива из местной биомассы методом гелиопиролиза. Проанализированы температурный режим в реакторе пиролизной установки, экономия тепловой энергии, расходуемой на конкретные нужды оборудования, а также тепловая производительность установки. Снижение энергопотребления в технологии пиролиза является серьезной проблемой. Это связано с необходимостью подвода энергии (теплоты) для поддержания температурного режима реактора, дополнительного нагрева биомассы, а также особенностями процесса разложения отходов, для которого требуется очень большая тепловая энергия. Обычно пиролиз осуществляется за счет потребления угля, природного газа или электроэнергии. В статье предложено использовать для обогрева пиролизного реактора гелиопиролизную систему с параболоцилиндрическим солнечным концентратором, что позволяет достичь температуры 400–700 °C. Разработана принципиальная схема экспериментальной пиролизной установки солнечного концентратора и получены образцы альтернативных топлив. Так, термическая переработка стеблей хлопчатника дала около 20 % пирогаза, 60 % жидкого топлива, 8–20 % твердого альтернативного топлива при загрузке исходной биомассы 3,76 кг. Рассмотрен тепловой и материальный баланс установки. Показано, что применение солнечного концентратора позволяет уменьшить удельные энергозатраты на процесс пиролиза до 30 %. Предложенная гелиопиролизная установка снижает расход тепловой энергии на собственные нужды, повышает общий коэффициент полезного действия и обеспечивает стабильный температурный режим пиролиза.

Ключевые слова: гелиопиролиз, концентратор, пиролизный реактор, биомасса, количество теплоты, энтальпия, солнечное излучение, тепловой КПД, альтернативное топливо, температура, коэффициент теплопередачи, время

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Introduction

Demand for energy is growing in Uzbekistan as a result of industrial development and population growth. According to estimates approved by the State Statistics Committee of the Republic of Uzbekistan, in 2019 Uzbekistan’s oil reserves reached 100 million tons and natural gas reserves – 1.1 trillion cubic meters, total reserves of petroleum products (diesel, kerosene, gasoline, natural gas) in the country, 4 billion tons of conventional fuel [1]. At present, 86 % of the electricity generated in the country is produced by thermal power plants, 90 % of them run on natural gas. In recent years, special attention has been paid to reducing energy consumption in production and product’s costs, as well as the introduction of mechanisms for the use of renewable energy sources. In particular, the Resolution of the President of the Republic of Uzbekistan No. PD-3012 “On the program of measures for further development of renewable energy, energy efficiency in the economy and social spheres in 2017–2021" and Resolution of the Cabinet of Ministers of the Republic of Uzbekistan dated November 25, 2015 No 343 "On measures to encourage the construction of biogas plants in livestock and poultry farms" provides comprehensive measures to ensure energy efficiency in the economy and social spheres of the country [2, 3]. The potential for the use of solar energy in the country is high, and in about 270–300 sunny days of the year (2700–3000 h) radiant energy can be used effectively for various purposes [4]. In world practice, the use of solar energy for lighting, heating, cooling, ventilation, heating and electricity generation of buildings is established. Nowadays, it is important to use solar concentrators for use in technological processes that require high temperatures from solar energy. In recent years, Uzbekistan has conducted research on the use of solar energy in various technological processes and achieved practical results [5–8].

Also in recent years, research on the use of pyrolysis devices in the production of alternative fuels from biomass shows that significant theoretical and practical results have been achieved in this area. Currently, foreign scientists are conducting research on the use of solar concentrators in the pyrolysis process. In particular, the Mexican scientist Morales studied the pyrolysis process using parabolic concentrators, but the studies did not fully explore the practical possibilities associated with the daily location of the sun and seasonal radiation levels [9]. A rapid pyrolysis system using a parabolic reflector was studied by Bangladesh scientist Joardder [10]. In China, Zeng et al. [11] proposed a two-stage heliostatic parabolic concentrator with a display system to control the heating rate and temperature of the pyrolysis reactor. Their research examined the effect of temperature (600–2000 °C and heating rate 5–450 °C/s on the productivity and properties of the hard coal obtained as a result of the process, rather than on the performance of the system during this period. A solar pyrolysis device with a two-axis tracking system was developed and tested by Lebanese scientist Zeitter using a Fresnel lens. In the process, a temperature of 550 °C was generated and pyrolysis of fuel from household waste was studied [12]. In the CIS countries, G. I. Palchenok and N. G. Khutskaya has been studied by the use of solar concentrators in biomass pyrolysis [13]. G. N. Uzakov, R. T. Rabbimov and X. A. Davlonov conducted research on the production of alternative fuels by pyrolysis from local biomass in the country [14, 15].

Materials and methods

The aim of the present study is to develop a solar concentrator heliopyrolysis device for biomass pyrolysis and to analyze heat and material balance. Taking into account the solar energy potential of the region, a technological scheme of the gelipyrolysis process for thermal processing of biomass has been created (Fig. 1).

The average temperature regime during biomass pyrolysis is 350–500 °C. Biomass raw material reserves are a very common alternative energy source, from which 1 m^3 biogas gives 21.0–27.2 MJ/m^3 of combustion heat, 0.6 liters of gasoline, 1.7 kg of wood equivalent to heat energy [16]. Reducing energy consumption in pyrolysis technology is a major challenge. This is because energy (heat) must first be supplied to maintain the temperature regime of the reactor. Typically, the processes carried out in a pyrolysis unit are carried out at the expense of coal, natural gas or electricity consumption. For the operation very large amount of thermal energy is required to decompose biomass waste, and additional heating of biomass requires excessive energy consumption.

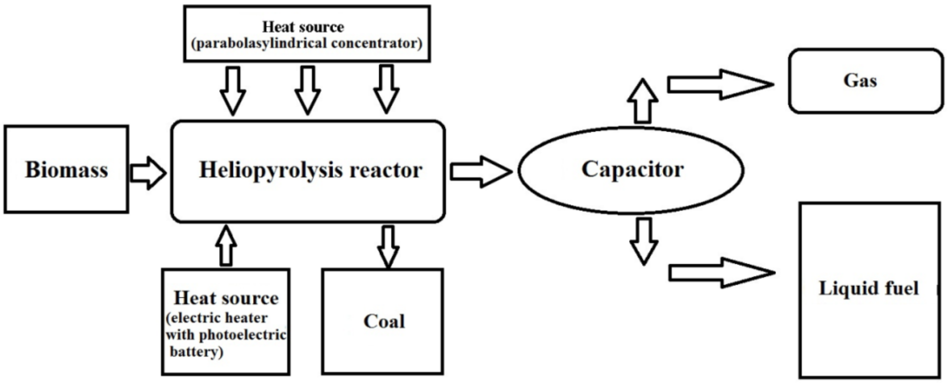

Fig. 1. Technological scheme of heliopyrolysis process

These technical and economic problems can be overcome by using a heliothermal heating system. As a result of research in this area, a method of using solar concentrators in the process of biomass pyrolysis, i. e. the method of heliopyrolysis, has been proposed (Fig. 2).

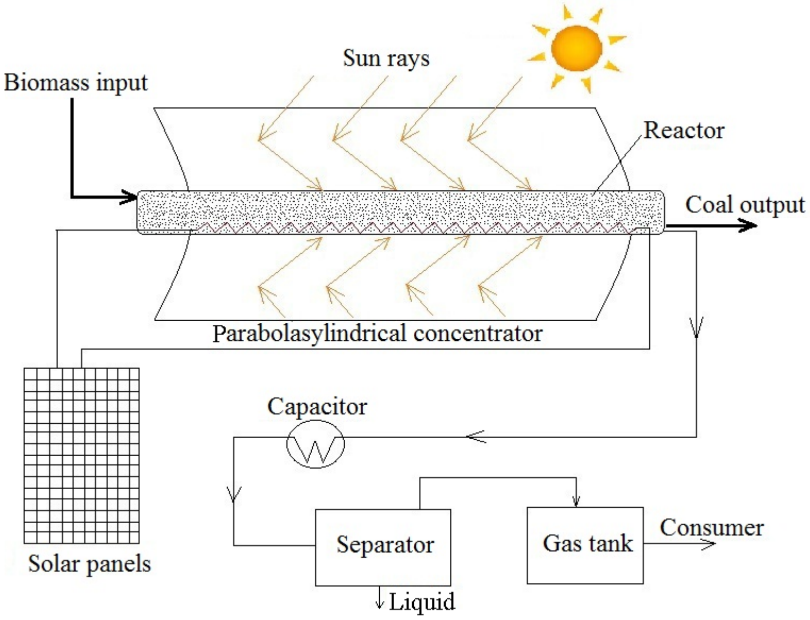

Fig. 2. Schematic diagram of a heliopyrolysis device

The solar concentrator-based heliopyrolysis device does not harm the environment and reduces the energy consumption for the process. The heat required for the process is generated by parabolacylindrical solar concentrators. The advantage of the proposed method is that the pyrolysis reactor can be continuously heated by solar energy using solar concentrators. Initially, the pyrolysis reactor is heated to a certain temperature by a solar heating system, while the pyrolysis reactor is heated continuously, i. e. during the pyrolysis cycle by a solar heating system at the same time as a conventional or electric heating system [17–19].

Fig. 3. Heliopyrolysis unit with rotary reactor and solar concentrator:
1 – parabolacylindrical concentrator;
2 – reactor; 3 – base foundations;
4 – gas outlet

It is important to study the heat balance of a pyrolysis reactor to obtain fuel from biomass by the heliopyrolysis method as it is important to heat the reactor surface with the aid of the sun and to provide heat continuously. An experimental version of a heliopyrolysis device with a rotating reactor and a solar concentrator in the proposed device is shown in Fig. 3.

The pyrolysis reaction takes place inside a stainless steel reactor. The main components of a solar pyrolysis system are the reactor, the parabolacylindrical solar concentrator, and the condenser. The reactor is heated from the outside by means of parabolacylindrical solar concentrators together with a continuous heating system. In this case, parabolacylindrical solar concentrators are used as a heat source for additional heating of the reactor. As a result, using this combined device allows obtaining heat at a temperature of 350–500 °C. Pyrolysis vapors move to the condenser through the formation of a pressure inside the reactor above the atmospheric one. Condensate (biofuel) from pyrolysis vapor accumulates in liquid collectors. The separated gas is collected in a gas holder.

In this research work, the theory of heat-mass transfer of thermal engineering and solar devices and methods of calculating heat balance equations were used.

Results and discussion

To calculate the results of experimental research on a computer, the program for modeling the device of heliopyrolysis and calculation of exergetic balance for the production of alternative fuels from biomass was developed [20].

The heat balance can be written as follows, W:

$$Q_{reak} = Q_{proc} + Q_{loss} - Q_{sol.en} - Q_{elec}. \qquad (1)$$

The amount of heat required to increase the temperature of the loaded biomass to the value of the pyrolysis process Q_{proc}, W:

$$Q_{proc} = m_b c_b \left(t_{proc} - t_b\right) 3.6 \cdot 10^{-3}, \tag{2}$$

where m_b is mass of biomass, kg; c_b is biomass heat capacity, J/kg·°C; t_{proc} is temperature required for the process, °C; t_b is biomass temperature, °C.

The amount of heat released into the environment through the reactor in the process Q_{loss}, W [21–23]:

$$Q_{loss} = \frac{2\pi l\lambda\left(t_{proc} - t_{biom}\right)}{\ln\frac{d_2}{d_1}}, \tag{3}$$

where λ is thermal conductivity, W/(m·°C); l is reactor length, m; t_{proc} is the temperature required for pyrolysis, °C; t_{biom} is biomass temperature, °C; d_2 is the inside diameter of the reactor, m; d_1 is the outside diameter of the reactor, m.

Solar energy density $Q_{sol.en}$, W, in the focal zone of a parabolacylindrical concentrator [24, 25]:

$$Q_{sol.en} = 2P\,\mathrm{tg}\left(\frac{U_m}{2}\right) LRE_o, \tag{4}$$

where P is focal parameter; U_m is the angle of incidence of sunlight; L is concentrator length, m; E_o is the amount of the falling solar radiation, W/m^2; R is light reflection coefficient.

The amount of heat released from a solar-powered electric heater Q_{elec}, W [26–28]:

$$Q_{elec} = IU\tau \cdot 3.6 \cdot 10^{-3}, \tag{5}$$

where I is current strength, A; U is electrical voltage, V; τ is time, h.

If we assume that the sum of the amount of heat needed to heat the loaded biomass and the heat lost to the environment is equal to the total amount of heat used for the process Q_{total}:

$$Q_{total} = Q_{proc} + Q_{loss}. \tag{6}$$

If we consider the sum of the amount of heat generated in the solar concentrator and the amount of heat generated using an additional electric heater to be equal to the amount of heat input to the heliopyrolysis device Q_{input}:

$$Q_{input} = Q_{sol.en} + Q_{elec}. \tag{7}$$

The amount of heat required for a heliopyrolysis device is determined using the following equation Q_{demand}:

$$Q_{demand} = Q_{total} - Q_{input}, \tag{8}$$

where Q_{demand} is the amount of heat required for the process, J.

The calculation results are presented in Tab. 1 and 2.

Table 1

Reactor heat balance parameters

Raw materials (biomass)	Physico-energetic parameters of the reactor								
	Mass of biomass m_b, kg	The size of the reactor V_r, l	Thermal conductivity λ, W/(m · C)	Biomass temperature t_b, °C	Temperature required for pyrolysis t_{proc}, °C	Heat of the pyrolysis process Q_{proc}, 10^3 W	Heat loss Q_{loss}, 10^3 W	Solar energy $Q_{sol.en}$, 10^3 W	Amount of heat required Q_{demand}, 10^3 W
Wood shavings	2.70	9	45.4	40	350	6.70	3.4	2.7	7.30
Small cattle manure	4.71	9	45.4	40	350	11.68	3.4	2.7	12.12
Cotton stalks	3.76	9	45.4	40	350	9.33	3.4	2.7	10.03

Table 2

Material balance of heliopyrolysis process

Raw materials (biomass)	Loaded biomass, kg	The products of heliopyrolysis		
		Pyrogas, m^3	Liquid, l	Solid fuel, kg
Wood shavings	2.70	0.60 (22 %)	1.0 (38 %)	1.10 (40 %)
Small cattle manure	4.71	0.80 (18 %)	2.4 (52 %)	1.41 (30 %)
Cotton stalks	3.76	0.75 (20 %)	2.2 (60 %)	0.75 (18 %)

The results of a comparative study on the extraction of alternative fuels from conventional and heliopyrolysis methods from wood shavings are given in Tab. 3.

Table 3

Thermal and technical characteristics of the heliopyrolysis process

Raw materials (biomass)	Loaded biomass, kg	Biomass moisture,%	Loaded biomass temp., °C	In the traditional way				When applying a solar concentrator to the system	
				process temp., °C	process time (min)	consumable heat, kW	consumable natural gas, m^3	the heat covered by the sun, kW	saved fuel (natural gas), m^3
Wood shavings	2.70	20	40	350–500	180	10.1	0.9–1.0	2.7	0.30
Small cattle manure	4.71	15	40	350–500	180	10.5	1.0–1.2	2.7	0.25
Cotton stalks	3.76	10	40	350–500	180	10.0	0.8–1.0	2.7	0.35

The energy consumption diagram of the heliopyrolysis process is shown in Fig. 4.

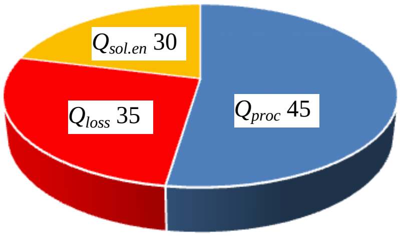

Fig. 4. Energy diagram of the process of heliopyrolysis, %

CONCLUSION

The efficiency of biofuel production varies mainly depending on the operating temperature of the pyrolysis reactor, the size of the biomass particles and the duration of operation. Experiments showed that 1.0 m^3 of natural gas was burned when the moisture content of 2.7 kg of biomass was 20 % and to raise the internal temperature of the reactor to 350 °C for the pyrolysis process to take place. At the same time, 10.1 kW of energy was used to form the pyrolysis process. The process saved 0.3 m^3 of natural gas or 2.7 kW of energy through the use of solar concentrators. The use of solar concentrators has made it possible to reduce the amount of fuel consumed for the process by 30 %. The experimental results can be used in the design and calculation of the heliopyrolysis device.

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