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Economic efficiency evaluation of applying the general-purpose heat and power plant based on the reciprocating steam engine

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Abstract. The paper presents the application perspectives of the general-purpose heat and power plant based on the reciprocating steam engine for driving various mechanisms. Renewable energy sources are used as fuel for the plant operation. The economic efficiency estimating calculation results of the proposed general-purpose heat and power plant on site are represented.

1. Introduction

One of the most significant global problems facing the modern world is the shortage of energy resources. Consequently, improving the energy efficiency and implementing the energy-saving technologies in the 1990s have become the public policy issues of the industrially advanced countries including the United States, Japan, and the European Union. Generally, the main directions of such a policy are the restrictive and incentive measures application. The first involves the introduction of relevant energy consumption standards and requirements, failure to comply with which results in fines imposed on economic entities or in the withdrawal of an operating license. The second measures (incentive) provide tax benefits to the enterprises implementing energy-saving programs. In some countries, particularly in Norway, a wide application of educational measures to promote energy-saving technologies has become the integral part of the energy efficiency policy [2]. The Russian Federation has been paying special attention to the energy saving issues [3, 4, 5]. But despite this fact, it must be recognized that currently the energy-efficient technologies are not well utilized in our country.

The European Union's reference document on best available techniques for the energy efficiency [6] lists the climate change as a result of the increased greenhouse gas emissions due to the fossil fuels burning, as well as the power system sustainability reduction due to the continued large-scale consumption of the non-renewable fossil fuel reserves as the main reasons for making the energy efficiency improvement a priority.

Hence, one of the most effective steps to improve the energy efficiency of the industrial and residential sectors is the application of the small-scale power plants consuming the renewable energy sources. In the given paper, a general-purpose heat and power plant based on the reciprocating steam engine is proposed as such a plant.

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2. General-purpose heat and power plant based on the reciprocating steam engine

In recent years, small-scale power plants and small-scale cogeneration plants based on the reciprocating internal combustion engines have been increasingly used for the uninterrupted heat and power supply to various facilities. Small-scale power plants can be equipped with steam reciprocating engines. A similar plant was previously described in paper [7].

The main advantage of the heat and power plant (HPP) based on a steam reciprocating engine is the possibility of simultaneous electricity and heat production. Another advantage is the versatility relative to the types of the used fuel, such as logging and wood residues, livestock and poultry wastes or wastes produced by other industries, firewood, coal, producer gas or peat. This makes it possible to use the cheapest and most available types of fuel in the region under consideration on the one hand and on the other hand to reduce the consumption of the fossil non-renewable energy sources. In addition, a reciprocating steam engine can drive not only a generator for producing electricity, but also other machinery: air or gas compressors, pumps.

The profitability of a thermal power plant is influenced by the factors such as the energy production efficiency, energy transportation costs and energy consumption efficiency. At the primary investigation stage, one could confirm that utilizing the proposed heat and power plant will minimize the energy transportation costs. Furthermore, using the waste steam as an energy source of various heating systems will significantly increase the efficiency of energy consumption.

Let us consider a typical circuit diagram of the HPP which is shown in figure 1.

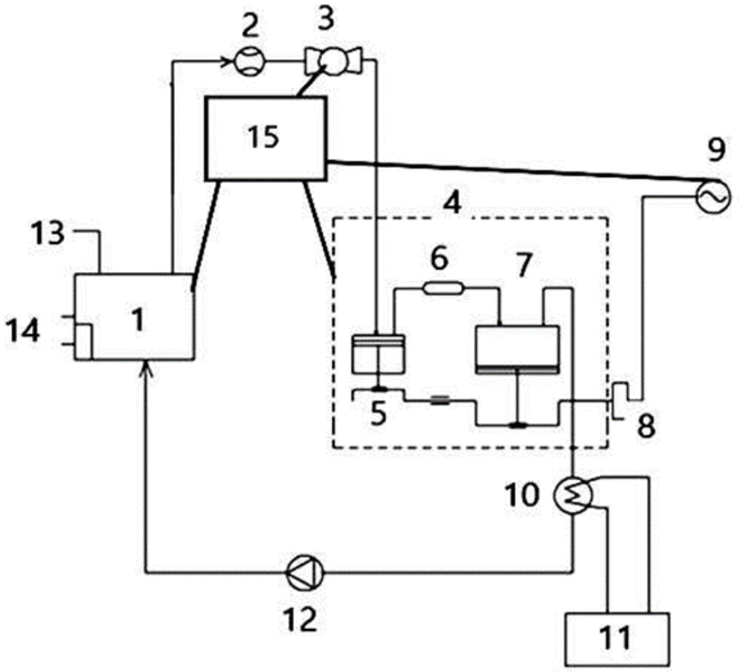

Figure 1. Typical circuit diagram of the heat and power plant: 1 is a steam boiler; 2 is a steam flow meter; 3 is a steam flow control valve; 4 is a steam reciprocating engine; 5 is a high-pressure cylinder; 6 is a steam receiver; 7 is a low-pressure cylinder; 8 is a gear unit; 9 is an electric generator; 10 is a capacitor; 11 is a heat consumer or cooling tower; 12 is a condensate pump; 13 is the air supply to the steam boiler; 14 is the fuel supply to the steam boiler; 15 is the control panel of the energy system.

The initial data on the steam reciprocating engine calculation are presented in table 1.

Table 1. The initial data on the steam reciprocating engine calculation.

No	Parameter	Designation	Measurement units	Value
1	Effective power	N_e	kW	100
2	Rotation speed	n	rpm	300
3	Input pressure	p_1	MPa /atm.	12/1.2
4	Output pressure	p_2	MPa/atm.	0.15/1.5
5	Superheated steam temperature before SRE	t_1	K/°C	596/323
6	Steam temperature after SRE	t_2	K/°C	383/110
7	Steam flow rate	G_{steam}	kg/h	1600
8	Number of high-pressure and low-pressure cylinders	i_c	ea	2

Design parameters of the steam reciprocating engine were defined on the basis of the thermal calculation, the results being presented in table 2.

Table 2. Design parameters of the steam engine main dimensions.

No	Parameter	Designation	Measurement units	Value
1	High-pressure cylinder diameter	D_{hpc}	mm	289
2	Low-pressure cylinder diameter	D_{lpc}	mm	442
3	Rod length	L_r	mm	875
4	Crank radius	R_c	mm	175
5	Gear ratio	i	ea	5

In addition to defining the parameters presented in the table, the calculations of the piston rods stability, hold-down studs strength and other calculations were performed.

3. The economic efficiency determination of the general-purpose heat and power plant application

The economic efficiency of the general-purpose heat and power plant application was assessed based on comparing the thermal energy production cost in the district heating network and the thermal energy production cost when using the general-purpose heat and power plant.

The type of fuel used has a significant impact on the results obtained. The most promising is the utilization of the renewable energy sources, such as wood and its processing residues (branches, bark, twigs), peat, agricultural wastes of plant or animal origin. Every year in Russia about 150 million cubic meters of wood are harvested, and more than 30 million cubic meters of wastes are produced when harvesting and processing. Using the residues as fuel is a promising area due to the low cost on the one hand, on the other hand it will allow to reduce the consumption of non-renewable fuels. Another promising type of fuel is peat [1]. Combustible municipal solid wastes can also be used as fuel, which will help to solve the problem of their disposal.

One should note that the application of a gas generator as part of the HPP is a promising area, thereby simultaneously enabling to influence the environmental situation in the nearby region. The given configuration of the heat and power plant requires conducting a special study, and the economic efficiency of such a plant will primarily depend on the specific type of fuel burned in the gas generator, obtained composition of the producer gas and its calorific value. Thus, the region characteristics will have a significant impact on the economic efficiency of the mentioned plant configuration. However, it can be affirmed that in any case the efficiency will be quite high taking into account the required costs of the household wastes disposal by other methods.

When calculating the economic efficiency of the heat and power plant considered in the paper, to increase the validity of the results obtained, the most common variant, namely maple firewood with the calorific value of 1600 kcal/dm^3 and specific weight of 0.65 kg/dm^3 was used as fuel.

The configuration of the heat and power plant will depend on its purpose at the site. The economic efficiency of the general-purpose heat and power plant based on the reciprocating steam engine, the parameters and approximate configuration of which are given above, was calculated. The calculation did not take into account the economic effect of the mechanism driven by the reciprocating steam engine, since its value can only be defined for a specific object.

In determining the cost of the heat and power plant, open-source data were used. The cost of the reciprocating steam engine was calculated based on the expert assessments by comparing it with the cost of manufacturing the equipment of the same type. The costs of the equipment installation and commissioning were also taken into account. The total capital expenditures was about 16 million roubles.

Economic efficiency was calculated for a time period of one month. The required heat amount as the amount of heat needed to heat water to the boiling point, heat required to convert liquid into vapour and heat needed to superheat steam to the desired temperature, was defined on the assumption of the need to provide the superheated steam flow rate of 1600 kg/h with the boiler efficiency of 88%. The final value for ensuring the operation of the reciprocating steam engine on the projected parameters was 1.195 Gcal/hour or 860.4 Gcal/month, which corresponds to the current central heating tariff of 1.376.640 roubles per month.

Let us assess the current costs of obtaining the same thermal energy amount when operating the HPP according to the following expenditure items: the firewood cost, water system condensate flow rate cost, maintenance staff salaries, equipment maintenance cost, electricity costs for own needs (for the water-circulating pump operation, control and lighting system power).

The maintenance staff number was 8 persons working flexitime. The duties of the staff include the firewood supply, HPP mechanisms operating modes control, maintenance and other work not requiring high qualification of employees. The cost of maintenance consumables and required amount of fuel (firewood) was also taken into account.

Thus, the total operating cost was about 656 thousand roubles per month, which has the economic benefit value of about 720 thousand roubles. The payback period of the plant is approximately 1.9 years.

The proposed calculation is estimate, the economic efficiency value of the proposed plant on a case-by-case basis will depend on the performance characteristics of the operation facility and configuration of the HPP. The required manufacturing output of heat power resources, operation conditions and mode of HPP, available fuel types, driven manufacturing mechanism characteristics have the greatest influence on the economic benefit value.

4. Conclusions

The results obtained show that using the heat and power plant under consideration is highly promising, despite the preliminary nature of the calculations performed. The plant actual efficiency will significantly exceed the data obtained, since the calculation deliberately did not take into consideration the effect of the manufacturing mechanism driven by the reciprocating steam engine, the losses of heat transportation to the object under study in the centralized heating system, the possibility of using cheap fuels available on the HPP site.

An additional and very significant potential of this area is the possibility of solid domestic waste recycling using the plant under consideration. Moreover, one of the advantages of applying the proposed HPP is the cascade effect of the absence of the need to burn non-renewable fuels, as well as the environmental pollution prevention.

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