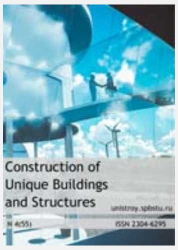

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Primary energy sources of cogeneration units

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ABSTRACT

The fuel and energy complex of Russia is going through a crisis state. The main problem is the interruptions of the power supply of remote areas. One of the most promising solutions in this situation is the development of the small power for the decentralized energy supply. A cogeneration or combined heat and power systems have a great potential in the solution of this issue. In this paper, an analysis of different energy sources of cogeneration, the prime movers, is made from the point of view of the advantages and disadvantages, both technical and operational and environmental. Depending on the existing requirements, as the primary engine could be used: the reciprocating engine (or piston engine), the steam turbine, the gas turbine, fuel cell systems and the Stirling engine. In the paper there are reviewed principle of operation, size range, electrical, thermal and total efficiencies and fuels that are used for each of these cogeneration technologies.

Content

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1. Introduction

Nowadays the fuel and energy complex of Russia is going through a crisis state. The main manifestation of the crisis lies in the fact that the disturbance and interruptions of heat, power and fuel supply of individual regions and consumers have become commonplace [1].

One of the most promising solutions in this situation is the development of the small power. A cogeneration has a great potential in the solution of this problem and also gives the opportunity for economic development of the country.

A cogeneration or combined heat and power (CHP) system produces steam that provides thermal energy to heat exchangers and mechanical energy through expansion to turbine units or generation of process heat and power. The turbine units then transfer the mechanical energy to generators, which in turn produce electricity. The principle technical advantage of cogeneration systems is their ability to improve the efficiency of fuel use in production of electrical and thermal energy. Less fuel is required to produce a given amount of electrical and thermal energy in a single cogeneration unit than is needed to generate the same quantities of both types of energy by separate conventional technologies [2]

The purpose of this work is to analyze the sources of cogeneration.

To achieve this goal it is necessary to solve the following tasks:

1. To explore the variety of cogeneration units;
2. To show the comparative characteristics of different types of cogeneration units.

Cogeneration is the use of a heat engine to generate useful heat and electricity at the same time. In other words, it is thermodynamically efficient use of fuel. In the process of cogeneration, a common production of power and heat, the energy contained in fuel is utilized to high extent that may amount up to 95% [3]. Owing to the purposeful utilization of the heat generated in the power production process, there is no need to produce this heat elsewhere. This saves both fuel and financial means necessary to purchase the heat.

CHP units are highly-efficient devices for combined production of heat and power. The waste heat generated in the power production process is purposefully used for heating or cooling. The principle of work of cogeneration unit is shown in fig. 1 [4].

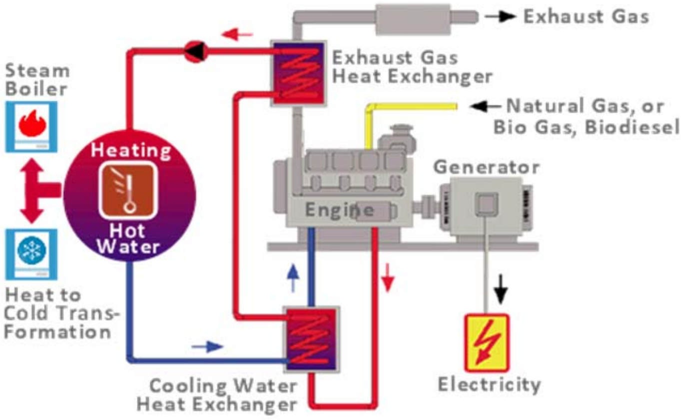

Fig. 1. The scheme of the cogeneration unit.

CHP unit consists of four main parts (see Fig.1): the primary engine, the generator, the heat recovery system and the control system.

The primary engine. Depending on the existing requirements, as the primary engine could be used: the reciprocating engine (or piston engine), the steam turbine, the gas turbine, fuel cell systems, the Stirling engine and the internal combustion engine (ICE) [5].

Electric generator. Generators are designed to convert mechanical energy of the rotating shaft of the engine into electricity. In cogeneration units there are usually used synchronous generators [6].

Heat recovery exchanger. The heat recovery exchanger is one of the main components of any cogeneration unit. The principle of its operation is based on using of energy of exhausted hot gases of the primary engine [1].

2. Materials and Methods

2.1. Research on varieties of cogeneration plants

2.1.1. The CHP plant based on reciprocating engine

Reciprocating engines, that are used in power systems, have the commensurate with the turbine efficiency in electricity generation. On the other hand, the exploitation of reciprocating engine-based cogeneration systems is complicated by the dissipation of thermal energy. The part of thermal energy is used by the engine cooling system, because the engine and oil used in lubrication system should be cooled constantly. The power to heat ratio of reciprocating engines is from 1:0.5 up to 1:1.5. Also, reciprocating engine creates low frequency noise while operating, so it should be taken into account [1, 7,8].

Reciprocating engines fall into one of two categories distinguished by their method for igniting the fuel; these are the spark ignition (Otto-Cycle) and compression ignition (Dieselcycle) engines. In the spark ignition engine, a spark plug is used to ignite a premixed air-fuel mixture after it is introduced in the cylinder. By contrast, the diesel engine compresses the air introduced into the cylinder to a high pressure (compressed) thus causing a temperature rise above the auto-ignition temperature of the fuel, which is then injected into the cylinder under high pressure.[9] Reciprocating engines are even further categorized by crankshaft speed, operating cycle (2- or 4-stroke), and whether turbocharging is used [10-18].

The vast majority of reciprocating engines are four stroke. In this type of engine, power is generated through reciprocating movements of a piston in a cylinder attached to a crankshaft, in a sequence of four strokes: intake, compression, power (or expansion) and exhaust, (Fig. 2). In the intake stroke, the piston moves downward in the cylinder and in doing so, creates a partial vacuum, which draws in air or a fuel-air mixture through an intake valve and into the cylinder. When the piston returns upward in the compression stroke, ignition takes place; in the case of the diesel engine, the fuel is injected near the end of the compression stroke and ignited by the high temperature of the compressed air in the cylinder, whereas, in spark-ignition engines, the compressed fuel-air mixture is ignited by an ignition source such as a spark plug. In the power stroke, acceleration of the piston occurs due to the expansion of the hot, high-pressure combustion gases. In the final stage of the process (exhaust stroke), the combustion products are expelled from the cylinder through an exhaust valve [10, 11].

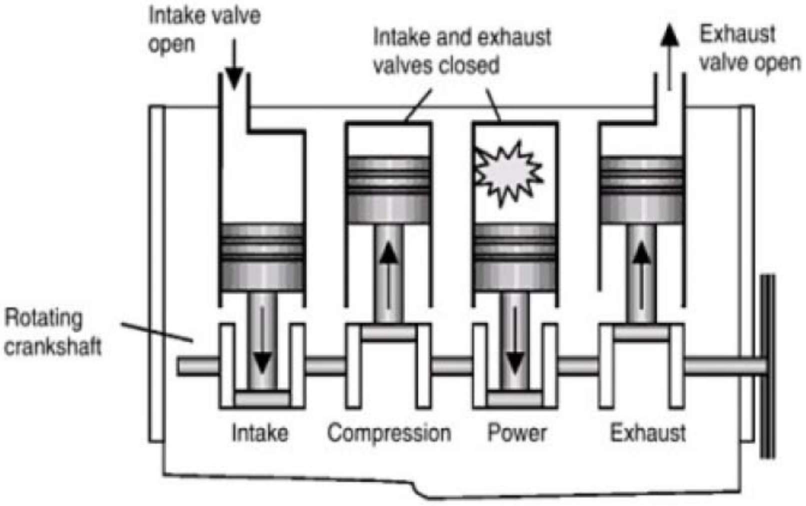

Fig. 2. Illustration of basic four-stroke internal combustion engine [9].

According to scientific research of professor Hryashchev YU.E, Ph.D, and Sokolov M.YU [19], the most efficient fuel mapping is that one with system with direct fuel injection [20]. For the stationary cogeneration plant the most perspective view of gas fuel is liquefied natural gas (methane) [21, 22].

A novel two-phase heat engine termed ‘Up-THERM’, which could be used as a CHP prime mover , was developed by Kirmse at al. [12]. They based on Glushenkov research [23].

For cogeneration the most optimal reciprocating engine-based unit is gas-piston one [1]. A typical reciprocating engine-based cogeneration system is shown in Fig. 3, which consists of an engine, generator, heat recovery system, exhaust system, controls and acoustic enclosure [10]. For the industrial cogeneration power plant are usually used gas-piston engines running on natural gas and biogas [24-38]. The efficient current range of electrical power of gas-piston units is conditional from 1 to 12 MW [1].

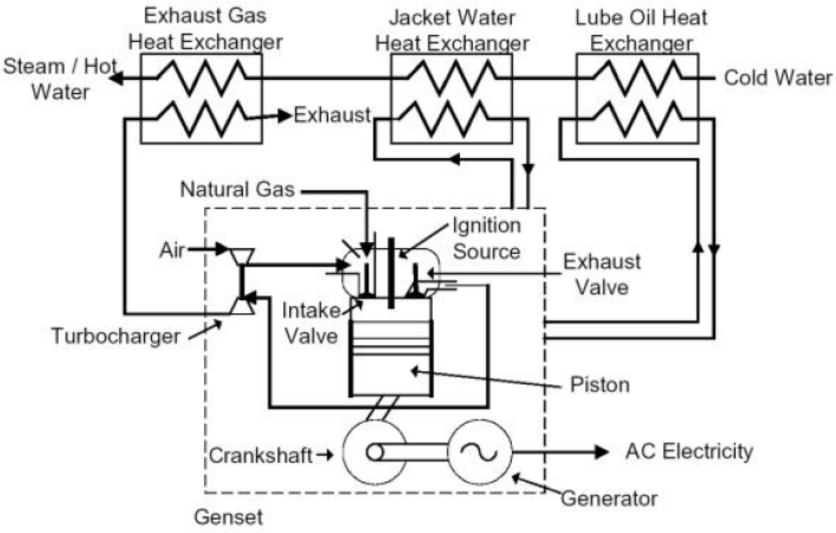

Fig. 3. Illustration of Reciprocating Engine Based Cogeneration System [39].

2.1.2. The steam turbine-based CHP plant

Steam turbines have been used as a primary engines of industrial cogeneration power plants for many years. The steam, generated in steam boiler, expends and passes through the turbine blades under high pressure. The turbine rotates and produces the mechanical energy, that is transformed by the generator into electrical energy [1, 11, 40,].

Electric power of the system depends on differential pressure of the steam at the inlet and outlet of the turbine. The efficiency coefficient of the steam turbine in electricity generation is the lowest of all the technologies (from 7 to 20%) [1]. However, the total efficiency in combined heat and power can reach 80% based on a conventional unit of fuel consumed (caloric value) [11,35]. From this it follows that it is advisable to use steam turbines in areas where thermal energy demand is much higher than in electric.

There are two types of steam turbines [1]:

1. The steam condensing extraction turbine (the outlet steam pressure of the turbine is below atmospheric) (Fig.4).
2. The steam back-pressure turbine (the outlet steam pressure of the turbine is above atmospheric) (Fig.5);

In the figures 4 and 5 the following notation is used: F – fuel, ST – steam turbine, E – electicity, H_{CHP} – useful heat from cogeneration.

The additional condenser in steam condensing extraction turbines increases the electrical efficiency, but also is difficult to be used in low potential heat [1,41].

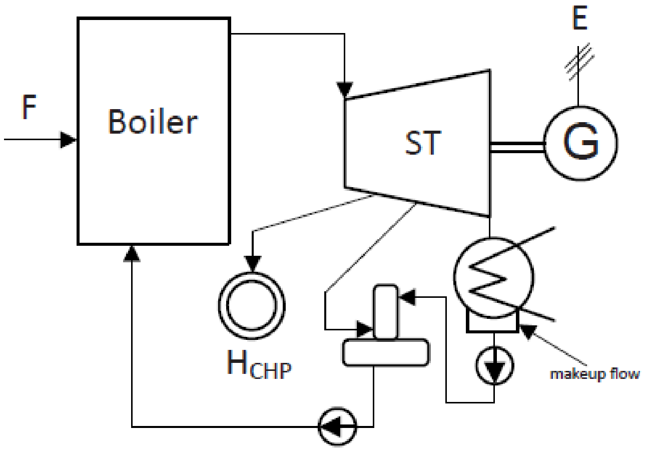

Fig. 4. Steam condensing extraction turbine-based plant

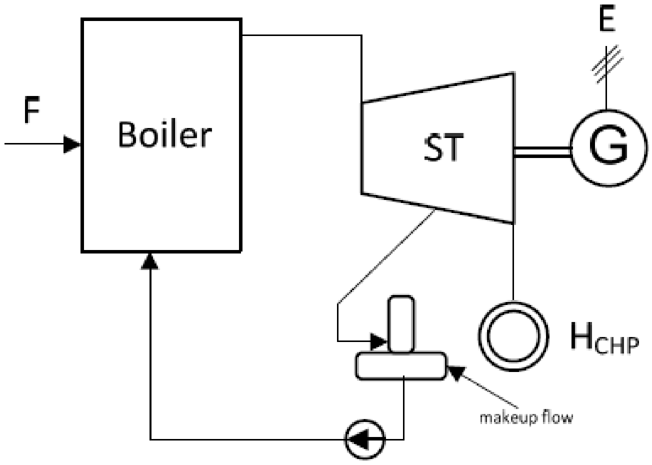

Fig. 5. Steam backpressure turbine

The performance assessment of both types of steam turbines was made by M. Gambini and M. Velini [42,43].

2.1.3. The cogeneration plant based on gas turbine

Gas turbines became popular in the market in the 90s after the transition to gas fuel in the energy sector. Despite the fact that the maximum efficiency is achieved at capacities of between 5 and 250 MW, some manufacturers produce models in the range of 1-5 MW [1].

The principle of operating of gas turbines is as follows: gas, injected into the combustion chamber of the compressor, is mixed with the air, forming a fuel mixture, and ignited. The resulting products of combustion of high temperature pass through the turbine blades and make the turbine rotate. The mechanical energy is transferred through the shaft to the step-down gearbox electric generator. The thermal energy of exhaust gases comes from the turbine to the heat exchanger. In the Fig. 6 is the scheme of gas turbine with heat recovery, where the following notation is used: F – fuel, GT – gas turbine, E – electricity, H_{CHP} – useful heat from cogeneration, HRSG – heat recovery steam generator [11, 40].

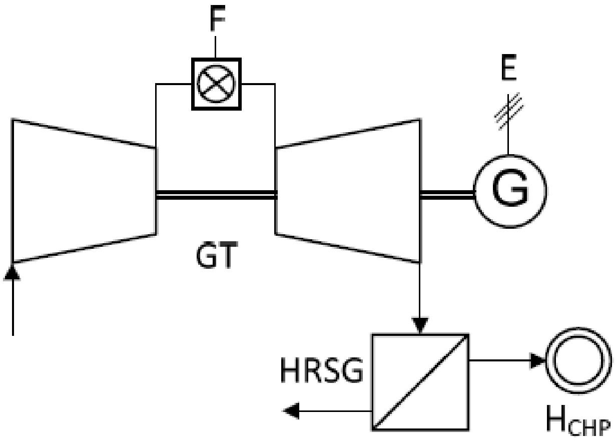

Fig. 6. Gas turbine with heat recovery

For the gas turbines it is usually used natural gas and other types of gaseous fuel. Also gas turbines have high requirements to quality of fuel preparation (mechanical inclusions, humidity)[43-46].

The efficiency of gas turbine is 25 – 35%, depending on the parameters of a particular model of turbine and fuel characteristics. As part of cogeneration systems, the total efficiency increases to 90% based on a conventional unit of fuel consumed (caloric value). The performance assessment of gas turbine is presented in the paper [42].

The operating of gas turbines is accompanied by a high level of noise, so they are usually used in industrial type buildings [48].

2.1.4. Microturbines

Microturbines are miniaturized versions of combustion gas turbines; both being mass flow devices and are thermodynamically the same. They were initially developed in response to the need for light-weight, compact, high-powered generators in the military and aerospace industry. Much of today's microturbine technology was derived from automotive and truck turbocharger technologies, small jet engines, and auxiliary power units used for ground power for aircraft [10, 49].

Microturbines produce both heat and electricity on a relatively small scale, which typically range between 25kW and 500kW and efforts are being made to produce smaller power outputs of a few kilowatts [10, 50-53].

2.1.5. The cogeneration plant based on Stirling engine

The Stirling engine was patented in 1816 by Robert Stirling [54, 55], and the first solar application of record was by John Ericsson in 1872 [55]. Since its invention, prototype Stirling engines have been developed for automotive purposes; they have also been designed and tested for service in trucks, buses, and boats [55]. The Stirling engine has been proposed as a propulsion engine in passenger ships and road vehicles such as city buses [55, 56]. The Stirling engine has also been developed as an underwater power unit for submarines, and the feasibility of using the Stirling engine for high-power systems has been explored by NASA. However, the Stirling cycle engine is well suited for stationary power and domestic use [57].

Stirling engines can be operated on a wide variety of fuels, including all fossil fuels, biomass, solar, geothermal, and nuclear energy [58-60], with external combustion that facilitates the control of the combustion process and results in low air emissions, low noise and more efficient process [61]. The most outstanding feature of the Stirling engine is its ability to work at low temperatures, namely below the temperature of boiling water [62]. More precisely, even the temperature of the human body is sufficient to put the engine into motion. Such a kind of an engine can use low temperature energy sources that are widespread in nature: the hot water from solar collectors, geothermal water, hot industrial wastes [63].

In the ideal Stirling engine cycle [55, 64], a working gas is alternately heated and cooled as it is compressed and expanded. The working fluid is contained in the motor and the mass of the fluid remains constant [65]. Gases such as helium and hydrogen, which permit rapid heat transfer and do not change phase, are typically used in the high-performance Stirling engines [55,65]. Also, air is used as working fluid [62,66, 67].

The Stirling engines are often used in the electricity generating condensing boilers [68]. The Stirling engines are 15-30% efficient in converting heat energy to electricity, with many reporting a range of 25 to 30% [66]. Since these engines show high thermal efficiencies they are most suitable for CHP systems and CCHP systems (Combined Cooling, Heating and Power) [69-81].

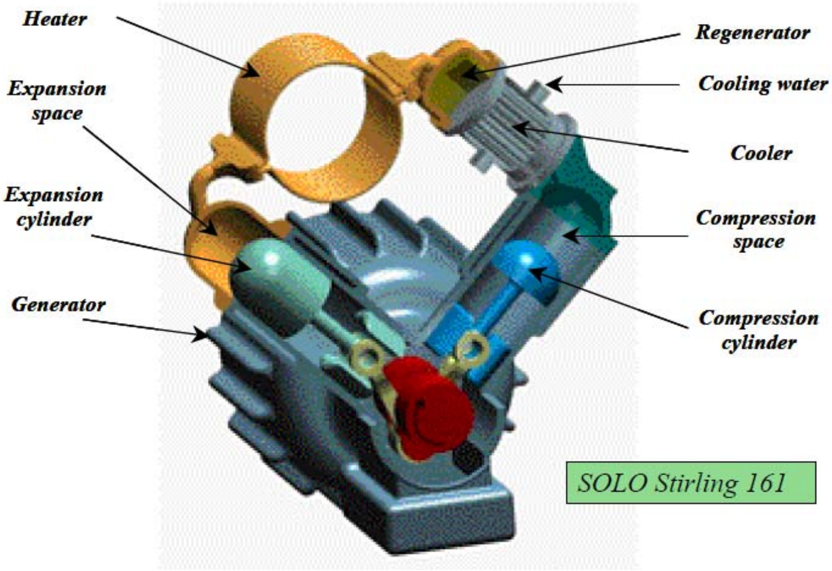

Fig.7. The module Solo Stirling V161 [84]

One of the first manufactures that applied the Stirling engine for micro-cogeneration was Stirling Power System. They used the V160 engine, which was developed in Sweden to actuate heat pumps [82]. After successful experiments with SPS V160, Solo Kleinmototen GnbH company created a new engine Stirling V161(Fig. 7) [82]. For this engine was developed absolutely new combustion system fuel based on Flox-method (company-developer – WS Waermeprozesstechnik) [83]. It has the electrical efficiency 22-24,5%, the thermal one – 65-75% , and the total efficiency – 92-96% [80].

The serial production of micro-CHP Solo Stirling was started in 2003. The know-how of this CHP plant is known to a limited circle of specialists, that does not allow to expend production. However, in the near future it is planned to increase the production volume [84, 85].

2.1.6. Fuel cells

Although the principle on which fuel cells operate have been known for more than 150 years, their commercial success and widespread adoption has been hindered by cost and durability issues. Nevertheless, practical applications of fuel cells have been demonstrated in niche applications such as space flight and cogeneration [86, 87]. Fuel cells use electrochemical reactions to produce the chemical energy stored in a fuel into electricity and thermal energy. They are similar to batteries in that they contain electrodes and an electrolyte to enable the electrochemical production of electricity. However, they differ from each other in that they are not storage devices but can only produce electricity continuously so long as fuel and an oxidant (usually air) is supplied [10, 40, 88-91].

3. Results and Discussion

In the Table 1 the main results of the analysis are shown.

Table 1. Performance characteristics of cogeneration units reviewed [1, 63, 92-96].

Engine	Steam turbine	Gas turbine	Reciprocating engine	Stirling engine	Fuel cells
Size range, MW	1 – 1000	0.25 – 300	0.003 – 20	0.005 – 0.5	0.001 – 10
Power to heat ratio	1:3 – 1+:8	1:1.5 – 1:5	1:0.5 – 1:3	1:6	1:1.6 – 1:2.4
Electrical efficiency, %	7 – 20	25 – 42	35 – 45	15 – 30	25 – 60
Total efficiency, %	under 80	65 – 87	65 – 90	under 91	60 – 95
Fuels	Any kind	Gas, biogas, diesel fuel, kerosene	Natural gas (NG), biogas, diesel fuel, kerosene	Any kind	Hydrogen, NG, landfill gas, methanol

Table 2. Summary of advantages and disadvantages cogeneration technologies reviewed [92-94, 97, 98]

Engine	Advantages	Disadvantages
Steam turbine	• Lowest first cost of all cogeneration systems • Low cost fuel for electricity production	• The lowest electrical efficiency of all the technologies
Gas turbine	• High reliability • No cooling required • Can utilize waste fuels • "High-energy" output of thermal energy	• Relatively low electrical efficiencies • High requirements to quality of fuel preparation

Engine	Advantages	Disadvantages
Reciprocating engine	• Low first cost • High efficiencies at part load operation • High reliability • Fuel versatility • Short start-up times to full loads	• Limited to lower temperature cogeneration applications • High maintenance costs • Must be cooled even if recovered heat is not used • High levels of vibrations and low frequency noise • Requires frequent maintenance intervals • Relatively high air emissions
Stirling engine	• Relatively few moving parts, mechanically simple • Low noise and vibration-free operation • Low maintenance, and high reliability • Long life • Fuel versatility including solar power • Low emissions	• High cost • Low electrical efficiency
Fuel sells	• No moving parts, except fans • Quiet operation • High electrical efficiencies under varying loads • Low emissions • Modular designs	• High cost • Fuels requiring processing unless pure hydrogen is used • No existing infrastructure for large-scale supply of hydrogen

4. Conclusions

In this work, an energetic analysis of the sources of cogeneration was accomplished. The paper aimed at the presentation of advantages, disadvantages and main characteristics of different cogeneration technologies. In Tables 1 and 2 the maim results of work are shown. According to the research:

1. It is reasonable to use steam turbines in areas where thermal energy demand is much higher than in electric one because of its low electrical efficiency;
2. The maximum efficiency of gas turbines is achieved on larger capacities, so it is rational to use them for large scale cogeneration;
3. The electric efficiency is better for micro-CHP systems with reciprocating engines followed by Stirling engines. The thermal efficiency is better for micro-CHP systems with Stirling engines with reciprocating engines being in the second place;
4. Fuel cells have the highest electrical efficiency, but because of its costliness they are unlikely to appear on the market in the near future.

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Первичные источники энергии когенерационных установок

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ИСТОРИЯ

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КЛЮЧЕВЫЕ СЛОВА

Тонкостенные оцинкованные стальные профили;
термопрофиль;
коррозия;
испытания на коррозию;
лакокрасочное защитное покрытие.

АННОТАЦИЯ

В настоящее время топливно-энергетический комплекс России находится в кризисном состоянии, проявляющемся в нарушении снабжения топливом, электрической и тепловой энергией отдельных регионов и потребителей. Одним из наиболее перспективных решений данной проблемы является развитие малой энергетики. Большим потенциалом здесь обладает когенерация – процесс совместной выработки электрической и тепловой энергии. Когенерационная установка (КГУ) является оборудованием с высоким коэффициентом полезного действия (до 95%), позволяющим значительно повысить эффективность использования топлива, снизить вредные выбросы в атмосферу и уменьшить затраты на передачу электроэнергии. В качестве первичных источников энергии (первичных двигателей) на когенерационных установках применяются газопоршневые двигатели, газовые и паровые турбины, двигатели Стирлинга и топливные элементы. В статье рассмотрены принцип действия, диапазон мощностей, электрический, тепловой и общий коэффициенты полезного действия, используемые виды топлива и выявлены достоинства и недостатки каждой из перечисленных когенерационных технологий.

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