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RATIONAL AREAS OF USING THERMOELECTRIC HEAT RECUPERATORS

An analysis of the literature devoted to the methods of recovery of waste heat from various energy-intensive devices is presented. A comparative analysis of existing methods of recuperation of low-temperature waste heat is presented – the conventional and organic Rankine cycles, the Kalina cycle, etc. The characteristics of the existing thermoelectric heat recuperators are given, as well as the analysis of the possibilities of their further development and the most rational areas of their application.
Key words: recuperator, waste heat, efficiency, power, specific cost.

Introduction

General characterization of the problem. Most types of equipment for technological processes in industry, heat engines (turbines, internal combustion engines, etc.) disperse a huge amount of heat waste during their operation. At the same time, more than half of this heat is not only not used in any way, but also leads to negative consequences for the environment – to its thermal pollution [1 – 4].

Table 1 shows the main sources of waste heat and their characteristic temperatures. Waste heat is conventionally divided into three groups according to the temperature range [5]:

- high-temperature (> 650 °C);
- medium-temperature (230 – 650 °C);
- low-temperature (< 230 °C).

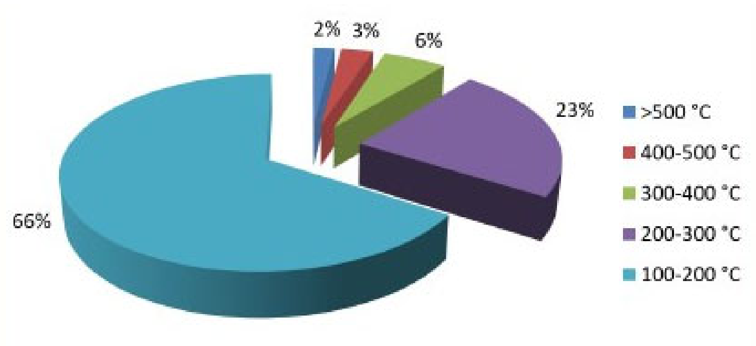

Fig. 1. Distribution of waste heat sources by temperature range [6].

Wherein, as can be seen from the diagram shown in Fig. 1, the majority of thermal waste (more than 66 %) falls in the low-temperature range [6]. Another 23 % of waste heat has a temperature of up to 300 °C. This temperature range is favourable for heat recovery through thermoelectric conversion of thermal into electrical energy.

At the same time, other methods of heat waste recovery work at such temperatures, including the generation of electrical energy through mechanical work.

Therefore, *the purpose of the work* is to analyze the possibilities of practical use of thermoelectricity for heat waste recovery and to determine the most rational areas for this, where thermoelectric energy conversion has a competitive advantage over other methods.

Table 1

Main sources of thermal waste and their temperature range [5].

Sources of thermal waste		Temperature range, °C
High-temperature waste heat (> 650 °C)	Nickel processing furnace	1.370 – 1.650
	Steel electric arc furnace	1.370 – 1.650
	Basic oxygen furnace	1.200
	Aluminum reverberation furnace	1.100 – 1.200
	Copper refining furnace	760 – 820
	Steel heating furnace	930 – 1.040
	Copper reverberation furnace	900 – 1.090
	Hydrogen installations	650 – 980
	Incinerators	650 – 1.430
	Glass melting furnace	1.300 – 1.540
	Coke oven	650 – 1.000
	Iron dome	820 – 980
Medium-temperature waste heat (230 – 650 °C)	Steam boiler exhaust	230 – 480
	Gas turbine exhaust	370 – 540
	Piston engine exhaust	320 – 590
	Ovens for heat treatment	430 – 650
	Drying and baking	230 – 590
	Cement kiln processes	450 – 620
Low-temperature waste heat (< 230 °C)	Exhaust gases from recovery devices in gas boilers, ethylene furnaces, etc	70 – 230
	Process steam condensate	
	Cooling water from:	50 – 90
	oven door	
	annealing furnaces	30 – 50
	air compressors	70 – 230
	internal combustion engines	30 – 50
	air conditioning	70 – 120
	Ovens for drying, baking and hardening	30 – 40
	Hot processed liquids / solids	90 – 230
		30 – 230

1. Traditional methods of waste heat recovery

1.1. Generation of electrical energy through mechanical work

The Rankine cycle [7, 8]. The most commonly used system for generating electricity from waste heat involves using the heat to generate steam, which then drives a steam turbine. The scheme of waste heat recovery with the Rankine cycle is shown in Fig. 2.

The conventional Rankine cycle is the most efficient option for the utilization of waste heat from exhaust gas streams at temperatures above 340 – 370 °C.

At low waste heat temperatures, steam cycles become less economical, as low-pressure steam will require more bulky equipment. Moreover, the low temperature of the waste heat cannot provide sufficient energy to superheat the steam, which is a requirement to prevent steam condensation and erosion of the turbine blades. Therefore, low-temperature heat is better suited for the organic Rankine cycle or the Kalina cycle, which use liquids with lower boiling points compared to water.

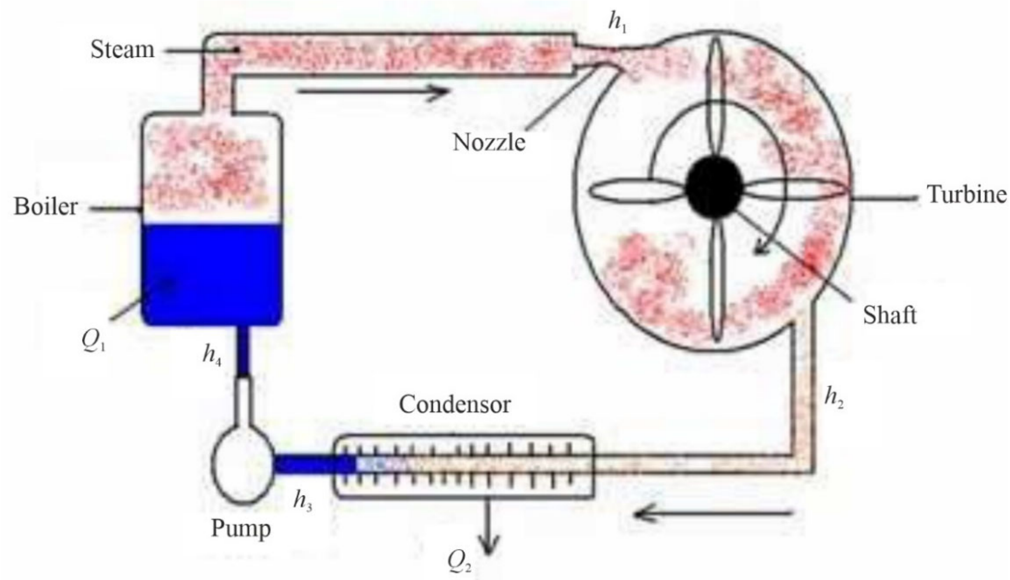

Fig. 2. Waste heat recovery according to the Rankine cycle.

The organic Rankine cycle – ORC [7, 9 – 11] operates similarly to the steam Rankine cycle, but uses an organic working fluid instead of steam. Options include silicon oil, propane, haloalkanes (such as "CFCs"), isopentane, isobutane, and toluene, which have lower boiling points and higher vapor pressures than water. This allows the Rankine cycle to operate at much lower waste heat temperatures - sometimes as low as 65 ºC. The most appropriate temperature range for an ORC will depend on the fluid used, as the thermodynamic properties of the fluids will affect cycle efficiency at different temperatures.

Compared to steam, the fluids used in ORCs have a higher molecular weight, allowing for compact designs, higher mass flow, and higher turbine efficiency (up to 80 – 85 %). However, since the cycle operates at lower temperatures, the overall efficiency is only about 10 – 20 %, depending on the condenser and evaporator temperatures. Although this efficiency is much lower than that of a high temperature steam power plant (30 – 40 %), it is important to remember that low temperature cycles are less efficient than high temperature cycles. Efficiency limits can be expressed by the Carnot efficiency - the maximum possible efficiency of a heat engine operating between two temperatures. A Carnot engine operating with a heat source at 150 ºC and releasing it at 25 ºC is only 30 % efficient. In this light, an efficiency of 10 – 20 % is a significant percentage of the theoretical efficiency, especially compared to other low-temperature options, such as the use of piezoelectrics, which are only 1 % efficient.

The Kalina cycle [7, 11] is a variation of the Rankine cycle, which uses a mixture of ammonia and water as the working fluid. A key difference between single-fluid cycles and cycles that use dual fluids is the temperature profile during boiling and condensation. For single-fluid cycles (e.g., steam or organic Rankine cycles), the temperature remains constant during boiling. As heat is transferred to the working medium (such as water), the temperature of the water slowly rises to its boiling point, where the temperature remains constant until all the water evaporates. In contrast, a binary mixture of water and ammonia (each of which has a different boiling point) will increase its temperature during evaporation. This makes it possible to better match the thermal compatibility with the waste heat source and the cooling medium in the condenser. Consequently, these systems provide significantly greater energy efficiency.

The cycle was invented in the 1980s, and the first power plant based on the Kalina cycle was built in Canoga Park, California in 1991.

<u>*Table 2*</u>

Methods of converting waste heat into electrical energy through mechanical work [7-11].

№	Method	Efficiency	Working temperatures	Electric energy cost	Service life
1.	The Rankine cycle	20 – 30 %	> 350 °C	0.8 – 1.8 $ / W	15 – 20 years
2.	The Kalina cycle	~ 15 %	100 – 540 °C	1.2 – 1.8 $/W	20 – 30 years
3.	The organic Rankine cycle	~ 8 – 15 %	100 – 590 °C	1.4 – 2.2 $/W	20 – 30 years

A comparison of the main parameters of mechanical methods of converting the energy of waste heat into electrical energy is given in table. 2. As can be seen from the table, for successful competition in the low-temperature region, thermoelectric energy recuperators need to reach a cost of no more than $1/W.

1.2. Direct conversion of thermal into electrical energy

For the recovery of low-temperature waste heat, the most favorable among the methods of direct conversion of thermal into electrical energy is thermoelectric [12 – 16].

In addition to thermoelectric energy conversion, other technologies are being developed that allow generation of electricity directly from heat. These include methods such as thermoacoustic, pyroelectric, thermomagnetic, thermoelastic, piezoelectric, and others. [6, 7, 17 – 22]. There is no information in the literature on testing such systems in industrial heat recovery devices, although some have undergone prototype testing in applications, such as automotive heat recovery.

2. Existing thermoelectric waste heat recuperators

Based on the analysis of the literature data, it is possible to single out the currently most common areas of use of thermoelectric heat recuperators: industrial plants, internal combustion engines, thermal power plants, boilers, gas turbines, domestic heat.

2.1. Thermoelectric heat recuperators for industrial installations

It should be noted that heat recovery from stationary industrial plants (especially at temperatures below 600 K) is of great interest for thermoelectricity, as it allows to fully realize its advantages. Estimates show that only in the USA, from thousands of industrial processes, about 3300 TJ of energy is wasted annually [38, 53], part of which can be returned to the active balance with the help of direct thermoelectric energy conversion. Moreover, thermoelectric recuperators can be used not only to increase the overall efficiency of energy conversion, but also to provide backup power to the most important nodes of industrial installations, which significantly increases their reliability [110].

Today, active research is underway of the recovery of waste heat [43 – 51] from such energy-intensive industrial facilities as steel mills [26, 36 – 41, 54, 55], cement kilns [24, 27 – 35, 38 – 40, 52, 54], glass melting furnaces [38 – 40, 52], lime annealing furnaces [38, 39, 52], furnaces for the production of ethylene [38, 39], waste processing plants [104, 105], furnaces for smelting aluminum and other metals [38, 39, 52], etc.

Thus, the scientists of KELK Ltd. and JFE Steel Corporation (Japan) [36, 37] jointly created and tested a thermoelectric recuperator using waste heat from a steel furnace (Fig. 3). Its power is about 9 kW with an efficiency of 8 %.

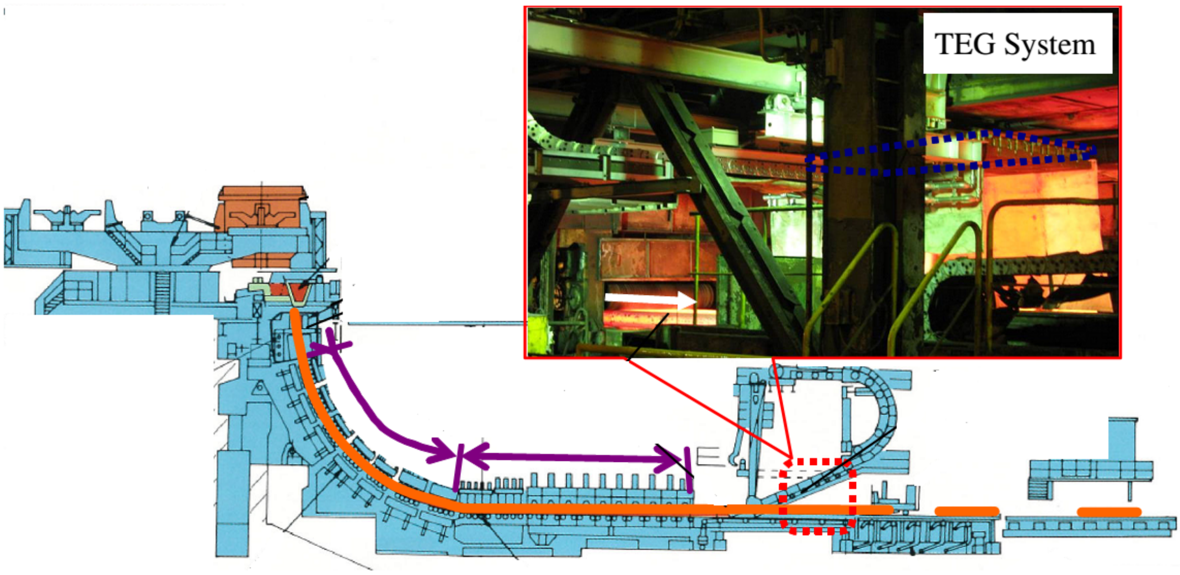

Fig. 3. Thermoelectric generator installed on steel production line of company JFE (Japan) [36].

A thermoelectric recuperator using waste heat from the kiln to produce cement was installed at the cement kiln at the Awazu plant of Komatsu (Japan) (Fig. 4). The power of such a recuperator is about 10 kW.

The waste heat recuperator of cement kilns [35] was also developed by scientists of the Industrial Technology Research Institute (Taiwan) and the Institute of Thermoelectricity (Ukraine). The peculiarity of such a generator is its placement at some distance from the rotating cement kiln, while it does not affect the technological processes inside the kiln.

A project to recover waste heat from waste recycling plants using thermoelectricity was jointly implemented by Fudzitaka (Japan) and the Institute of Thermoelectricity (Ukraine) [104, 105]. The power of one block of such a recuperator installed at the Tokio Gas plant was 1 kW.

The US Department of Energy is showing interest in the use of waste heat from various technological processes in industry. With its support, a group of works dedicated to the recovery of waste heat [38, 39, 52] from steel plants, cement furnaces, glass furnaces, lime kilns, ethylene production furnaces, aluminum and other metal smelting furnaces was created [38, 39, 52]. Economic and technical assessments of the possibility of creating such equipment are given in these works. However, it did not come to real use.

Fig. 4. Installation of thermoelectric generator on cement kiln of the Awazu plant of company Komatsu (Japan) [31].

Very interesting are the works devoted to the use of waste heat from industry using a combined method that unites thermoelectric energy conversion and the organic Rankine cycle [50, 51]. This allows increasing the conversion efficiency up to 13 %.

2.2. Thermoelectric heat recuperators from internal combustion engines

Recently, a large number of publications have been devoted to the topic of heat recovery from internal combustion engines [28, 29, 52, 56 – 103]. These are works related to the recovery of waste heat mainly from passenger car engines (Fig. 5).

In the studies of Japanese scientists [28, 29], the use of a thermoelectric recuperator that employs the thermal energy of the exhaust gases of a Suzuki motorcycle is considered. The power generated in this way is 10 W at a weight of 3 kg and does not allow talking about the prospects of its mass use.

The BMW company [63, 64] conducted a series of studies and tests of a thermoelectric energy recuperator for passenger car exhaust gases. A power of 200 W was achieved with a recuperator weight of 13 kg.

The thermoelectric recuperator manufactured by Nissan Motors [56, 61, 77] showed rather low efficiency. Its efficiency was only 0.1% at a generated power of about 36 W. However, the authors believe that increasing the efficiency to 5% under the same conditions will allow the output power to increase to 950 W.

The Hi-Z company [56, 61, 82, 83] presented the design of a thermoelectric heat recuperator installed on a GM Sierra car. The maximum power generated by such a device was 255 W with an efficiency of 2 %.

The results of research aimed at optimizing the parameters of a thermoelectric heat energy recuperator from a car engine are presented in [66]. The design power of 600 W with an efficiency of 4 – 5 % was confirmed by a series of experiments

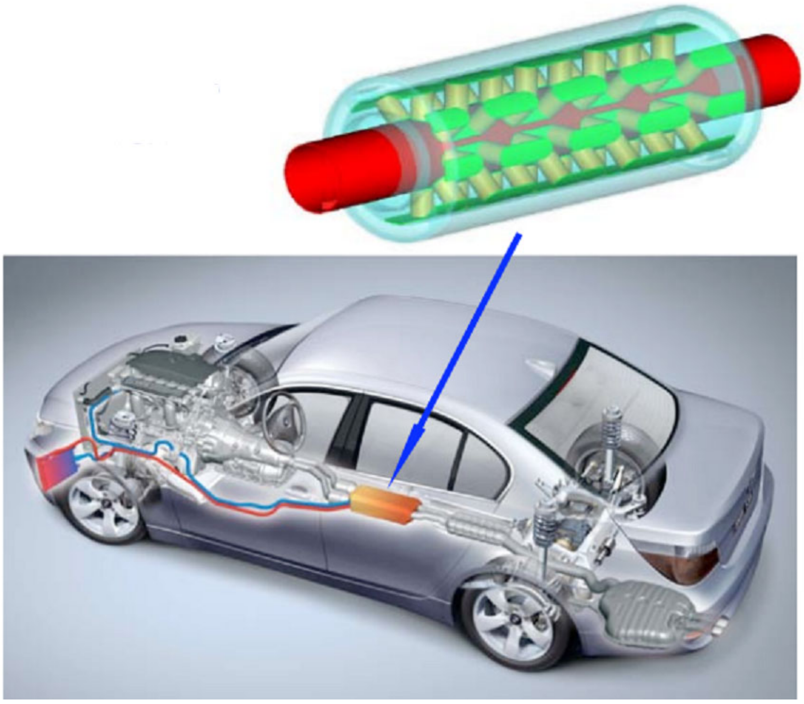

Fig. 5. Thermoelectric recuperator for cars [52].

However, it should be noted that the use of thermoelectric recuperators in passenger cars has a number of disadvantages [60, 70, 71]. The real gain in power is not significant enough. This leads to the search for more efficient applications of thermoelectricity. First of all, heat recovery from diesel engines of large ships (in addition to high power, their advantage is the possibility of heat removal from the cold side of the thermoelectric converter into the surrounding water), as well as large trucks and special equipment [75, 80, 82, 93, 97].

Thus, the Hi-Z company [61, 75, 80, 82] presented a thermoelectric energy recuperator of exhaust gases from the NTC-350 truck diesel engine. After a cycle of tests and refinements, a power of 1 kW was achieved. The efficiency of such a recuperator was as low as 1.3 %.

Also interesting are the works devoted to the use of thermoelectric recuperators in hybrid cars [71], where the energy generated during the operation of the internal combustion engine is used to recharge car batteries. In [100, 103], the results of calculations of a combined recuperator using thermoelectric conversion in combination with the organic Rankine cycle are given.

2.3. Thermoelectric recuperators for thermal power plants

Increasing the efficiency of energy conversion at thermal power plants is an extremely important task.

Paper [106] presents the results of studies of a thermoelectric heat recuperator using waste thermal energy from power plants of the Tokyo Electric Power company. Through the joint efforts of the Komatsu Research Center and KELK [107], such a thermoelectric recuperator was created and its experimental studies were carried out (Fig. 6).

Economic and technical assessments of the possibility of creating similar recuperators were also carried out in [38, 39], but the project was not implemented in practice.


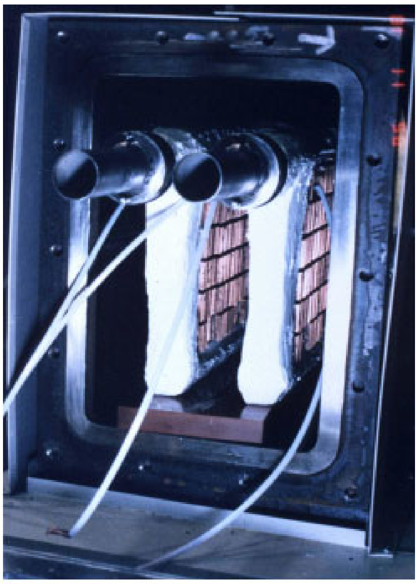

Fig. 6. Thermoelectric recuperator installed at the thermal power plant of the Tokyo Electric Power Company [106].

2.4. Thermoelectric recuperators of waste heat from boilers

Boilers for obtaining steam and hot water are used in almost all large enterprises, in schools and hospitals, large office buildings and for household needs [109]. The heat source for such boilers is usually the combustion energy of gas or other fuel.

In [38, 39], research was carried out and the design of a thermoelectric recuperator was developed, which uses waste thermal energy from industrial boilers (Fig. 7). The efficiency of this converter was realized at the level of 2 %.

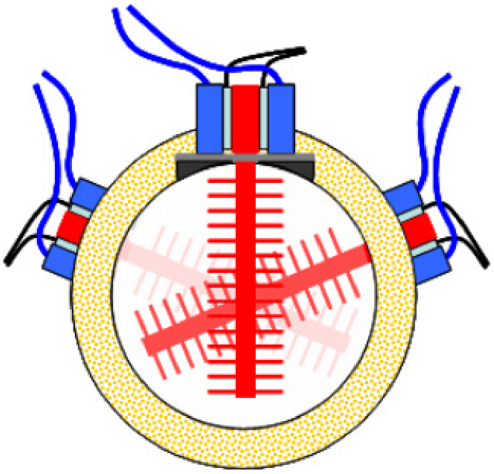

Fig. 7. Installation of a thermoelectric generator in the air duct of the boiler [38].

Scientists from the Brno University of Technology (Czech Republic) developed and tested a thermoelectric recuperator for the utilization of waste heat from a boiler that uses biomass as fuel [108]. The power generated by such a device is 8.5 W, and the overall efficiency of the boiler increases to 76 %.

2.5. Thermoelectric recuperators of heat from gas turbines

Papers [23 – 25, 110] are devoted to the topic of waste heat utilization from gas turbines. Exhaust gases from turbines of pumping stations on gas mains were used as a source of thermal energy.

The design of such a recuperator (Fig. 8) ensures the generation of electric power at the level of 7 kW, which is enough to power gas pumping stations in emergency modes of operation. In this way, the backup power supply of the stations is provided, which significantly increases the reliability of its operation.

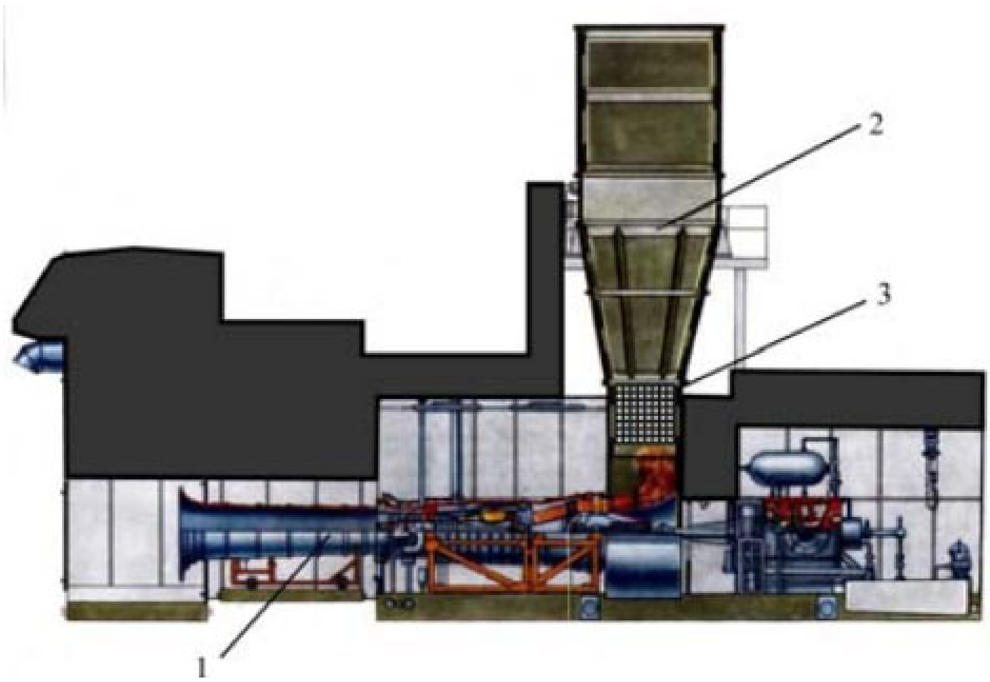

*Fig. 8. Gas pumping unit. 1 – gas turbine, 2 – exhaust device,
3 – thermoelectric heat recuperator [110].*

2.6. Thermoelectric recuperators of household waste heat

Possibilities of thermoelectric recovery are not limited exclusively to large industrial sources of thermal energy. Recently, the direction of utilization of thermal energy of various household devices to obtain electrical energy, which is necessary for powering low-power equipment (lighting the room with a safe voltage of 12 V, charging batteries of household devices, ensuring air circulation through the use of fans, powering LCD TVs and other radio equipment) [16] has been intensively developing.

Papers [111-115] present the results of the development of a thermoelectric heat recuperator from biomass combustion in a household kitchen stove (Fig. 9). The temperature difference on the thermoelectric modules is created on one side by the flame C, and on the other by the water tank A. The efficiency of such generators is about 4 – 5 %, and the specific cost of the generated electricity is $ 2.7 – $5/W.

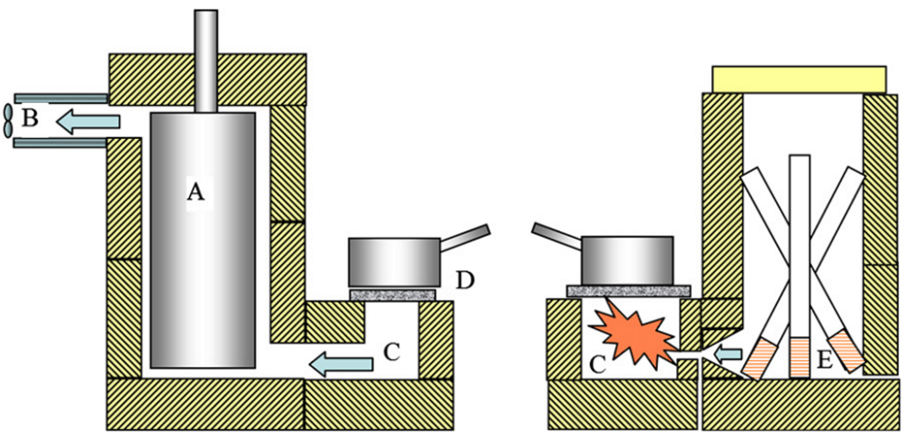

*Fig. 9. Heat recovery system from biomass combustion in a household stove (A – water tank,
B – gas outlet and fan, C – hot gases from fuel combustion, D – stove, E – combustion chamber) [112].*

Similar devices that make it possible to utilize household heat waste are being developed by many organizations, however, unfortunately, it is too early to talk about their mass production and availability of such products.

1.7. Alternative uses of thermoelectric heat recuperators

One of the applications of thermoelectricity for the utilization of waste heat is a recuperator that uses waste heat from the biomass drying process [116]. Such a recuperator is schematically shown in Fig. 11. The power generated by it is used to power fans that circulate hot air in such a system.

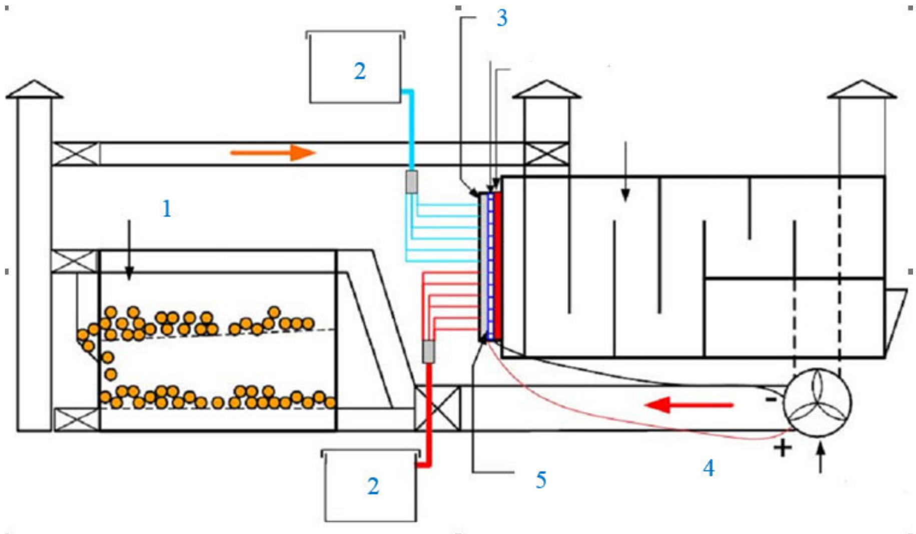

Fig. 11. Thermoelectric recuperator using waste heat from the biomass drying process: 1 – drying chamber, 2 – container with hot water, 3 – generator cooling system, 4 – hot air supply, 5 – thermoelectric converter [116].

Toshiba has developed a 55 W thermoelectric recuperator with an efficiency of 1.8 % [111]. For the conversion, it uses waste heat from the operation of an electrical transformer.

An interesting direction in the development of thermoelectricity is its use to power low-power devices. Reduced power consumption and the emergence of highly efficient voltage converters that begin operating at a level of 30 mV have determined the emergence of a new solution for powering low-power devices on the market. It works by converting waste heat into electrical energy. This makes it possible to increase the service life and reliability of a wide range of autonomous devices that require regular replacement of batteries [124].

In particular, in this way, the power supply of wireless detectors, sensors, indicator meters, parameter monitoring systems and information transmission systems in hard-to-reach or moving parts of equipment is solved, which makes it possible to monitor the condition of the equipment and plan its maintenance. Another promising area is the use of space heating control systems inside the house and reading indicators from various resource consumption meters.

Miniature thermoelectric recuperators used to power low-power equipment and sensors on board the aircraft are considered in [117-122]. Fig. 12 shows the installation of such a device under the wing of the aircraft. The authors present the results of a series of tests of such sources, which confirms their high efficiency.

Thus, the efficiency of currently created thermoelectric energy recuperators is within 1 – 7 % in the range of waste heat temperatures of 50 – 500 °C. The cost of such generators is from 2.7 to 13.5 $ / W with a service life of 10 – 30 years.

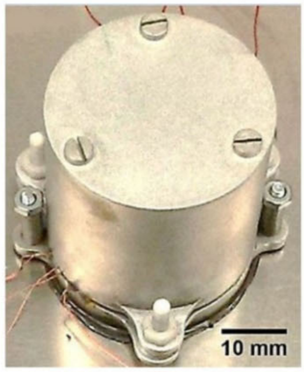

Fig. 12. Place of installation and appearance of a thermoelectric recuperator using waste heat from an Airbus A 380 aircraft turbine [116].

Such indicators do not allow thermoelectricity to compete with the Rankine and Kalina steam cycles and indicate the need for further improvement of thermoelectric recuperators.

A detailed analysis of the possibilities of reducing the cost of thermoelectric waste heat recuperators is given in [125]. It follows from it that achieving the required cost of 1 $/W is possible, provided that heat exchange systems are created with a cost of up to 1 $/(W/K).

Conclusions

1. The most common areas of using thermoelectric heat recuperators are considered, namely - industrial installations, internal combustion engines, thermal power plants, boilers, gas turbines, domestic heat.
2. It has been established that the most effective is the use of thermoelectric recuperators of waste eat from energy-intensive industrial facilities, as well as from powerful internal combustion engines installed, for example, on large trucks or ships.
3. The use of miniature thermoelectric recuperators for powering low-power equipment, as well as the recycling of household waste heat, is also promising.
4. A comparative analysis of existing methods of recuperation of low-temperature waste heat is provided – the conventional and organic Rankine cycles, the Kalina cycle, etc. It is shown that for successful competition in the low-temperature region, thermoelectric energy recuperators need to reach a cost no higher than $1/W, which is possible if heat exchange systems with a cost of up to $1/(W/K) are created.

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РАЦІОНАЛЬНІ ОБЛАСТІ ВИКОРИСТАННЯ ТЕРМОЕЛЕКТРИЧНИХ РЕКУПЕРАТОРІВ ТЕПЛА

Приведено аналіз літератури, присвяченої методам рекуперації відпрацьованого тепла від різних енергоємних. Представлено порівняльний аналіз існуючих методів рекуперації

низькотемпературних відходів тепла – традиційного та органічного циклів Ренкіна, циклу Калини та ін. Наведено характеристики існуючих термоелектричних рекуператорів тепла, а також аналіз можливостей їх подальшого розвитку та найбільш раціональні області їх застосування.
Ключові слова: рекуператор, відпрацьоване тепло, ККД, потужність, питома вартість.

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