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EFFECTIVENESS OF THERMOELECTRIC RECUPERATORS FOR RATIONAL TEMPERATURES OF HEAT SOURCES

The paper presents the results of analysis of thermoelectric recuperators of waste heat for the temperature range 100 -300°C of the heat carrier. Based on computer model, optimization of sectional recuperators is carried out, the efficiency of each section and recuperator as a whole is calculated. The specific cost and payback time of sectional generators is calculated. Conclusions are made on the economic feasibility of using such recuperators. Bibl. 130, Fig. 9, Tabl. 1.

Key words: thermoelectric 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.) generate a large amount of waste heat during their operation. In so doing, 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]. In this case, the majority of thermal waste (nearly 90 %) has temperature up to 300 °C (Fig. 1). This determines the relevance of creation of waste heat recuperators for this temperature level.

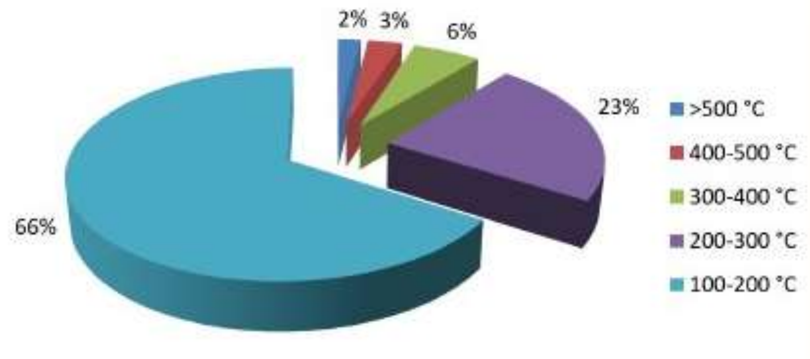

Fig. 1. Distribution of thermal waste sources by temperature range [6].

The most popular ways of thermal into electrical energy conversion are mechanical. Their characteristics are shown in the table. As is seen from the table, mechanical methods are efficient at high temperatures. At low temperatures (up to 300°C) they considerably lose their effectiveness or do not work altogether. Another disadvantage is the need to use bulky equipment (boilers, evaporators, turbines). Under such circumstances, direct thermal into electrical energy conversion by means of thermoelectricity can become a competitive mechanical method.

Table.

Mechanical methods of waste heat conversion into electrical energy [7- 11]

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

Therefore, *the purpose of the work* is to establish general features that thermoelectric recuperators must meet, which will ensure their rational use.

Unlike thermoelectric generators which use costly heat sources and for which the main criterion of effectiveness is their efficiency, thermoelectric recuperators use waste heat. Therefore, to determine their effectiveness, it is necessary to apply other approaches, namely to establish their specific cost and payback time [129].

Known thermoelectric recuperators of waste heat

Based on the analysis of literature data, it is possible to identify the most common areas of using thermoelectric heat recuperators, namely industrial plants, internal combustion engines, thermal power plants, boilers, gas turbines, and domestic heat. Waste heat recuperators [43-51] from such energy-intensive industrial facilities as steel plants [26, 36-41, 54, 55], cement kilns [27-35, 38-40, 52, 54], glass furnaces [38-40, 52], furnaces for annealing lime [38, 39, 52], furnaces for the production of ethylene [38, 39], garbage recycling plants [104, 105], furnaces for smelting aluminum and other metals [38, 39, 52] are under active investigation.

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

A thermoelectric recuperator using waste heat from a cement kiln was installed at the Awazu plant of Komatsu (Japan). The power of such a recuperator is about 10 kW. The waste heat recuperator from cement kilns [35] was also developed by scientists from Industrial Technology Research Institute (Taiwan) and Institute of Thermoelectricity (Ukraine). The feature of this generator is its placement at some distance from the cement kiln which rotates, while it does not affect the technological processes inside the kiln. The project for waste heat recovery from garbage recycling plants using thermoelectricity was implemented jointly by Fujitaka (Japan) and Institute of Thermoelectricity (Ukraine) [104, 105].

A large number of publications are devoted to heat recovery from internal combustion engines of cars [28, 29, 52, 56 - 103] and motorcycles [28, 29]. However, it should be noted that the use of thermoelectric recuperators in cars has a number of disadvantages [60, 70, 71]. The real power gain is not significant enough. This leads to a search for more efficient applications of thermoelectricity. First of all, it looks promising to recover heat from diesel engines of large ships (in addition to high power, their advantage is the ability to remove heat from the thermoelectric converter to the surrounding water), as well as large trucks and special equipment [75, 80, 82, 93, 97]. There are also interesting works devoted to the use of thermoelectric recuperators in hybrid vehicles [71], where the energy generated during the operation of an internal combustion engine is used to recharge the batteries of the vehicle.

Ref.[106] presents the results of studies on a thermoelectric heat recuperator, which uses waste heat energy from power plants of Tokyo Electric Power. By joint efforts of the Komatsu Research Center and KELK [107], such a thermoelectric recuperator was created and its experimental studies were carried out.

In [38, 39], studies of a thermoelectric recuperator, which uses waste heat from industrial boilers, are presented. The efficiency of such a converter reaches 2%.

The Brno University of Technology (Czech Republic) has developed a thermoelectric recuperator for recovery of waste heat from a boiler, which uses biomass as a fuel [108].

The topic of heat recovery from gas turbines is discussed in [23, 110]. The exhaust gases from the turbine of pumping stations on gas mains were used as a source of thermal energy.

Refs. [111-115] present the results of development of a thermoelectric recuperator of heat from the combustion of biomass in a household kitchen stove. The temperature difference on thermoelectric modules is created on the one hand by flame, and on the other – by water tank.

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

Toshiba has developed a thermoelectric recuperator for an electric transformer [111].

Miniature thermoelectric recuperators used to power low-power equipment and sensors on board the aircraft are considered in [117-122]. Such devices are mounted under the wing of the aircraft and use the hot heat of the turbine.

It should be noted that heat recovery from stationary industrial plants (especially at temperatures below 600 K) is of great interest for thermoelectricity, since it allows one to fully realize its advantages. Estimates show that in the United States alone, about 3.300 TJ of energy are released annually from thousands of industrial processes [38, 53], some of which can be returned to active balance by 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 critical units of industrial installations, which can significantly increase their reliability [23-25].

Determination of general properties of thermoelectric recuperators

Physical model of a thermoelectric sectional heat recuperator is shown in Fig.2.

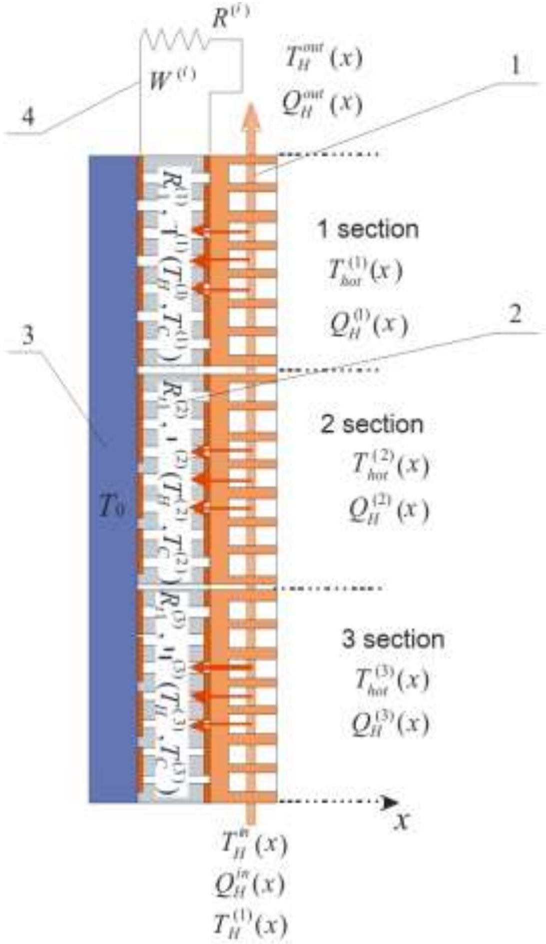

Fig. 2. Physical model of thermoelectric sectional heat recuperator:
1 – hot heat exchanger; 2 – thermopiles
3 – cold heat exchanger 4 – matched electrical load of the section.

Each section of the recuperator consists of hot heat exchanger (1), thermopile (2) with thermal resistance $R_{t2}^{(i)}$ and efficiency $\eta(T_H, T_0)$; cold heat exchanger (3) with temperature T_0. Thermopiles of each recuperator section are loaded on matched electrical load $R^{(i)}$ (4). Hot gas input flow has temperature T_H^{in} and thermal power Q_H^{in}. Hot gas gives part of heat $Q_H^{(i)}(x)$ at temperature $T_{hot}^{(i)}(x)$ to the hot heat exchanger. At the recuperator outlet the gas flow has temperature T_H^{out} and thermal power Q_H^{out}. From the hot heat exchanger heat is passed to the thermopile, heating its hot side to temperature $T_H^{(i)}(x)$. To calculate maximum possible recuperator power, we will ignore thermal losses. For the optimization of TEG it is necessary to find the distribution of temperatures and heat flows in thermopiles of each section. Such a calculation for this model was made through use of numerical computer methods.

To calculate the electrical power of TEG, we use the equation of energy balance in the form

$$W = \sum_{i=1}^{N} \left[\int \left(Q_H^{(i)}(x) - Q_C^{(i)}(x) \right) dx \right]. \quad (1)$$

The necessary temperatures and heat flows are found from thermal conductivity equation

$$-\nabla\left(\kappa_{TE}(T)\nabla T\right)=Q_J\,, \tag{2}$$

where κ_{TE} is effective thermal conductivity of thermopile, Q_J is the Joule heat which is released in the bulk of the thermopile.

The boundary conditions for (2) will be given by

$$Q_H^{in(1)}=Q_H^{in},\;\; Q_H^{in(i+1)}=Q_H^{out(i)},\;\; Q_H^{out(N)}=Q_H^{out}\,, \tag{3}$$

$$Q_H^{(i)}(x)=\left(T_H^{(i)}(x)-T^{(i)}(x)\right)/\,R_t^{(i)}\,, \tag{4}$$

$$Q_C^{(i)}(x)=\left(T_0\,(x)-T^{(i)}(x)\right)/\,R_{t2}^{(i)}\,, \tag{5}$$

The set of relations (1) - (5) makes it possible to determine the distribution of temperatures and heat flows in each of the sections

To restrict the hot temperature of the module, the thermal resistance between the hot heat exchanger and the thermoelectric module is determined from equation (4).

The power of each section and total efficiency of TEG can be found from equations

$$W^{(i)}=\int Q_H^{(i)}(x)\eta(T_H^{(i)}(x),\,T_0)dx\,, \tag{6}$$

$$\eta_{TEG}=\frac{1}{Q_H^{in}}\sum_{i=1}^{N}W^{(i)}\,. \tag{7}$$

The system of equations (1) - (5) was solved by numerical methods on a two-dimensional mesh of finite elements.

To calculate the efficiency of the thermoelectric recuperator, thermoelectric materials based on Bi-Te were selected which are one of the best in terms of quality in the considered temperature range [127].

At the first stage, the optimization of the hot temperatures of the recuperator sections was carried out (Fig. 3). Fig. 4 shows the relative number of thermoelectric modules of the same type in a section to achieve optimal temperature distribution.

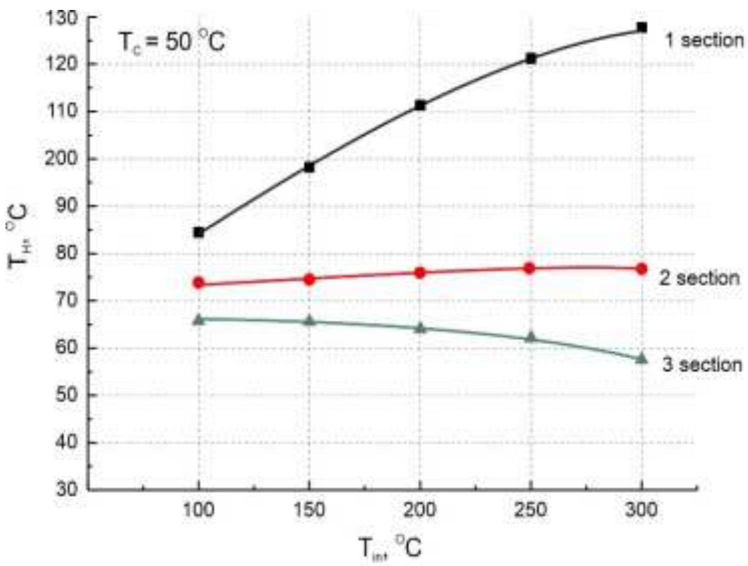

Fig. 3. Dependence of the optimal hot temperature of the sections on the temperature of heat carrier.

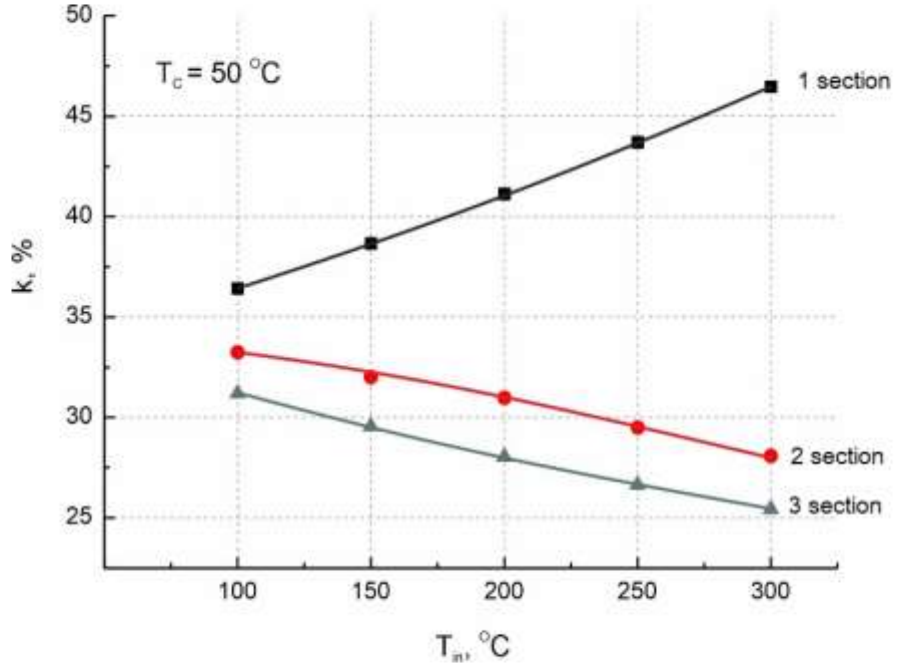

Fig. 4. Relative number of thermoelectric modules in a section to achieve optimal temperature distribution.

The next step is to determine the dependence of the efficiency of thermoelectric modules (Fig. 5) and the recuperator as a whole (Fig. 6) on the temperatures of the input heat carrier.

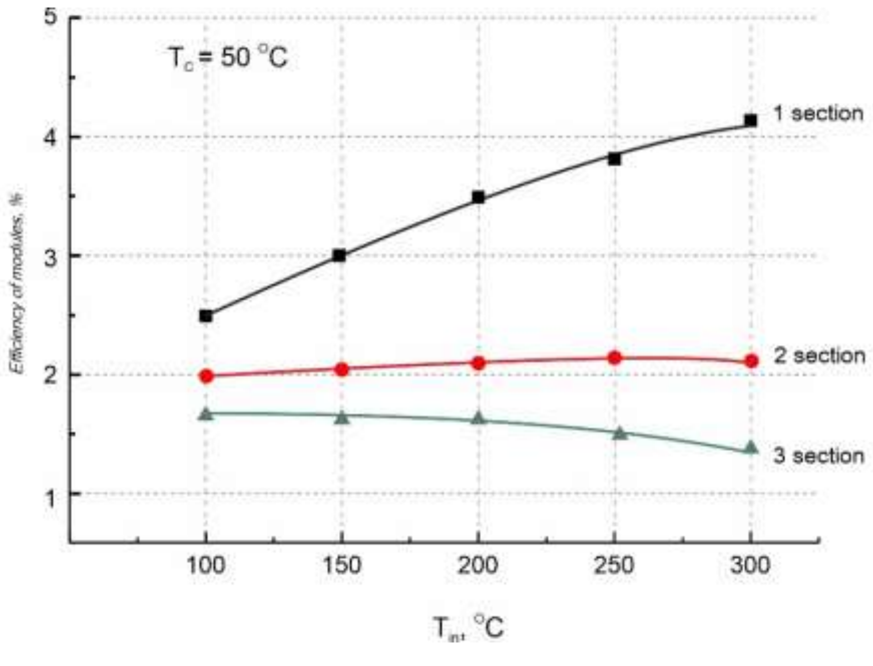

Fig. 5. Dependence of the efficiency of modules of sections on the temperature of inlet heat carrier.

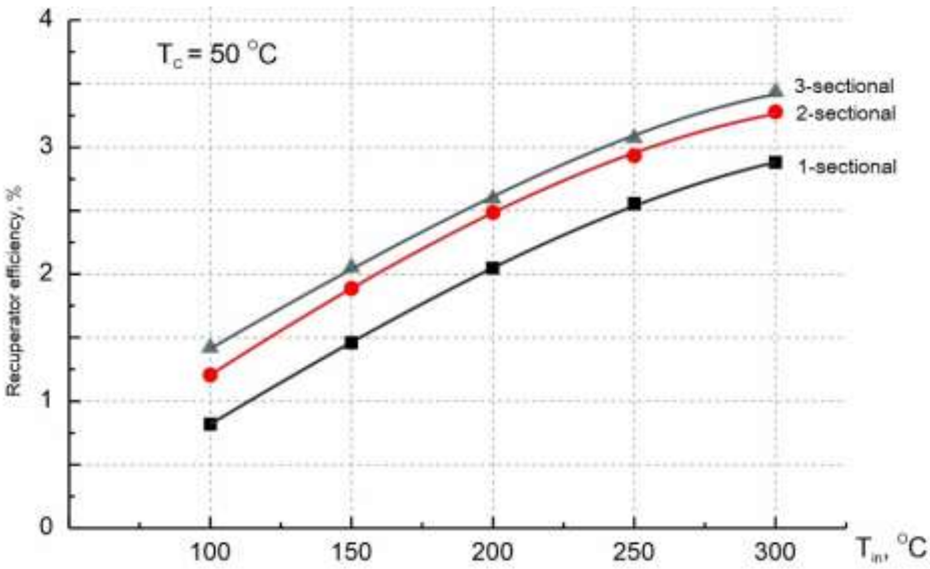

Fig. 6. Dependence of recuperator efficiency on the temperature of inlet heat carrier.

As is evident from Fig. 6, the use of the second section of the thermoelectric heat recuperator leads to an increase in efficiency by ~18%, and the third – only by 3%.

The percentage contribution of each section of thermoelectric heat recuperator to its total power is shown in Fig. 8. As can be seen from the figure, the percentage contribution of the first section of recuperator to total power is 85 – 90%, the second – 8 – 12%, the third – about 2%.

To assess the economic feasibility of using a thermoelectric recuperator, its specific cost was calculated (Fig. 8), based on the results obtained in [128]. As can be seen from the figure, the use of the third section in the considered temperature range is not economically feasible. The use of the second section is also questionable.

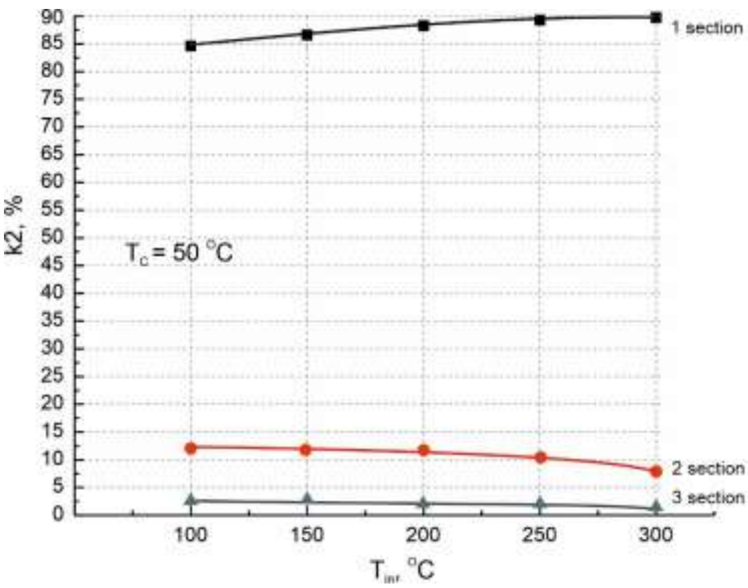

Fig. 7. Contribution of each section to total power of recuperator.

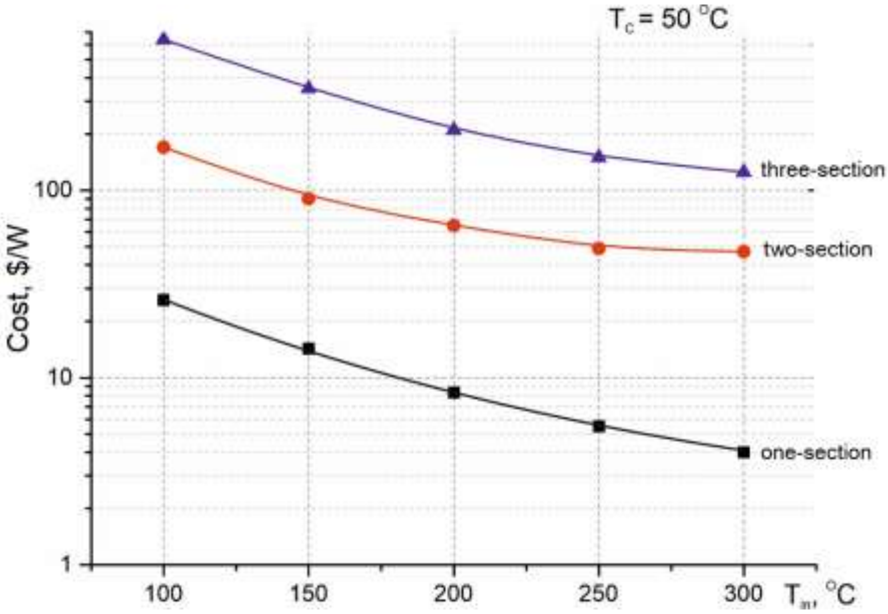

Fig. 8. Specific cost of sectional recuperators.

For a better understanding of the economic efficiency of thermoelectric recuperators, we will calculate their payback time, based on a comparison of the cost of their electrical energy with the cost of industrial electrical energy. Fig. 9 shows the results of such calculations. For example, a comparison was made with the average cost of electricity in Ukraine 0.12 $ / (kWh) (according to the data of the company Ukrenergo [130]).

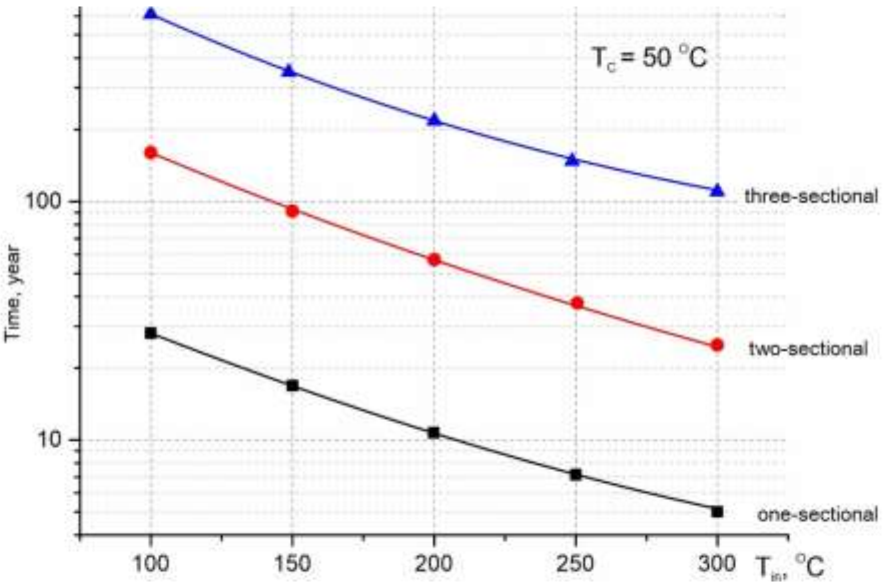

Fig. 9. Payback time of sectional recuperators.

From the analysis of Fig. 9 it becomes clear that for the specified temperature range (100 - 300 ° C) it is economically feasible to use only one section. A small gain in power when using other sections does not cover material costs.

Conclusions

1. The dependences of the optimal temperatures of the recuperator sections on the inlet gas temperature in the range from 100 to 600 ° C are established. For the first section from 37 to 47 ^{O}C, the second - from 33 to 27 ^{O}C, the third - from 32 to 25 ^{O}C.
2. The number of thermoelectric converters in each section is determined to achieve the optimal temperature distribution in the sections. For low inlet gas temperatures the number of thermocouples in the sections is approximately the same. With a rise in temperature, the share of thermocouples in the first section increases.
3. The specific cost of a thermoelectric recuperator and its payback time are calculated. It is shown that the cost of each subsequent section is approximately an order of magnitude greater than the cost of the previous one. Therefore, for the range of hot temperatures of the heat carrier 100-300^{O}C it is economically feasible to use only one section.

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ЕФЕКТИВНІСТЬ ТЕРМОЕЛЕКТРИЧНИХ РЕКУПЕРАТОРІВ ДЛЯ РАЦІОНАЛЬНИХ ТЕМПЕРАТУР ДЖЕРЕЛ ТЕПЛА

У роботі наводяться результати аналізу термоелектричних рекуператорів теплових відходів для діапазону температур теплоносія 100 -300ºС. На основі комп’ютерної моделі проведено оптимізацію секційних рекуператорів, розраховано ККД кожної секції та рекуператора в цілому. Розраховано питому вартість та час окупності секційних генераторів. Зроблено висновки про економічну доцільність використання таких рекуператорів. Бібл. 130, рис. 9, табл. 1.

Ключові слова: термоелектричний рекуператор, відпрацьоване тепло, ККД, потужність, питома вартість.

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ЭФФЕКТИВНОСТЬ ТЕРМОЭЛЕКТРИЧЕСКИХ РЕКУПЕРАТОРОВ ДЛЯ РАЦИОНАЛЬНЫХ ТЕМПЕРАТУР ИСТОЧНИКОВ ТЕПЛА

В работе приводятся результаты анализа термоэлектрических рекуператоров тепловых отходов для диапазона температур теплоносителя 100 -300^{0}С. На основе компьютерной модели проведена оптимизация секционных рекуператоров, рассчитан КПД каждой секции и рекуператора в целом. Рассчитаны удельная стоимость и время окупаемости секционных генераторов. Сделаны выводы об экономической целесообразности использования таких рекуператоров. Библ. 130, рис. 9, табл. 1.
Ключевые слова: термоэлектрический рекуператор, отработанное тепло, КПД, мощность, удельная стоимость.

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