

Розроблена схема енергетичної установки на базі двигуна внутрішнього згоряння 1Ч 6,8/5,4 з іскровим запаленням та двохступеневої системи утилізації тепла відпрацьованих газів. Підібрано основні елементи першої та другої ступені системи утилізації. У якості першої ступені використано роторно-поршневу розширювальну машину, а у якості другої ступені конверсію палива.

Проведено дослідження ефективних параметрів двигуна 1Ч 6,8/5,4 з системою глибокої двохступеневої утилізації тепла відпрацьованих газів на різних режимах роботи. Отримано залежності змінення питомої ефективної витрати палива від потужності енергетичної установки при використанні тільки конверсії палива та в поєднанні з розширювальною машиною.

Отримано залежності параметрів роботи роторно-поршневого двигуна від витрати робочого тіла. Визначено температуру робочих тіл в реакторі та теплову потужність відпрацьованих газів в залежності від навантаження двигуна, а також необхідну кількість енергії для перетворення етанолу в синтез-газ. Отримано залежності ступеня конверсії етанолу від температури реакції та масової витрати через реактор. Визначена залежність питомої теплоти хімічної реакції від ступеня конверсії.

Встановлено, що при досягненні повної конверсії за реакцією розкладання весь рідкий етанол повністю перетворюється в горючий синтез-газ, основними компонентами якого є водень, оксид вуглецю та метан. Розрахункова питома нижча теплота згоряння синтез-газу складає 28,79 МДж/кг. Для отримання 1 кг синтез-газу витрачається 4,0 МДж теплової енергії.

Визначено, що за умови застосування конверсії палива та відповідно добавок синтез-газу, питома ефективна витрата етанолу, в залежності від режиму роботи двигуна, знижується до 12 %. Кількість енергії, яку необхідно використати в реакторі для отримання синтез-газу, складає 50...65 % від теплоти, що виділяється з відпрацьованими газами на даному режимі роботи.

Встановлено, що застосування роторно-поршневий розширювальної машини в якості першого ступеня утилізації тепла відпрацьованих газів дозволило отримати приріст потужності енергетичної установки на 27 %.

Встановлено, що застосування двох ступенів утилізації, призводить до зниження питомої ефективної витрати палива на 29 %

Ключові слова: конверсія, етанол, синтез-газ, відпрацьовані гази, паливо, роторно-поршнева розширювальна машина

UDC 621.438

DOI: 10.15587/1729-4061.2019.174061

RESEARCH INTO THE RECOVERY OF EXHAUST GASES FROM ICE USING AN EXPANSION MACHINE AND FUEL CONVERSION

O. Mytrofanov

PhD, Associate Professor*

E-mail: oleksandr.mytrofanov@nuos.edu.ua

A. Poznanskyi

PhD**

E-mail: andreypoznansky@gmail.com

A. Proskurin

PhD, Associate Professor*

E-mail: arkadii.proskurin@nuos.edu.ua

Yu. Shabalin

Director

LLC «Motor-Plus»

Shevchenka str., 22,

Mykolaiv, Ukraine, 54030

E-mail: motorplusplant@gmail.com

*Department of Internal Combustion Engines, Plants and Technical Exploitation***

Department of Mechanical Engineering and Manufacturing Engineering*

***Admiral Makarov National

University of Shipbuilding

Heroiv Ukrainy ave., 9,

Mykolaiv, Ukraine, 54025

Received date 24.04.2019

Accepted date 27.06.2019

Published date 28.08.2019

Copyright © 2019, O. Mytrofanov, A. Poznanskyi, A. Proskurin, Yu. Shabalin

This is an open access article under the CC BY license

(<http://creativecommons.org/licenses/by/4.0>)

1. Introduction

At present, nearly 80 % of the consumption of petroleum-based fuel are spent by transportation means of various purposes. Given the threat of reduced oil reserves, stricter requirements to environmental protection, as well as the need for energy security, intensive research is being carried out to improve the fuel efficiency of internal combustion engines (ICE). Active search is under way for effective ways to the deep recovery of secondary energy sources (SER) from energy-generating units (EU) [1–3], as well as the use of alternative fuels [4–6].

The systems for recovering the low-potential thermal energy that have been implemented so far have some significant disadvantages (high manufacturability and cost of equipment, dimensions), which hinders their use at EC equipped with ICE of small power. This necessitates using new approaches to solving this task. When assessing the feasibility of a heat recovery scheme, one must take into consideration:

- EU operating conditions;
- a possibility to reserve the heat recovery means;
- simplicity and reliability of operation, simple design;
- the cost-effective operation of the installation when accounting for the cost of the equipment.

2. Literature review and problem statement

When recovering the heat from SER of ICE, the main purpose is to obtain additional mechanical or electrical energy.

Basic methods for recovering the heat from modern ICE are:

- turbocompound systems;
- steam-turbine plants based on the Rankine cycle;
- plants with a low boiling working body;
- cooling the supercharged air by utilization refrigerators.

It is known that in order to recover heat from SER the company MAN Diesel & Turbo (Germany) used the turbo-compound systems [7, 8]. In such systems, exhaust gases are supplied along parallel channels to the power turbine and turbocharger. Fuel economy for medium-speed engines reaches 6 %, depending on the operating mode. Advantages of turbocompound heat recovery systems are their convenient dimensions, the lack of additional heat carriers. The downside is the narrow range of operation (for example, 40...60 % MCR). When setting the heat recovery plant for a wide range of operation, efficiency of the installation does not exceed 3 %, when configured for a narrow range – reaches 5 %. However, there remain the unaddressed issues related to possible schemes to apply a given heat recovery technique for lower power engines, such as motors for land mobile machinery (automobiles, construction, agricultural equipment).

The heat recovery systems that have been implemented up to now based on the Rankine cycles with the use of various working bodies have low efficiency and considerable weight and size parameters. Paper [9] suggested using a steam turbo-compression as an alternative to steam heat recovery plants. In this case, exhaust gases are spent solely on heating water vapor, which is used to drive the turbocharger and power turbine. However, there are the unsolved issues related to the technical implementation of a given technique, namely the selection of necessary equipment for the heat recovery system and its characteristics.

The use of low-boiling substances at heat recovery plants improves their efficiency. Thus, a series of low-boiling working fluids, such as silicone oils, propane, fluoro-chloro-carbons (freon), isopentane, isobutane, *n*-pentane, toluene have a low boiling point and the higher pressure in the vapor phase than water. Such cycles are denoted by the acronym ORC (Organic Rankine Cycles). Papers [10, 11] report key results from a thermodynamic study into effectiveness of ORC, which employs, as a working body, the low-boiling substances, in line with ASHRAE classification, to generate electricity. However, some issues related to high cost and toxicity of these liquids were not considered, which significantly limits the use of such schemes.

Studies [12, 13] consider patterns in cooling the supercharged air by the heat-utilizing ejector refrigerating machines, in which a compressor function is performed by the ejector. However, the authors do not deal with the issues on the mass and weight indicators for these installations and a possibility to use them in stationary engines.

Thus, the heat recovery techniques considered above have not been used for engines of low power and especially at spark-ignition engines.

One of the promising ways for heat recovery, which can be successfully used for these ICEs and meet all specific requirements, is the recovery of heat from exhaust gases (EG) to implement the conversion of hydrocarbon fuel into a gaseous fuel (syngas).

Papers [14, 5] report results from experimental studies into performance and emissions of pollutants from the engine with a direct injection and spark ignition, designed for a joint work with the high-pressure recuperation system based on the steam conversion of methanol. The engine that uses the products from steam conversion of methanol demonstrates an increase in efficiency by up to 18...39 %, as well as a decrease in emissions of NO_x, CO, CH, and CO₂. However, the authors failed to consider the design features for implementing a given scheme and the relationship between a working cycle of the engine and parameters for the recuperation.

As regards the field of recovering the heat from EG there remains a large number of unresolved issues and tasks. Especially in the field of application of different heat recovery techniques or their combinations for the low-power spark-ignition piston engines. We have therefore proposed to implement the scheme of deep two-stage recovery of heat from secondary energy resources for ICE with a spark ignition. A heat recovery scheme combines two promising techniques – the utilization of mechanical energy in a rotary piston expansion machine (stage one) and the utilization of heat energy in a reactor for fuel conversion (stage two). This approach could make it possible to significantly improve the effectiveness and efficiency of low-power EU in general.

3. The aim and objectives of the study

The aim of this study is to design EU based on ICE with a spark ignition and a system for deep two-stage recovery of heat from OG. This would make it possible to define the parameters for operation and effectiveness of using a rotary piston expansion machine, as well as a reactor for fuel conversion as the stages in heat recovery.

To accomplish the aim, the following tasks have been set:

- to assemble a scheme of EU with a deep two-stage system for recovering the heat from EG in ICE, as well as to select the basic elements for its first and second stages;
- to define characteristics for the operation of the first stage of heat recovery in the form of a rotary piston expansion machine;
- to determine characteristics for the operation of the second stage of heat recovery (a reactor for fuel conversion), namely the dependence of the degree of ethanol conversion on the reaction temperature and mass flow rate of fuel;
- to analyze the effectiveness of application of a deep two-stage system for recovering the heat from exhaust gases.

4. Description of the scheme and the selection of elements for an energy-generating unit with deep recovery of the heat from exhaust gases

A principal diagram of the energy-generating unit is shown in Fig. 1. Its main elements are the internal combustion engine with a spark ignition 1Ch 6.8/5.4 8, a rotary piston expansion machine 4, a reactor for fuel conversion 6.

We selected a rotary-piston expansion machine as the first stage of heat recovery (Fig. 2) [16]. For the second stage of heat recovery we have designed and fabricated a reactor for fuel conversion (Fig. 3). The reactor was installed instead of the silencer in the engine; in this case, the reactor was used for heat recovery and noise silencing.

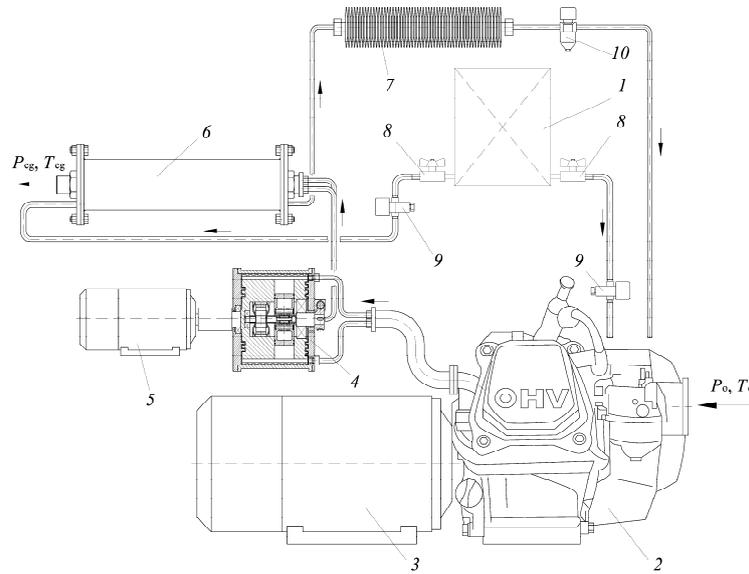


Fig. 1. Principal diagram of the energy-generating unit with a deep recovery of heat from exhaust gases: 1 – discharge tank with liquid fuel; 2 – internal combustion engine 1Ch 6.8/5.4; 3 – generator of electric current; 4 – rotary-piston expansion machine; 5 – generator of low power electric current; 6 – reactor for fuel conversion; 7 – synthesis gas cooler; 8 – cut-off valve of liquid fuel; 9 – electromagnetic fuel valve; 10 – electromagnetic gas valve with filter

Next, exhaust gases enter the reactor for fuel conversion 6. Reactor 6 also receives a liquid fuel from discharge tank 1, where under the influence of heat from EG there occurs a reaction that converts the starting fuel into syngas. The resulting gaseous fuel in the reactor consists of 43 % H₂, 34 % CO, 23 % CH₄.

Thus, part of the heat from exhaust gases returns to the working cycle, that is the thermochemical heat recovery is achieved. The resulting synthesis gas has a lower calorific value of 28.79 MJ/kg, its density is 0.63 kg/m³.

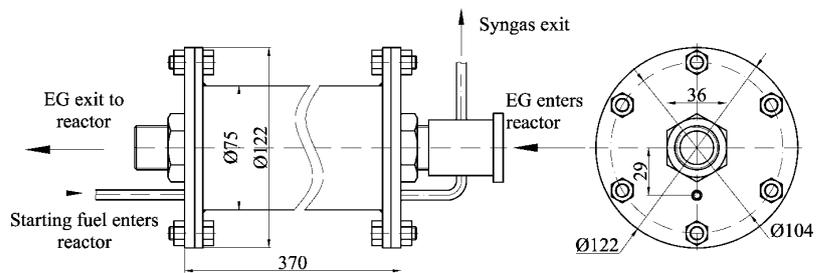


Fig. 3. Reactor for fuel conversion

After the conversion reactor, synthesis gas enters heat exchanger 7 for cooling, next, through an electromagnetic gas valve with a filter, it enters engine 2. The basic parameters for the process of transforming the starting fuel into synthesis gas are:

- a degree of fuel conversion ξ , that is the share of fuel, which was converted into synthesis gas during reaction;
- the relative fuel consumption for conversion Δg^n , that is the mass of fuel needed to obtain 1 kg of synthesis gas;
- specific heat of chemical reaction q_{rc} – the amount of energy needed to overcome the reaction of conversion of 1 kg of starting fuel.

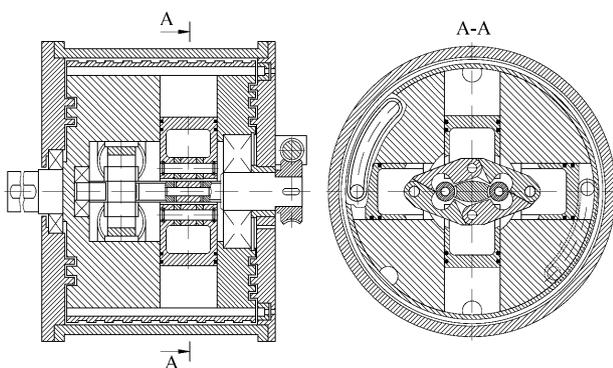


Fig. 2. A rotary-piston expansion machine

Liquid fuel from discharge tank 1 is fed to engine 2, loaded with a standard generator 3. Exhaust gases from engine 2 enter, from a common collector, the inlet chambers at a rotary-piston expansion machine 4, which in turn sets into motion the electric current generator 5. The rotary-piston expansion machine utilizes the mechanical energy from the gases that were used in a working cylinder, that is the first stage of heat recovery occurs.

5. Results of studying the operation of stages of deep recovery

5.1. Characteristics of the operation of the first stage of recovery

The first stage of recovering the heat from exhaust gases involves a rotary-piston expansion machine. Heat recovery efficiency directly depends on the flow rate and pressure of EG at the outlet from ICE. Fig. 4 shows the averaged dependence of the rotor rotation frequency and the effective capacity of a rotary-piston engine on EG flow rate. An increase in the ICE power output leads to an increase in the amount of

EG and, accordingly, there is an increase in the power of the rotary-piston engine. Thus, when the ICE reaches the power of 2.5 kW, the power of a rotary-piston engine would equal 1 kW at 756 rpm.

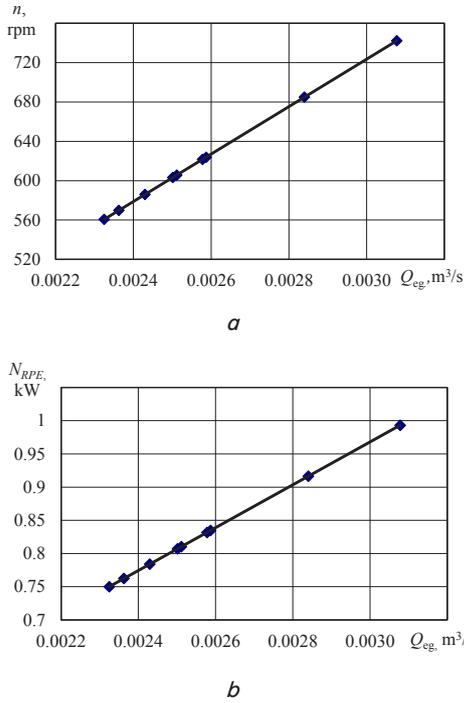


Fig. 4. Dependences of parameters for a rotary-piston engine on the flow rate of a working body: *a* – rotor rotation frequency; *b* – effective power

5. 2. Characteristics for the operation of the second stage of recovery

The second stage in the recovery of heat from exhaust gases involves a reactor for fuel conversion. A given technique makes it possible to obtain a gaseous fuel with a higher calorific value, as well as improve the combustion process itself in the working cylinder. Fig. 5 shows the experimentally measured temperature values (absolute measurement error is $\pm 10^\circ C$) for EG, liquid ethanol, and synthesis gas (products of ethanol conversion) at the inlet and outlet to the reactor, depending on the engine load, as well as the approximating curves (accuracy of approximation R^2 is between 0.81...0.92).

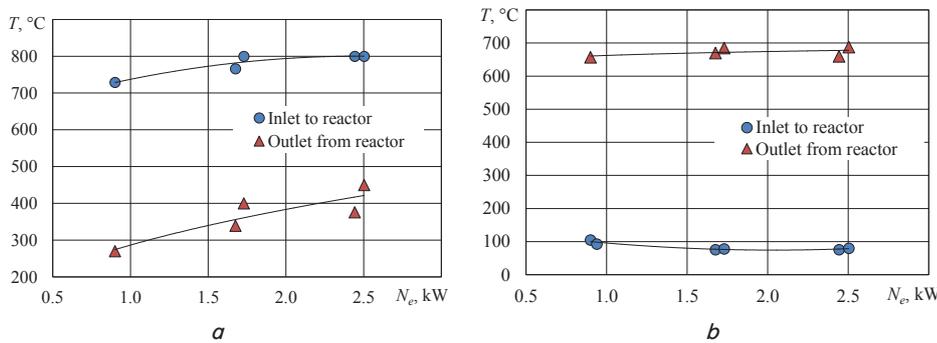


Fig. 5. Temperature of working bodies in the reactor: *a* – exhaust gases; *b* – ethanol

Our measurements of ethanol mass at the inlet and outlet of the reactor (absolute measurement error is ± 10 g) have made it possible to derive a dependence of the degree

of conversion on the reaction temperature (the temperature of synthesis gas at the outlet from the reactor) (Fig. 6) at approximation accuracy $R^2=0.96$, as well as the dependence of conversion degree on the mass flow rate of ethanol through the reactor (Fig. 7) at approximation accuracy $R^2=0.93$.

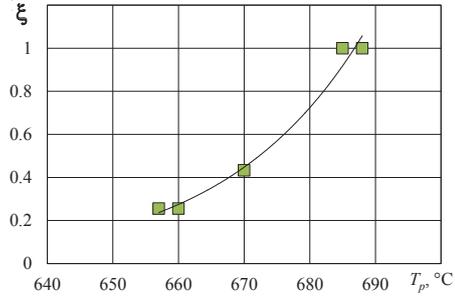


Fig. 6. Dependence of ethanol conversion degree on the reaction temperature

Complete conversion of ethanol was achieved at a temperature of 685 $^\circ C$ and above. When reaching the complete conversion, obtaining 1 kg of synthesis gas requires 1 kg of ethanol, that is the entire liquid ethanol, which entered the reactor, was completely converted into a gaseous fuel.

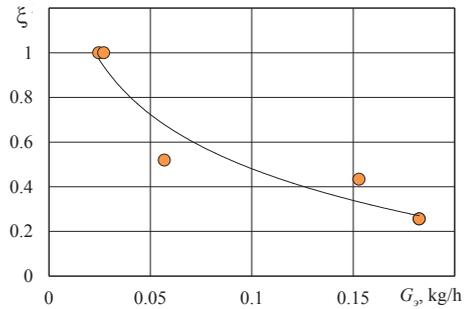


Fig. 7. Dependence of conversion degree on the mass flow rate of ethanol through the reactor

It is necessary, for the effective implementation of the heat recovery of heat from EG based on the conversion of fuel at piston ICE, that the temperature-energy potential of exhaust gases should be enough to obtain synthesis gas from ethanol of the required amount and composition. The amount of energy needed to obtain synthesis gas is determined from:

$$Q_n^{sg} = Q_h + Q_{ev} + Q_{ov} + Q_{r.c} + Q_l,$$

where Q_h is the amount of energy spent on heating ethanol up to a boiling point;

Q_{ev} is the amount of energy spent on evaporation of ethanol;

Q_{ov} is the amount of energy spent on overheating the gaseous ethanol to the temperature of conversion;

$Q_{r.c}$ is the amount of energy spent on overcoming the endothermic effect from the reaction of chemical transformation of ethanol into synthesis gas;

Q_i is the amount of energy that takes into consideration the inevitable heat losses into the environment through the reactor.

Fig. 8 shows the experimentally measured values for the exhaust gases thermal power at the outlet from an engine and the power used in the reactor (absolute measurement accuracy is ± 50 W) for different engine loads, as well as the approximating curves (approximation accuracy R^2 is in the range of 0.82...0.91).

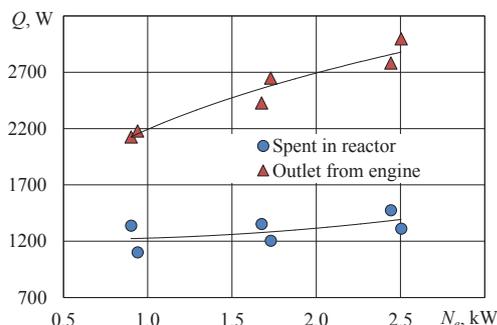


Fig. 8. Thermal power of exhaust gases

Table 1 gives results from experimental measurements of the amount of energy that is spent in the conversion reactor to obtain synthesis gas.

Table 1

Energy spent in the conversion reactor to obtain synthesis gas

| Parameter | Load engine, N_e | | | |
|---|--------------------|--------|--------|--------|
| | 1.0 kW | 1.5 kW | 2 kW | 2.5 kW |
| Heating ethanol to a boiling point, W | 7.65 | 6.73 | 6.90 | 8.16 |
| Ethanol evaporation, W | 29.41 | 27.56 | 27.83 | 30.23 |
| Overcoming the endothermic effect from the reaction of converting ethanol into synthesis gas, W | 47.15 | 41.49 | 42.55 | 50.31 |
| Overheating of gaseous ethanol to conversion temperature, W | 64.95 | 58.31 | 59.71 | 69.16 |
| Total energy required to obtain synthesis gas, W | 149.15 | 134.09 | 137.00 | 157.86 |

The greatest amount of energy is spent on overheating gaseous ethanol (40...45 % of the total amount of energy) that is associated with a high temperature value at non-catalytic conversion.

5. 3. Analysis of the efficacy of applying a deep two-stage system to recover heat from exhaust gases

To assess the effectiveness of the application of EG heat recovery only for conversion of fuel at the engine 1Ch 6.8/5.4, we compared specific effective fuel consumption when the engine is running on ethanol and ethanol consumption when utilizing the addition of synthesis gas (Fig. 9). With the addition of synthesis gas, the specific effective ethanol consumption at 1Ch 6.8/5.4 decreased by 12 %.

According to the results shown in Fig. 10, when achieving the full conversion, obtaining 1 kg of synthesis gas

requires 4.0 MJ of heat energy. According to data given in Table 1 and shown in Fig. 8, obtaining synthesis gas at an energy-generating unit based on the engine with a spark ignition 1Ch 6.8/5.4 requires using 50...65 % of thermal energy from exhaust gases. As a result, 4...6 % of heat is recovered, which is repeatedly used in the organization of the working cycle of the engine.

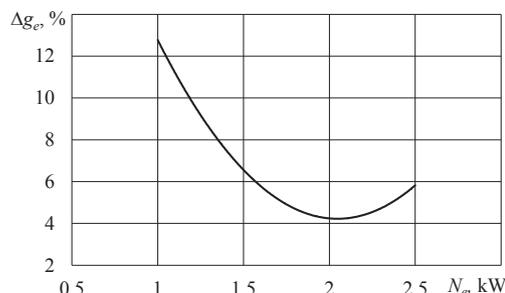


Fig. 9. Evaluation of application of fuel conversion

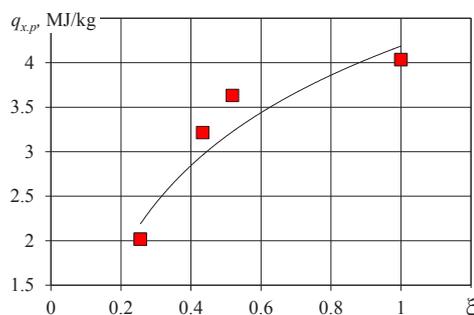


Fig. 10. Dependence of specific heat from chemical reaction on conversion degree

When using two stages of heat recovery the effective power of the energy-generating unit under maximum operating modes increased from 2.5 to 3.43 kW. In this case, the specific efficient fuel consumption decreased from 460 to 327 g/(kWh). Fig. 11 shows a dependence of change in specific effective fuel consumption on the power generated under the condition of deep recovery of heat from OG and without it.

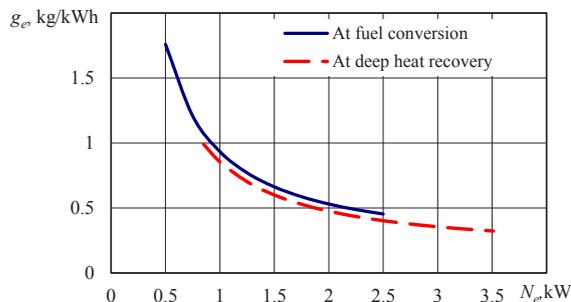


Fig. 11. Dependence of specific effective fuel consumption on effective power of the energy-generating unit

In other words, using the deep heat recovery makes it possible to decrease fuel consumption at the level of 29 %. In this case, the total power of the energy-generating unit increased by up to 40 %.

6. Discussion of results of studying the effectiveness of application of the deep two-stage system to recover heat from exhaust gases

Table 2 gives data on efficiency (lower fuel consumption) when applying different ways of heat recovery, which are widely used at ICE. However, it is worth noting that all of them are implemented in the diesel engines of large dimensions and power. Due to the high manufacturability, cost, and dimensions, their application for low-power engines is impractical.

Table 2
Effectiveness of using the techniques for heat recovery at ICE [7]

| Heat recovery techniques | Decrease in fuel consumption, % |
|---------------------------------------|---------------------------------|
| Mechanical turbo-compound plants | 1..3 |
| Electrical turbo-compound plants | 5..7 |
| Steam-turbine units (Rankine cycle) | 4..5 |
| Hybrid turbo-compound installations | 9..11 |
| Units with a low boiling working body | 7..9 |
| Thermoelectric generators | 0.5..2.2 |
| Continuous metal hydride units | 8..12 |

Therefore, the proposed scheme of the energy-generating unit (Fig. 1) with a deep two-stage system to recover heat from OG is a promising technique to improve fuel economy of piston engines with a spark ignition and a cylinder capacity of 240...500 cm³. Specifically, these types of engines are widely used for land transport EU, stationary and mobile power plants, as well as the drives for various assemblies.

The first stage of heat recovery employs mechanical energy of EG over the entire range of EU operation (Fig. 4) and makes it possible to additionally obtain up to 1 kW of net power.

The second stage of heat recovery utilizes thermal energy of EG to decompose the starting fuel (ethanol) into a combustible synthesis gas. As a result of the endothermic decomposition reaction, part of the heat returns to the cycle. In this case, the composition of synthesis gas includes hydrogen, which also has a positive impact on the process of combustion at engine. As a result of these two factors the specific effective fuel consumption decreases by up to 12 % (Fig. 9).

Existing technologies, as well as reactors for fuel conversion [17–19], utilize different catalysts, which reduces the temperature of the reaction and produces gaseous fuel of different composition. However, the major drawback is their high price and fast contamination, which contributes to a continuous decrease in their active capacity. For a given type

of ICE with a spark-ignition, the EG temperature makes it possible to carry out a conversion reaction (Fig. 5, 6) without the use of catalysts that is implied by the design of the devised reactor (Fig. 3).

The selected elements for each stage make it possible to gradually recover their portion of heat and thus reduce fuel consumption by the entire EU by up to 29 %.

Our study was conducted at the engine with positive ignition and naturally aspirated (atmospheric engine). Since the turbocharged engines have higher indicators for efficiency of using the energy of combusted fuel, studying the parameters for operation of this type of engines is promising and can expand and significantly supplement the data already available. Also promising is to explore the application of the proposed deep two-stage recovery of heat from EG for the low-power diesel engines.

7. Conclusions

1. We have proposed a scheme for an energy-generating unit with a deep two-stage system to recover heat from EG, and designed its main elements (a reactor for fuel conversion and a rotary-piston expansion machine). A feature of a given scheme is the possibility of its application at low-power engines with a spark ignition.

2. Depending on the operation mode of ICE the flow rate of a working body through the expansion machine is 8.3...11.3 m³/h, and the speed of rotor rotation is 560...760 rpm. In this case, using a rotary-piston expansion machine as a first stage to recover heat from EG has made it possible to obtain a power gain at the energy-generating unit from 2.5 to 3.43 kW.

3. The application of a fuel conversion reactor as a second stage enables returning up to 4...6 % of heat of the total volume of EG. In this case, the required amount of heat for implementing the starting fuel conversion is 50...65 %.

4. It has been established that reaching the complete conversion during decomposition reaction results in that all liquid ethanol, which entered the conversion reactor, was fully transformed into a combustible synthesis gas. The main components of synthesis gas are hydrogen (43 %), carbon monoxide (34 %), and methane (23 %). The estimated specific lower calorific value of synthesis gas is 28.79 MJ/kg. In this case, obtaining 1 kg of synthesis gas requires 4.0 MJ of thermal energy.

5. When using only a fuel conversion reactor, specific effective fuel consumption, depending on the mode of engine operation, decreases to 12 %. Using the expansion machine in a combination with the reactor makes it possible to decrease the specific effective fuel consumption by up to 29 %.

References

- Gajendra Babu, M. K., Subramanian, K. A. (2013). *Alternative Transportation Fuels: Utilisation in Combustion Engines*. CRC Press is an imprint of Taylor & Francis Group, an Informa business, 464. doi: <https://doi.org/10.1201/b14995>
- Srinivasnaik, M., Sudhakar, Dr. T. V. V., Balunaik, Dr. B. (2015). Bio-fuels as Alternative fuels for Internal Combustion Engines. *International Journal of Scientific and Research Publications*, 5 (12), 531–536.
- A Study of the Effects of Running Gasoline with 15% Ethanol Concentration in Current Production Outboard Four-Stroke Engines and Conventional Two-Stroke Outboard Marine Engines (2011). National Renewable Energy Laboratory. URL: <http://www.nrel.gov/docs/fy12osti/52909.pdf>
- Saadatfar, B., Fakhrai, R., Fransson, T. (2013). Waste heat recovery Organic Rankine cycles in sustainable energy conversion: A state-of-the-art review. *The Journal of MacroTrends in Energy and Sustainability*, 1 (1), 161–188.

5. Tahani, M., Javan, S., Biglari, M. (2013). A comprehensive study on waste heat recovery from internal combustion engines using organic Rankine cycle. *Thermal Science*, 17 (2), 611–624. doi: <https://doi.org/10.2298/tsci111219051t>
6. Larsen, U., Nguyen, T.-V., Knudsen, T., Haglind, F. (2014). System analysis and optimisation of a Kalina split-cycle for waste heat recovery on large marine diesel engines. *Energy*, 64, 484–494. doi: <https://doi.org/10.1016/j.energy.2013.10.069>
7. Waste Heat Recovery System (WHRS) for Reduction of Fuel Consumption, Emissions and EEDI (2012). MAN Diesel & Turbo. Copenhagen, 32. URL: [https://turbomachinery.mandieselturbo.com/docs/librariesprovider4/Turbomachinery_doc/waste-heat-recovery-system-\(whrs\).pdf](https://turbomachinery.mandieselturbo.com/docs/librariesprovider4/Turbomachinery_doc/waste-heat-recovery-system-(whrs).pdf)
8. Noor, A. M., Puteh, R. C., Rajoo, S. (2014). Waste Heat Recovery Technologies In Turbocharged Automotive Engine – A Review. *Journal of Modern Science and Technology*, 2 (1), 108–119.
9. Fu, J., Liu, J., Yang, Y., Ren, C., Zhu, G. (2013). A new approach for exhaust energy recovery of internal combustion engine: Steam turbocharging. *Applied Thermal Engineering*, 52 (1), 150–159. doi: <https://doi.org/10.1016/j.applthermaleng.2012.11.035>
10. Vélez, F., Segovia, J. J., Martín, M. C., Antolín, G., Chejne, F., Quijano, A. (2012). A technical, economical and market review of organic Rankine cycles for the conversion of low-grade heat for power generation. *Renewable and Sustainable Energy Reviews*, 16 (6), 4175–4189. doi: <https://doi.org/10.1016/j.rser.2012.03.022>
11. Wang, E., Zhang, H., Fan, B., Wu, Y. (2012). Optimized performances comparison of organic Rankine cycles for low grade waste heat recovery. *Journal of Mechanical Science and Technology*, 26 (8), 2301–2312. doi: <https://doi.org/10.1007/s12206-012-0603-4>
12. Radchenko, N. I., Sirota, A. A., Radchenko, R. N., Konovalov, D. V. (2013). Cooling potential of scavenge air of low speed diesel engine of transport ship. *Aviatsionno-kosmicheskaya tekhnika i tekhnologiya*, 8 (105), 67–72.
13. Radchenko, R. N., Radchenko, N. I., Bes, T., Sirota, A. A. (2012). Cooling of air at the inlet of main engine of transport ship. *Aviatsionno-kosmicheskaya tekhnika i tekhnologiya*, 10 (97), 61–67.
14. Poran, A., Tartakovsky, L. (2017). Performance and emissions of a direct injection internal combustion engine devised for joint operation with a high-pressure thermochemical recuperation system. *Energy*, 124, 214–226. doi: <https://doi.org/10.1016/j.energy.2017.02.074>
15. Tartakovsky, L. (2018). High-pressure thermo-chemical recuperation – a way toward sustainable propulsion systems. *Procedia Manufacturing*, 21, 37–44. doi: <https://doi.org/10.1016/j.promfg.2018.02.092>
16. Frolov, V. K., Teterev, V. S., Voloschuk, O. I., Shabalin, Y. V. (1995). Pat. No. 7592 UA. Piston machine. No. 4345140/SU; published: 29.09.1995.
17. Borodin, V. I., Truhacheva, V. A. (2007). Termodinamicheskii analiz vysokotemperaturnoy pererabotki estestvennogo polimera – drevesiny. *Sovremennye naukoemkie tekhnologii*, 1, 47–48. Available at: <https://elibrary.ru/item.asp?id=9899973>
18. Kamenev, V. E., Kornilov, G. S., Hripach, N. L. (2004). Gibridnoe avtotransportnoe sredstvo s energeticheskoy ustanovkoy, rabotayuschey na vodorodnom toplive. *Al'ternativnaya energetika i ekologiya*, 2 (10), 28–36. Available at: <http://naukarus.com/gibridnoe-avtotransportnoe-sredstvo-s-energeticheskoy-ustanovkoy-rabotayuschey-na-vodorodnom-toplive>
19. Krylov, O. V. (2000). Uglekislotnaya konversiya metana v sintez-gaz. *Rossiyskiy Himicheskii Zhurnal*, XLIV (1), 19–33. Available at: <http://www.chem.msu.su/rus/jvho/2000-1/19.pdf>