Technical and Economic Evaluation of Turbogenerators in Small Power Plants

L.Yu. Lezhnev, F.A. Shustrov, V.A. Neverov, V.S. Korotkov

Abstract*: Insufficient development of power supply infrastructure, necessity to create reserve power supply sources promotes development of distributed power generation. The main accompanied issues are decrease in fuel consumption and increase in capacity of the sets. Global market of engine–generator sets is saturated and highly competitive. One of the approaches to achieve these aims and to improve competitiveness is application of turbogenerators. This article presents feasibility study of application of turbogenerators in internal combustion engines as a component of engine–generator set. The closest analogs of the developed turbogenerator are given. Advantages and disadvantages of the developed device are compared with those of analogs. Analysis of application of turbogenerator from the point of view of consumers is given, payback periods are determined.

Index Terms*: piston engine, recovery system, turbogenerator, small scale power generation, efficiency increase, fuel efficiency.

I. INTRODUCTION

Application of heat recovery systems attracts great attention due to increase in energy prices, development of energy saving technologies, and restrictions for harmful emissions with exhaust gases. Heat recovery systems based on turbogenerators can be useful and profitable in the regions of small scale and distributed power generation. This profit is obvious for remote areas without access to centralized power supply and strong dependence on fuel deliveries which are mainly carried out by water and air transport significantly increasing cost of fuel.

Nowadays the studies in the field of portable efficient recovery systems of exhaust gases facilitating decrease in fuel consumption, increase in efficiency, thus reducing the cost of generated electricity, are very urgent.

A. Description of preferred market

Global market of engine–generator sets (EGS) is saturated and highly competitive. The market value is estimated at US$16–18 billion, and in terms of power at 60–65 GW [1]. Herewith, about 50% are occupied by sets of small-scale power generation: up to 350 kVA. Starting from 2013, there is continuous growth of sales with annual increase of about 5%. The major market participants are Caterpillar, Cummins, GE Energy, Dresser–Rand, Generac Power Systems, MTU Onsite Energy, and others. According to the report by GlobalData, Market of diesel generators [2], territorially the largest market is Asia Pacific region: 26.8%. The second position is occupied by Europe (23.9%), then Middle East and Africa (21.6%). The portions of North America and South and Central America are 19.6% and 8.1%, respectively.

According to the data by Federal State Statistics Service of the Russian Federation, during the years 2010–2017 the production of EGS in Russia increased by 86% reaching 592 MW/year. At the same time, DISCOVERY Research Group informs [3] that in the years 2010–2016 the production output of EGS with diesel engines increased by about one third upon nearly unchanged market. The sales of diesel EGS after intensive increase in the years 2011–2013 sharply dropped and reached the level of the year 2010. In Russia there are more than 20 producers of EGS, such as: OAO Elektroagregat, OOO Promyshlennye silovye mashiny, GK TSS, OAO ZVEZDA, OAO Kolomenskii zavod, OAO KamAZ, OAO Avtodizel', OOO UDMZ, and others.

B. Main benefits

The main approach to improve attractiveness of EGS for consumers is to increase its efficiency by decrease in its fuel consumption. Fuel efficiency can be improved by application of turbogenerator. Modern internal combustion engines (ICE) are characterized by efficiency of 25–40%, which is illustrated by loss distribution in Fig. 1. At the same time the efficiency of EGS electric generators is 90–95%. In total the cumulative efficiency is 23–38%. However, a portion of energy of exhaust gases can be recovered to electricity (up to 10% of electric power of EGS) using turbogenerators. In this case minor resistance is generated at outlet of exhaust gases, however, most diesel and gas reciprocating engines in EGS are supercharged engines, which decreases this negative effect.

Revised Manuscript Received on June 05, 2019
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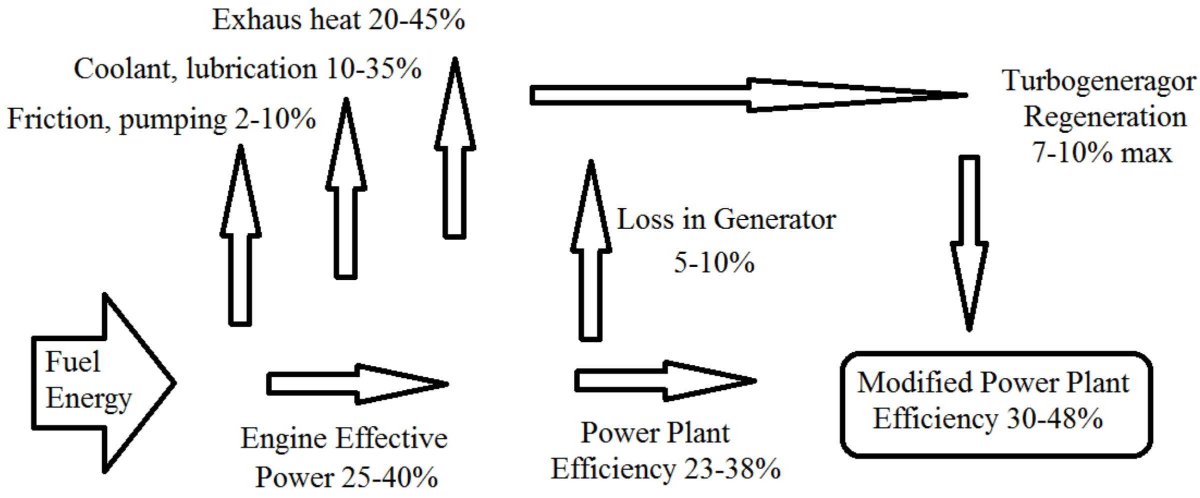

Fig. 1. Loss distribution in EGS.

C. The developed turbogenerator

The developed turbogenerator is intended for installation in ICE exhaust system. The design provides recovery of residual energy of engine exhaust gases for generation of electricity as well as decrease in fuel consumption of carbon dioxide emissions. The model of the developed turbogenerator is illustrated in Fig. 2. The turbogenerator was adjusted and optimized [4, 5].

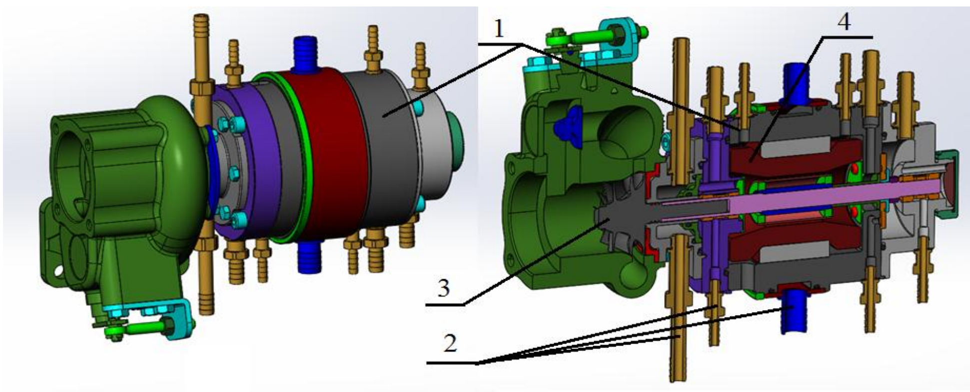

Fig. 2. 3D model of turbogenerator: 1 – housing with cooling jacket and covers; 2 – inlet and outlet connectors of coolant and lubricant; 3 – turbine; 4 – rotor and stator of electric machine.

The turbogenerator is comprised of the following main components: the housing with cooling jacket and covers 1, the inlet and outlet connectors of coolant and lubricant 2, the turbine 3, the rotor and stator of electric machine 4. Fluid cooling improves significantly reliability of turbogenerator.

The developed generator is characterized by high operational performances, such as:

– maximum electric power: 10 kW;
– exhaust gas flow rate: from 0.05–0.15 kg/s;
– nominal RPM of turbogenerator: 80,000 min^{-1};
– power range of basic engine: 80…120 kW;
– voltage: up to 600 V;
– maximum temperature of exhaust gases: 900°C;
– weight: 20 kg;
– dimensions: 0.30×0.25×0.15 m;
– increase in electric power of EGS by recovery: up to 10%;
– decrease in specific effective fuel consumption by EGS with turbogenerator in comparison with basic EGS: up to 7%;
– decrease in specific emissions of CO_2 due to turbogenerator: at least 5%;
– simple design;
– does not require for radical modification of EGS design;
– does not effect the amount of harmful emissions;
– suitable for petrol, diesel and gas engines.

Various electric turbocompressors and turbogenerators can be considered as analogs presented in ICE equipment market. The following western companies are actively involved in such development: BMW (DE), Volvo (SE), Toyota (JP), Honda R&D (JP), Magnetti Marelli (IT), Mitsubishi Heavy Industries (JP), John Deere (US), Cummins (US), Bowman Power Group Ltd (UK), Thin Gap LCC (US), Wärtsilä (FI), and others.

In the electric turbocompressor (Mitsubishi Heavy Industries) for marine engines, electric machine is rigidly connected with turbocompressor, thus, it can operate both as engine and as generator [6]. The manufacturer of high efficient and compact electric generators, ThinGap, proposes similar design of turbogenerator.

The experimental device by NPO Turbotekhnika passed engineless tests. The achieved power was 7 kW, theoretical power with cooling – 20 kW. The main field of application was as follows: as a component of two-stage ICE supercharger systems [7].

The closest analogs are produced by Bowman. Depending on the power of electric set motor, one or several turbogenerators are used. Turbogenerator installed on electric set provides decrease in the specific effective fuel consumption to 7% and increase in the cumulative power to 10% [8–10].

The specifications of the developed turbogenerator are compared with those of the mentioned devices in Table 1. It should be mentioned than most of the considered competitive products are manufactured outside Russia, which increases their cost for main consumers and improves competitive advantages of the planned products.

Table 1. Specifications of turbogenerators/electric turbocompressors

Turbogenerator description	Output electric power, kW	Engine power range, kW	RPM	Weight, kg
The developed turbogenerator	10	80…120	80,000	20
MHI MET–MB Turbochargers	750–1,000	3,000…10,000	10,000–28,000	n/a
NPO Turbotekhnika	7.5	300…400	80,000–10,0000	–
Bowman ETC 300	30	150…400	49,000–60,000	50
Bowman ETC 600	60	300…1,200	30,000–36,000	70
Bowman ETC 1000	110	600…2,000	30,000–36,000	258

As demonstrated by the comparison, the developed turbogenerator occupies certain market position without competitors. At the same time exactly the range up to 350 kVA (280 kW) provides 50% of sales. These facts evidence favorable forecast of application of the developed turbogenerator. Market launch of the developed turbogenerator can exert significant influence both on market structure and on competitive situation.

II. METHODS

This article discusses economic efficiency of turbogenerators for consumers exemplified by EGS based of MMZ 266.4–38 engine and electric generator, their specifications are summarized in Table 2.

Table 2. Specifications of engine and electric generator

MMZ D 266.4–38 engine (Minsk Engine Plant)	
Parameter	Value
Number of cylinders	6 row, vertical
Cylinder diameter/piston stroke, mm	110–125
Displacement, l	7,12
Nominal power, kW (HP, at least	127 (170.3)
Operating power, kW (HP) with auxiliary equipment	122 (163.6)
Crankshaft RPM at nominal power	1,500
Specific fuel consumption, l/(kWh) at nominal power	0.267
GS 100–400 generator	
Generator efficiency, %	86
Generator type	Synchronous
Nominal power, kW	100
Voltage, V	400
Current frequency, Hz	50
Current, A	180
AD AD100–T400–M diesel generator	
Maximum power, kW (kVA)	110 (138)
Nominal power, kW (kVA)	100 (125)
Fuel consumption at 100% load, l/h	26.7
Fuel consumption at 75% load, l/h	20.0
Fuel consumption at 50% load, l/h	13.3
Engine lifetime before major overhaul, engine hours	8,000

Let us compare operational properties of the sets without and with turbogenerator under the following conditions:

– cost of 1 l diesel fuel: US$0.69 (Moscow, January, 2019);

– cost increase of engine–generator: US$2,277;

– the generator operates continuously with pauses for maintenance.

The comparisons and predictions of payback are summarized in Table 3.

Table 3. Comparison of EGS operation properties

Property	EGS	EGS with TG
Nominal electric power, kW	100	100
Required engine power, kW	116.3	104.6
Fuel consumption at 100% load, l/h (kg/h)	27.00 (23.20)	24.55 (21.11)

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

Specific effective consumption relative to mechanical power	0.209	0.209
Specific effective consumption relative to electric power	0.232	0.211
Fuel consumption, l per day per month per year	648 19 440 236 520	589.2 17,676 215,058
Savings, l per day per month per year	– – –	58.8 1,764 21,462
Savings during warranty period, US$	–	11,247
Savings per year, US$	–	12,532
Payback upon nominal operation mode	–	54 days of 1,300 engine hours

Therefore, installation of turbogenerator is paid back during warranty period. During the warranty period of EGS operation, the savings are US$11,247. At the same time the actual lifetime of EGS can reach more than 8 thousand engine hours. Figure 3 illustrates profit resulting by application of turbogenerator. It can be seen that the growth is linear, after payback period the unit provides savings of fuel consumption.

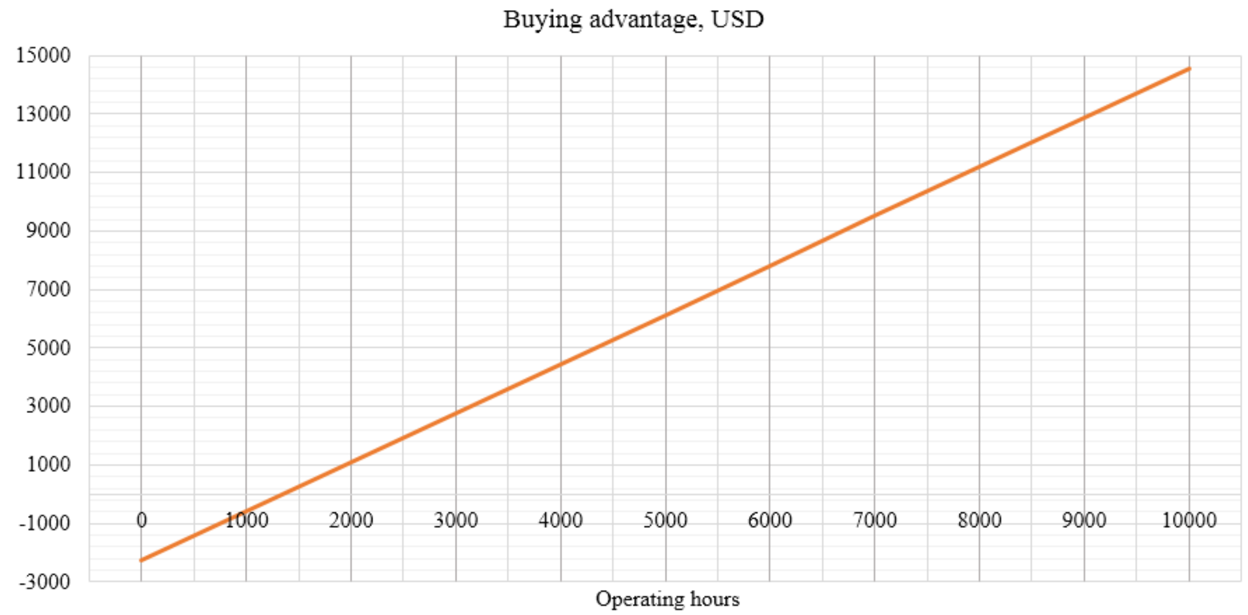

Fig. 3. Increase in benefits of turbogenerator.

The contracts between manufacturer and suppliers for delivery of components would permit to gain profit from production of turbogenerators. The cost of components required for production of unit product is US$1,742. In the case of annual production of 1,500 units, total revenue of suppliers will be US$2,612,885. Herewith, the highest benefit is obtained by manufacturer of electric machine since its cost constitutes the highest portion of production cost.

Product sales provide benefits for intermediate participants of manufacturer–consumer chain. Average marginality in the field of electric engineering is 7.5%. Then, at the sales amount of 1,500 units per year and the cost of US$2,277, the average revenues will be US$256,163.

In addition to production and product sales, qualified maintenance is required. Usually each maintenance is performed every 200–500 engine hours. The developed turbogenerator does not require for replacement of consumables and the applied motor oil is the same as for ICE EGS. Then, all expenses for its maintenance will be comprised of visual emanation of turbo compressor for leakage, testing generator operation, and observing power wires. These procedures are not energy intensive and do not require for complicated special equipment. In this regard the increase in expenses for single maintenance will be not higher than 10%. Herewith, maintenance periodicity of turbogenerators should be reasonably performed each 500 engine hours. In such case the increase in total maintenance expenses during warranty period will be US$130.

Decrease in load on engine will improve EGS lifetime. Special procedures of lifetime evaluation as a function of power are unavailable, though, it is possible to evaluate this performance approximately. ICE operation in EGS takes place at constant crankshaft RPM, herewith, the torque varies. Since decrease in the required power is 10%, then the torque also decreases by 10%. The torque is directly proportional to average effective pressure in engine cylinder. In its turn the normal force N acting on cylinder wall and related with its wear and engine lifetime is also directly proportional to the average effective pressure.

Thus, it is possible to assume that the ICE lifetime will increase by 10%. At the cost of 1 kWh of US$0.0842 (Moscow, January, 2019) and increased lifetime before major overhaul equaling to 8,800 engine hours instead of 8,000 engine hours, the benefit will be US$6,736.

Upon consideration of profit resulting from the application, the peculiarities of fiscal load on manufacturers should be mentioned. It is comprised of social tax (30.2%), property tax (2.2%), value added tax (20%), profit tax (20%). Table 4 summarizes final payments at the end of the fifth year of production of 1,500 turbogenerators per year. According to the predictions, the final amount will be US$1,260,326.

Table 4. Tax payments at the end of the fifth year

Description	Amount, US$
Social Tax	83,487
Property Tax	10,384
Profit Tax	519,190
Value Added Tax	647,265
Total:	1,260,326

III. CONCLUSION

It has been demonstrated that the use of turbogenerator as a component of EGS is economically efficient solution. It is stipulated by a set of engineering and economic reasons.

Advantages:

- Decrease in fuel consumption from 7 to 10%;
- Nominal power: 10 kW;
- Decrease in load on main engine: improvement of its lifetime;
- Relatively low cost of production;
- No competitiveness among foreign manufacturers (in this power range);
- Short payback periods for consumers (1,300 engine hours), together with fuel savings per warranty period: US$11,247, increase in lifetime by US$6,736;
- Minimum number of modifications in design of power unit;
- Further improvements of the performances are possible;
- Total annual profit of suppliers: US$2,612,884.6;
- Total annual issue of sellers: US$256,163;
- Increase in profit of maintenance companies during warranty period: US$130 per EGS;
- Increase in tax payment in 5 years of selling turbogenerators by US$1,260,326.

Disadvantages:

- Auxiliary unit requiring maintenance;
- No compatible devices of various sizes.

ACKNOWLEDGEMENTS

This work was supported by the Ministry of Science and Education of the Russian Federation, agreement No. 14.574.21.0154 of September 26, 2017. Unique project identifier: RFMEFI57417X0154.

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