Experimental study of an internal combustion engine fueled by a low-calorific value producer gas

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Abstract. This paper describes an experimental study of the operation of an internal combustion engine of fueled by a low-calorific value gas. The main operating parameters of low-power ICE were determined. Efficiency was also evaluated when the ICE was converted to operate on producer gas. In the experiment, it was shown that the engine reached a stable operating mode under load and data on the temperature and exhaust gases composition were obtained. According to our estimates, in the steady-state operation of the internal combustion engine with a load, the efficiency factor was about 22 %. When using the model gas, the from generator output power, was about 30-40 % of the nominal value, under variable load conditions. However, it was found that in steady-state operation, the power of the internal combustion engine was 40-55% of the nominal value.

1. Introduction

The problem of power supply for autonomous consumers [1] has been relevant for several centuries, however, with an increase in the standard of living, it is required to provide high-quality energy resources with guaranteed reliability. At the same time, it is necessary to solve the issues of environmental safety and economic efficiency in energy production even at low-power plants.

Decentralized energy supply areas often have local fuel resources, low-grade solid fuels and various wastes. One of these sources is biomass, such as wood waste from logging operations. At the same time, their conversion into high quality electrical and thermal energy can be carried out using gasification technologies, followed by the use of producer gas in internal combustion engines (ICEs). As a rule, the gas produced during air gasification has a low calorific value of the order of 4–5 MJ/m\(^3\), which makes its transportation unprofitable [2], whereas its use in gas internal combustion engines can provide the replacement of expensive imported diesel fuel and provide the consumer with electrical energy [3].

However, there is the problem of the reduce efficiency of internal combustion engines operating on off-design fuels. Difficulties also arise with the start of engines on low-calorific value producer gas; in this case, ignition doses of diesel fuel or, for example, methane are used.

Despite the flexibility of internal combustion engines in operation with variable load, possible fluctuations in the composition of the producer gas, its contamination with dust particles, tar (up to 10 g/nm\(^3\)) [4], and high gas humidity can negatively affect the reliability and failure-free operation of ICEs.
Therefore, after the gasification reactor, a gas purification unit for removal of solid particles and tar is required, as well as dehumidification for moisture condensation and cooling of hot gas [5].

In a previous thermal calculation of an internal combustion engine, the operating conditions were estimated for the electric power levels of 30–300 kW according to [6].

The authors and colleagues have developed a biomass conversion reactor with a power of 5 kW [7], but for a comprehensive assessment of the operation of a gasifier with an internal combustion engine, a separate study of the power part is required, therefore an experimental setup with a small-power ICE was made. The purpose of the work was to carry out an experimental study of the modes and features of ICE operation on a low-calorific value producer gas.

2. Material and methods

2.1. Experimental setup

The gasoline internal combustion engine was modified and converted to gas fuel. Test runs with a model gas were carried out using the Kronwerk 94649 LK1500 generator.

The Kronwerk generator is an autonomous power plant used to power electrical equipment in the absence of a household network or for remote consumers. The air-cooled engine with a volume of 94 cm$^3$ consists of a 4-stroke single-cylinder with a rated power of 1 kW and a maximum power of 1.2 kW.

Using this generator, a series of experiments were carried out with a model gas which was a mixture of combustible gases with CO$_2$ and N$_2$. Gas was supplied from a cylinder through a system of pressure gauges; air was sucked in through a branch pipe and mixed with the gas. After that, the mixture entered the internal combustion engine, exhaust gases were emitted at the outlet, and electricity was generated and fed to the load system (Figure 1).

![Figure 1. Schematic of the experimental setup: 1 – gas cylinder; 2 – gas mixing unit; 3 – generator; 4 – voltmeter and ammeter; 5 – load system with electric lamps; 6 – thermocouple; 7 – gas analyzer.](image)

The temperature and composition of the exhaust gases were measured, and the parameters of electrical energy under variable load conditions were determined. The load system consisted of four 100–150 W electric lamps. To determine the composition of the exhaust gases, a TESTO 340 Gas Analyzer and an Inficon Micro GC fusion Chromatograph were used.
Since the air gasification of biomass gives a producer gas with a high nitrogen content but with a low calorific value, a model gas for experimental engine runs has been produced. Its composition was as follows (molar fraction, %): \( \text{C}_2\text{H}_6 \) – 0.964; \( \text{C}_2\text{H}_4 \) – 0.959; \( \text{H}_2 \) – 17.26; \( \text{CH}_4 \) – 4.26; \( \text{CO} \) – 17.28; \( \text{CO}_2 \) – 13.09; \( \text{N}_2 \) – 46.187. This composition typical of the gas produced by air gasification of biomass.

All measured parameters were recorded over time and entered into an experimental database.

2.2. Calculation

In the calculation of the ICE efficiency, the generated power and the energy of the supplied gas were evaluated. The calorific value of the gas mixture was 6.75 MJ/m\(^3\).

The average gas consumption in the experiments was 18 liter per minute. Thus, the amount of energy supplied to the ICE was calculated by multiplying the gas consumption by its calorific value.

The energy output from the generator (N) was determined from the readings of the voltmeter and ammeter. In steady-state operation, the power level was 325–448 W (Figure 2).

\[
\text{Figure 2. Dependence of power on exhaust gas temperature.}
\]

The effective efficiency factor \( \eta_e \) is the ratio of the amount of heat converted into effective work by the engine \( L_e \) on the amount of heat \( Q_e \) supplied to perform this work.

\[
\eta_e = \frac{L_e}{Q_e}
\]  

(1)

The excess air factor was calculated from the exhaust gases composition by using the oxygen formula:

\[
\alpha = \frac{21}{21 - \text{O}_2}
\]  

(2)

The thermal calculation (Table 1) of the internal combustion engine was made for natural gas (methane) and the model gas. However, for the calculation, it was assumed that the engine produces the same power level.
Table 1. Thermal calculation results for the gas-fuelled engine.

| Index                                      | Notation | Measurement unit | Model gas | Methane |
|--------------------------------------------|----------|------------------|-----------|---------|
| Excess air factor                          | \( \alpha \) |                  | 2         | 2       |
| Specific weight of combustible gas         | \( \gamma_n \) | kg/nm\(^3\)     | 1.12      | 0.766   |
| Lowest heating value of combustible gas    | \( Q \)   | kcal/nm\(^3\)   | 1633      | 8000    |
| Volume of theoretically required air for   | \( L_o \) | nm\(^3\)/nm\(^3\) | 1.22      | 8.95    |
|   combustion of a volume unit of fuel      |          |                  |           |         |
| Electric power of the engine               | \( N_e \) | W\(_e\)         | 455       | 455     |
| Specific effective fuel consumption        | \( V_e \) | m\(^3\)/kW\(_e\) | 5.66      | 0.637   |
| Specific effective heat consumption        | \( q_e \) | kcal/kW\(_e\)   | 7553      | 4327    |
| Effective engine efficiency                | \( \eta_e \) | %                | 20.5      | 19.6    |

The estimated temperature in the cylinder of the internal combustion engine during the combustion of methane was 1320 °C, of model gas was 1240 °C. The calculation was made for dry gas (disregarding external moisture). The heat from syngas cooling can be transferred through the heat exchanger to dry the fuel or can be used to heat the air supplied to the gasifier.

3. Results and discussion

According to our estimates, the internal combustion engine in steady-state operation has an efficiency factor of about 22%. The average excess air factor is 2. Therefore, a comparison of the experimental data and thermal calculation results shows that they are in good agreement.

For example, the generator output power obtained using the model gas under variable load conditions operation was about 30–40% of the nominal value. In steady-state operation, the power of the internal combustion engine is 40–55% of the nominal value. The calculated maximum experimental power is 455 W.

However, when comparing the thermal calculation results for the ICE on the model gas and the ICE on methane, it can be seen that the specific gas consumption is higher for the model gas than for methane.

Figure 3 shows data on the exhaust gas composition for a number of experimental points; nitrogen is about 80 percent of the total composition. The presence of residual oxygen indicates an excess of air supply.

The amount of pollutants in the exhaust gases of the internal combustion engine was determined when using the model gas. The exhaust gases were found to contain a small amount of SOx (10–15 ppm), produced by the combustion of engine oil which penetrated into the combustion chamber when the engine was started and stopped.

The NOx emissions from the combustion of the model gas in the internal combustion engine were estimated. The steady-state amount of NOx is 10–12 ppm.

Since the consumption of the model gas changed with increasing electrical load, the NOx content also changed.
It is shown (Figure 4) that after the engine warms up, the exhaust gas temperature reaches a constant value of ~350 °C and does not depend on the load and gas consumption.

4. Conclusions

According to the results of the experimental study using the model gas, satisfactory operating conditions of the internal combustion engine under load were worked out. Data on the output power, temperature and composition of exhaust gases were obtained.

The generator output power, which obtained using the model gas at a voltage of 220±20V was about 30–40 % of the nominal value, under variable load conditions. However, it was found that in the steady state the power of the internal combustion engine is 40–55% of the nominal value. According to our estimates, in the steady-state operation of the internal combustion engine with a load, the efficiency factor is about 22 %, which corresponds to the calculated values.

The data on the exhaust gas temperature in the range of 320–370 °C at the calculated power level and the presence of residual oxygen indicate an excess of supplied air. In this connection, it is planned to modify the supply channel.
The results of the study will make it possible to further improve the operation of the internal combustion engine on a low-calorific value producer gas, which will be directly obtained by gasification of various solid fuels. The next stage of the study work is the launch of a biomass conversion reactor with this internal combustion engine.

Acknowledgements
This reported study was funded by the Russian Foundation for Basic Research (RFBR) No. 19-58-80016; the Department of Science and Technology of India (DST) No. CRG/2018/004610, DST/TDT/TDP-011/2017; the Ministry of Science and Technology of the People’s Republic of China (MOST) No. 2018YFE0183600; the National Research Council of Brazil (CNPq) No. 402849/2019-1; and the National Research Foundation of South Africa (NRF) No. BRIC190321424123; the resources of the High-Temperature Circuit Multi-Access Research Center were used (Ministry of Science and Higher Education of the Russian Federation, Project No. 13.CKP.21.0038).

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