Study of hydrogen gaseous fuel influence on the thermal condition of a diesel engine

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Abstract. The current article presents experimental results for the thermal condition of a diesel-hydrogen powered engine. The object of the study is an air-cooled single cylinder diesel engine. A quantitative assessment of the engine thermal condition is made. It is based on four engine body part temperatures and the temperatures of exhaust gases and engine oil. The study is carried through by comparing the engine indexes via regulation characteristics as a function of the hydrogen mass content and load characteristics with constant hydrogen content. Experimental results as a function of engine speed at constant engine power are also presented. The data registered during the experiment is for two different diesel injection advance angles. A temperature for one location on the combustion chamber roof (cylinder head) is calculated. The results of the experiment are presented in charts.

1. Introduction

The internal combustion engines (ICEs) are heat engines which convert the chemical energy of the supplied fuel into mechanical work. The energy transformation takes place during the combustion and the expansion processes. The heat released during the combustion of the cyclic fuel quantity has a direct effect both on the transient temperature value of the fuel mixture in the engine cylinder and on the thermal conditions of the elements forming the inner surface of the combustion chamber. On the other hand, an optimal combustion process is directly dependent on the thermal conditions of the whole engine [1, 2]. The thermal condition of an internal combustion engine is determined by the coolant temperature, the crankcase oil temperature, the exhaust gas temperature, and the engine components’ temperature.

Working on a gas-diesel cycle is one of the more effective ways to improve the emissions of diesel engines [3-6]. The gas-diesel cycle requires engine operation with two different fuel types: diesel fuel and gaseous fuels. However, the operation of a diesel engine with two fuels leads to changes of its combustion process [7-9], and therefore in its thermal conditions. Hydrogen, which is the most promising alternative fuel for internal combustion engines, has a number of properties [10,11]: high lower heating value \( H_u = 120 \text{ MJ/kg} \), ignition and combustion in a wide range of fuel-air ratios \( \alpha = 0.2 \ldots 10 \), high speed of flame front propagation, and other properties which directly affect the combustion process and the thermal conditions of the internal combustion engine [12,13].

2. Purpose of research

In connection with the above, the research aim is to make a quantitative assessment and analysis of the influence of hydrogen gaseous fuel on the thermal conditions of a diesel engine working on gas-diesel cycle.
3. Study subject and methodology
The subject of the current study is a single-cylinder four-stroke air-cooled diesel engine DV-550 (Bulgaria). The basic engine parameters are cylinder bore \( D = 91.5 \) mm; piston stroke \( S = 85 \) mm; compression ratio \( \varepsilon = 17.5 \); direct fuel injection into the cylinder, partially stratified mixture formation; nominal power \( N_e = 8 \) kW at engine speed \( n = 3000 \) min\(^{-1}\).

The methodology of research is based on regulating characteristics with variable gaseous fuel content [14]. These characteristics are obtained at constant engine speed – \( n = \text{const} \) while varying fuel consumption of diesel fuel \( B_D \) and hydrogen \( B_{H_2} \). Distinctive parameters are presented as a function of the hydrogen mass share in total fuel – the \( K_{H_2} \) coefficient. The \( K_{H_2} \) coefficient is described by the formula:

\[
K_{H_2} = \left( \frac{B_{H_2}}{B_h} \right) \times 100\%,
\]

where \( B_h \) is the total fuel consumption and equals \( B_h = B_D + B_{H_2} \). The load and speed engine characteristics (at constant hydrogen mass share in total fuel) can be built by obtaining full series of engine regulating characteristics.

4. Technical resources for the research
The engine subject of the current study is coupled to a \( SAC \ 28 \) direct-current dynamometer, by means of which the engine performance is measured. The brake power is measured with accuracy of 0.005 kgf. An electronic frequency meter registering the pulse frequency of an inductive sensor paired with a 60-tooth wheel is used to measure engine speed. The diesel fuel consumption is measured with a volumetric flow meter for liquid fuel. The consumed diesel fuel volume is measured with accuracy of 0.2 cm\(^3\). The hydrogen fuel consumption is determined with a G4-type volumetric flow meter for gaseous fuel. The hydrogen volume is measured with up to 0.2 dm\(^3\) accuracy. The full test bench description is given at [15].

For the purpose of the research, six temperatures are registered: engine oil temperature – \( T_{oil} \); exhaust gas temperature – \( T_{eg} \), measured at a distance of 100 mm from the exhaust manifold flange; three temperatures at the cylinder’s external wall – \( T_{cyl}^1, T_{cyl}^2, T_{cyl}^3 \), one temperature in the internal part of the cylinder head wall – \( T_{head} \). All thermocouples are K-type. The measurement of engine oil temperature and exhaust gases is done with electronic devices with an error of 0.75% ± 1 °C which guarantees a maximum accuracy of 1% for the maximum measured value of 450 °C. The other four temperatures are registered with a specialised system (data acquisition device) for temperature measurements \( NI \ 9211 \), manufactured by \( National \ Instruments \). The system works with the \( LabView \) software package. According to the manufacturer’s datasheet, the measurement system maximum error is 2.3 °C in the 0...400 °C interval which guarantees an accuracy of 1.14% for the maximum measured value of 200 °C.

The thermocouples for measuring the cylinder external wall temperatures are mounted between the cooling ribs at distances of 15, 22, and 29 mm from the plane dividing the cylinder head from the engine cylinder. The cylinder head temperature is measured with a thermocouple mounted in a threaded collar. The collar is mounted in a threaded hole drilled in the cylinder head. During the engine indicating process, a piezoelectric sensor used to register the cylinder pressure data is mounted in the threaded hole. The thermal conduction coefficient of the threaded collar material is the same as the thermal conduction coefficient of the cylinder head material.

During the data processing, the temperatures \( T_{cyl}^m \), calculated as an average of the three thermocouples mounted on the cylinder’s external wall, and the temperature of the cylinder head surface enclosing the combustion chamber \( T_{head}^w \) are calculated by using the following equations:

\[
T_{cyl}^m = \frac{T_{cyl}^1 + T_{cyl}^2 + T_{cyl}^3}{3},
\]
\[ T_{\text{head}} = \frac{T_{\text{head}} - T_{\text{oil}}}{1 - \frac{x}{\delta}}, \]  

(3)

where: \( x \) is the distance from the internal surface of the cylinder head to the thermocouple weld in the threaded collar (\( x = 7 \text{ mm} \)) and \( \delta \) is the threaded collar height (\( \delta = 33.5 \text{ mm} \)). Equation (3) is known from the heat conduction theory [16]. It is accepted that the temperature of the upper surface of the threaded collar is equal to the temperature of the oil in the oil pan as it is situated directly under the valve rocker arms axis and is in constant contact with the engine oil under the valve cover.

The diesel fuel injection advance angle \( - \theta \), which also has a significant influence on the combustion process parameters, therefore on the engine thermal condition [2], is measured with a special device with a stroboscopic lamp and a piezoelectric sensor. The sensor is installed on the high-pressure pipeline connecting the injection pump and the nozzle. The stroboscopic lamp is activated by the voltage induced by the sensor which is proportional to the deformation of the high-pressure pipeline in the moment of fuel injection. The \( \theta \) angle is recorded in numerical form in the moment when the moving and stationary marks for the piston top dead centre (TDC) match.

5. Study results

Most of the experimental results are recorded with stock engine fuel system setup where the diesel fuel injection advance angle is equal to 20 degrees (crankshaft rotation) before TDC, i.e. \( \theta = 20 \text{ deg} \). Full series of regulation characteristics with variable hydrogen fuel content at \( \theta = 20 \text{ deg} \) are obtained at three engine speed modes: \( n = 1500 \text{ min}^{-1}, n = 2000 \text{ min}^{-1}, \) and \( n = 2500 \text{ min}^{-1} \). The influence of the speed on the thermal condition of the engine is also investigated with the mean effective pressure \( - p_e \) and the hydrogen mass content coefficient \( K_{H_2} \) changing within narrow ranges.

In the course of the research it was established that with the stock setting of the diesel fuel ignition advance angle and engine load over 60% and percentage by mass of hydrogen over 10%, unacceptably high cylinder pressure rise rate values are reached. Therefore, a new series of regulation characteristics with variable hydrogen mass content in total fuel was obtained at speed \( n = 2000 \text{ min}^{-1} \) and diesel fuel injection advance angle \( \theta = 12 \text{ deg} \). In this series however, the temperature of the cylinder head \( T_{\text{head}} \) is not registered.

Some of the experimental results are shown on figures 1 to 7. The result analysis shows the following:

- When operating a DV-550 engine on a gas-diesel cycle and varying the hydrogen mass share in total fuel \( (K_{H_2}) \) at low and medium loads \( (p_e \leq 0.3 \text{ MPa}) \), the maximum differences in the average cylinder temperature compared to its temperature when operating only on diesel fuel are in
the range of 5.3…8.2%. The high values of the differences are observed when working with an injection advance $\theta = 20$ deg, and the low values – at $\theta = 12$ deg. At the same operating modes and injection advance $\theta = 20$ deg, the maximum differences in cylinder head temperature are 9%.

Figure 3. Body part temperatures of a DV-550 engine working on a gas-diesel cycle with variable hydrogen mass content, $n = 2000$ min$^{-1}$ and $\theta = 12$ deg

Figure 4. Body part temperatures (calculated), oil and exhaust gas temperatures of a DV-550 engine working on a gas-diesel cycle with variable hydrogen mass content, $n = 2000$ min$^{-1}$ and $\theta = 12$ deg

Figure 5. Comparison of distinctive temperatures as a function of the load of a DV-550 engine working on diesel fuel and on a gas-diesel cycle with hydrogen mass ratio $K_{H_2} = 15\%$, $n = 2000$ min$^{-1}$ and $\theta = 20$ deg

Figure 6. Comparison of distinctive temperatures as a function of the load of a DV-550 engine working on diesel fuel and on a gas-diesel cycle with hydrogen mass ratio $K_{H_2} = 15\%$, $n = 2000$ min$^{-1}$ and $\theta = 12$ deg

Figure 7. Comparison of distinctive temperatures as a function of the speed of a DV-550 engine working on diesel fuel and on a gas-diesel cycle with hydrogen mass ratio $K_{H_2} = 10\%$, $p_e \approx 0.44$ MPa and $\theta = 20$ deg

- When operating the engine with an injection advance $\theta = 20$ deg, the following trend is observed: with increasing engine load, the peak temperatures of the body parts shift to the higher hydrogen mass share in total fuel ($K_{H_2}$), and when working with an injection advance
\[ \theta = 12 \text{ deg} \] the tendency is reversed – with increasing engine load the peaks are shifted to a lower hydrogen mass share in total fuel \((K_{H_2})\).

- The studied operation modes do not show a significant change in the temperature of the exhaust gases when operating the engine on a gas-diesel cycle compared to the temperature when operating only on diesel fuel (the difference is up to 3%);
- According to the load characteristic at engine speed \(n = 2000 \text{ min}^{-1}\), the largest percentage differences in the measured temperatures of the body parts and the exhaust gases (when working on a gas-diesel cycle compared to those when working on diesel fuel only) are observed at injection advance \(\theta = 20 \text{ deg}\) and high loads. When operating the engine with an injection advance \(\theta = 20 \text{ deg}\) and low loads, a decrease in temperature of 5% is observed when operating on a gas-diesel cycle \((K_{H_2} = 15\%)\) compared to operation only on diesel fuel. At an injection advance \(\theta = 12 \text{ deg}\), no significant differences in the respective temperatures are observed (up to 3%).
- In the studied speed range of the DV-550 engine with an injection advance \(\theta = 20 \text{ deg}\) and approximately constant mean effective pressure \(p_e \approx 0.44 \text{ MPa}\), there is an increase in the average temperature of the cylinder (on average by 8%) when working on gas-diesel cycle compared to operation only on diesel fuel.

### 6. Conclusion

The results of the experimental study allow us to draw the following conclusions:

- The change of the percentage mass content of hydrogen in the total amount of fuel during the operation of a diesel engine on a gas-diesel cycle has an impact mainly on the maximum values of the temperatures, characterizing the thermal state of the engine. This effect is more pronounced at medium and high loads;
- When operating the engine on a gas-diesel cycle with hydrogen gaseous fuel, the change in the diesel fuel injection advance angle leads to a change in both the absolute values of the maximum temperature differences and the nature of their change depending on the percentage of hydrogen in the fuel;
- The change in speed under equal other conditions does not affect the differences in the engine thermal state during the gas-diesel cycle compared to the operation with diesel fuel.
- In conclusion, it can be noted that when operating the engine DV-550 on a gas-diesel cycle with hydrogen gaseous fuel in some of the modes, both in terms of load and in terms of hydrogen fuel percentage, there is a significant increase in temperatures characterizing the thermal state of the engine. When optimizing the diesel fuel injection advance angle, this negative trend can be minimized.

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