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Economic aspects of using hydrogen in compression ignition engine operating on gas-diesel cycle

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Abstract. The article gives an overview of the economic aspects of a single-cylinder internal combustion engine dual fuel operation with diesel fuel and hydrogen. The engine operating costs are calculated. Two separate cases are investigated. The first case is at constant engine speed – 1500 rpm, constant engine power (1.5 kW) and variable hydrogen mass fraction in the total fuel mass (from 0 to 50%) and the second case is at constant engine speed – (1500 and 2000 rpm), constant hydrogen mass fraction in the total fuel mass (10%) and variable engine power (1 to 4 kW). The following parameters (as a function of the corresponding variable) are determined for both cases: expenses for hydrogen and diesel fuel (in €/hour), price of the energy obtained at the engine crankshaft (in €/kWh), expenses for the CO_2 emissions emitted by the engine (in €/hour). The weighted average of the fuel mixture price (in €/kg) is also determined for the first case. The calculations are made using average fuel prices in Germany for April 2019. A predominant growth in the operating costs is observed as a function of the growing hydrogen mass fraction and increasing engine power. A significant reduction in the price of CO_2 emissions at constant engine power and growing hydrogen mass fraction is observed due to the lower exhaust gas toxicity.

1. Introduction

Hydrogen is among the purest fuels mankind knows. During hydrogen oxidation, only water is produced. Therefore, the harmful emissions of an internal combustion (IC) engine should tend to zero if hydrogen is used as a fuel. In practice, this is not the case because the higher in-cylinder temperatures caused by the hydrogen combustion create conditions for nitrogen oxide formation. There is a lot of research dedicated to this problem proposing a wide range of solutions such as urea injection in the engine exhaust, water injection in the engine intake or innovative methods for exhaust gas recirculation [1-3]. However, the use of hydrogen as a fuel has a number of benefits, such as reduction of the exhaust gas emissions, reduction of the fuel consumption, efficiency increase and thus environment protection. If used as an auxiliary fuel in compression ignition engines, hydrogen has a major influence on exhaust gas toxicity – greatly reduces the opacity and carbon oxide content [4-5]. The main obstacle to the mass use of hydrogen as a fuel for ICE is its high price. In this relation, the current study represents an analysis of the operating costs of a diesel engine working on a gas-diesel cycle with hydrogen.

The term "gas-diesel cycle" is used to describe the operation of a compression ignition engine with two fuels simultaneously – diesel fuel and gaseous fuel, hydrogen in the current case. A small amount of diesel fuel, which self-ignites and then ignites the gaseous fuel, is injected into the cylinder. The majority of heat during gas-diesel cycle operation is normally produced by the gaseous fuel. It may be injected directly into the cylinder or in the intake manifold and then enters in the cylinder during the intake process. For the aim of the current study the gas-diesel cycle is accomplished via external mixture formation of the gaseous fuel (hydrogen injected in the intake manifold). In order to determine the quantity of hydrogen in fuel, a coefficient K_{H2} is defined. It represents the ratio between the hydrogen fuel mass and the total fuel mass (hydrogen and diesel fuel). The operating costs calculations are performed for variable values of this coefficient and steady operation modes – constant engine speed and load. Calculations are also made for a constant K_{H2} coefficient, constant engine speed and variable engine loads. Such results can be useful for future economic assessments of the implementation of hydrogen as a fuel for mass use in road vehicles and industrial capacities. An economic assessment is of significant importance for the industry and the sector of services in the context of constant reduction of the available resources and rise of prices if keeping the same demand level.

The high price of hydrogen presumes a negative economic assessment for the operational costs of a compression ignition engine working on diesel-hydrogen cycle. Nevertheless, an approximate calculation of the operational costs of a compression ignition engine running on gas-diesel cycle deserves attention due to the abovementioned benefits of using hydrogen as fuel. Such calculation would be of use to engine, road vehicles and hydrogen manufacturers.

2. Purpose of the study

After taking into account the previous analysis, we can summarize that the purpose of the study is to define the monetary value of the operational costs of a compression ignition engine running on hydrogen-diesel cycle.

3. Methodology of the research

Some of the data used in the current article is gathered for the purpose of another research [6] conducted by the same authors and concerning the influence of hydrogen on a compression ignition engine performance. The experiments are conducted on a test bench which consists of a compression ignition engine and a direct-current dynamometer coupled via a common shaft. The direct-current dynamometer is used to regulate the engine load. Engine parameters are shown in table 1.

Table 1. Parameters of a compression ignition engine DV 550.

Parameter	Value	Dimension
Displacement volume	550	cm^3
Bore	91.5	mm
Stroke	85	mm
Number of cylinders	1	-
Number of valves per cylinder	2	-
Compression ratio	17.5	-

Both fuels – diesel fuel and hydrogen, are injected directly into the cylinder and in the intake manifold, respectively, and the hydrogen-diesel ratio is varied during the experiment. Fuel consumption for both fuels, exhaust gas toxicity and in-cylinder pressure are measured. The experimental setup and additional information for the referring experiment can be found in the corresponding article.

In order to fulfil the purpose of the study it is necessary to make a calculation of the engine operating expenses for gas-diesel cycle: fuel expenses (diesel fuel and hydrogen), expenses for engine maintenance – oil, filters etc. and expenses for the toxic components of the exhaust gases (if applicable). These expenses should be calculated in two separate cases. In the first case – as a function of the hydrogen mass share in the total fuel amount with engine running at constant speed and load. In the second case – as a function of the engine load with engine running at constant speed and constant hydrogen mass share in the total fuel amount. A 10% mass share of hydrogen is chosen because this is the maximum achievable share on all engine modes without engine design modifications. This is due to reaching dangerously high values of the in-cylinder temperature and pressure rise rate with the increase of hydrogen content in the fuel, especially with engine running under high loads [7].

The expenses for engine maintenance should not change as a function of the hydrogen mass share in the total fuel amount. That is because under a constant load and engine speed, the oil, filters – oil filter, air filter, fuel filter, etc., do not wear with different intensity as a function of the hydrogen quantity in the total fuel. It is possible for oil to keep its finest properties longer due to the lowered opacity in blown by gases and for the diesel fuel filter to have a longer life due the lower amount of diesel fuel passing through. Such study would require extended engine tests and therefore the maintenance costs are not taken into account for the calculation of engine operating costs.

The diesel fuel expenses P_{DF} can be calculated using the following equation:

$$P_{DF} = p_{DF} B_{DF}, \text{€/h}, \tag{1}$$

where p_{DF} is diesel fuel price, €/kg; B_{DF} – diesel fuel consumption, kg/h.

Similarly, for the hydrogen fuel expense P_{H2}, we have:

$$P_{H2} = p_{H2} B_{H2}, \text{€/h}, \tag{2}$$

where p_{H2} is hydrogen fuel price, €/kg; B_{H2} – hydrogen fuel consumption, kg/h.

The total fuel expenses P_F can be calculated using (1) and (2) with the equation:

$$P_F = P_{DF} + P_{H2}, \text{€/h}. \tag{3}$$

The expenses thus calculated vary as a function of the hydrogen-diesel fuel mass ratio exact numerical value information for which we can get from the K_{H2} coefficient given with the equation:

$$K_{H2} = \frac{B_{H2}}{B_F} 100, \%, \tag{4}$$

where B_F is total engine fuel consumption:

$$B_F = B_{DF} + B_{H2}, \text{kg/h}. \tag{5}$$

In this way, we obtain the function: $P_F = f(K_{H2})$.

If we divide the total fuel expenses by the total fuel mass which has entered in the engine we obtain the weighted average price P_{FA} per kilogram of fuel mixture:

$$P_{FA} = \frac{P_F}{B_F} = \frac{P_{DF}+P_{H2}}{B_{DF}+B_{H2}} = \frac{p_{H2}B_{H2}+p_{DF}B_{DF}}{B_{DF}+B_{H2}}, \text{€/kg}. \tag{6}$$

The thus calculated price for a kilogram of fuel mixture gives a possibility to determine the expenses for the mechanical energy produced by the engine. The price of electricity is usually measured in €/kWh. Therefore in order to calculate the price of energy produced by the engine we may use an indicator determined from the multiplication of the weighted average price per kilogram of fuel mixture P_{FA} and the engine specific fuel consumption:

$$P_{kW} = P_{FA}\, g_e, \text{€/kWh}, \tag{7}$$

where g_e is brake specific fuel consumption, kg/kWh.

However, if calculated this way, the price accounts for the entire energy acquired from both fuels (total energy price). In order to measure the share of energy expenses for each fuel, the P_{kW} parameter (total energy price) should be weighted by the ratio of power output produced from the corresponding fuel to the total engine power output produced with the whole fuel mixture. Two indicators are derived – for the price of 1kWh of energy, acquired from hydrogen combustion (or hydrogen energy price) P_{kWH2} and for the price of 1kWh of energy acquired from the diesel fuel combustion (or diesel fuel energy price) P_{kWDF}. In order to do that, it is necessary to calculate the output power for both fuels. This is a complex task because engine power is usually calculated for a single type of fuel.

Nevertheless, with the use of some assumptions and simplifications the following formula for engine power [8] can be adapted:

$$Ne = \frac{i\,V_h\,H_{LF}\,\rho_0}{30\,\tau\,l_0}\,n\,\frac{1}{\alpha}\,\eta_v\,\eta_i\,\eta_m\text{ , kW,} \tag{8}$$

where i is number of cylinders; V_h – displacement volume per one cylinder, m^3; H_{LF} – lower heating value of fuel, kJ/kg; ρ_0 – air-fuel mixture density, kg/m^3; τ – parameter for the engine type (2-stroke or 4-stroke); l_0 – theoretical amount of air necessary for the complete combustion of 1 kg of fuel, kg/kg.; n – engine speed, min^{-1}; α– air-fuel equivalence ratio; η_v – volumetric efficiency; η_i – indicated efficiency; η_m – mechanical efficiency.

The values of parameters i, V_h, τ, ρ_0, n, η_v, η_i и η_m can be assumed constant. The number of cylinders, engine displacement volume and the τ parameter are physical parameters which cannot be changed. Engine speed is constant for every engine mode investigated in the current study. The volumetric, indicated and mechanical efficiencies can also be assumed constant for a specified engine mode (constant engine power, speed and constant hydrogen-diesel fuel ratio). With enough precision, the air-fuel mixture density can be assumed constant for the specified engine mode and the corresponding hydrogen-diesel ratio. The formula for brake engine power could hence be simplified to:

$$N_e = C\,\frac{H_{LF}}{l_0}\frac{1}{\alpha}, \tag{9}$$

where $C = \frac{i\,V_h\,\rho_0}{30\,\tau}\,n\,\eta_v\,\eta_i\,\eta_m = \text{const.}$

If we determine the air equivalence ratio – α using the equation:

$$\alpha = \frac{B_a}{B_F\,l_0}, \tag{10}$$

where B_a is engine air consumption, kg/h, for N_e, we have:

$$N_e = C\,\frac{H_{LF}}{l_0}\frac{B_F\,l_0}{B_a} = C H_{LF}\frac{B_F}{B_a}\,. \tag{11}$$

For a single operating mode, the air consumption is constant and the brake power can be simplified to:

$$N_e = C_1 H_{LF} B_F, \tag{12}$$

where: $C_1 = \frac{C}{B_a}$.

So the engine power is proportional to the heat produced by the fuel:

$$N_e = C_1 H_{LF} B_F = C_1 Q_F, \tag{13}$$

where Q_F is heat produced by fuel, kJ/h.

Then for the power output produced by the hydrogen combustion:

$$N_{eH2} = C_1 H_{LH2} B_{H2} = C_1 Q_{H2}, \tag{14}$$

where H_{LH2} is lower heating value of hydrogen.

Similarly, for the power output produced by the diesel fuel combustion and for the total power output:

$$N_{eDF} = C_1 H_{LDF} B_{DF} = C_1 Q_{DF}; \tag{15}$$

$$N_{e\Sigma} = N_e = C_1 H_{LF} B_F = C_1 Q_F, \tag{16}$$

where: H_{LDF} – lower heating value of diesel fuel.

The lower heating value of the hydrogen-diesel fuel mixture H_{LF} is calculated as a weighted average of hydrogen and diesel fuel lower heating values, weighted with the corresponding fuel consumption (kg/h).

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The price of energy produced by the hydrogen P_{kWH2} and the diesel fuel P_{kWDF} can then be calculated using equations (7), (14), (15) and (16):

$$P_{kW\mathrm{H2}} = P_{kW}\frac{N_{eH2}}{N_{e\Sigma}} = P_{kW}\frac{Q_{H2}}{Q_F} = P_{kW}\frac{H_{LH2}.B_{H2}}{H_{LF}.B_F}, \text{€/kWh}; \tag{17}$$

$$P_{kWDF} = P_{kW}\frac{N_{eDF}}{N_{e\Sigma}} = P_{kW}\frac{Q_{DF}}{Q_F} = P_{kW}\frac{H_{LDF}\,B_{DF}}{H_{LF}\,B_F}, \text{€/kWh}. \tag{18}$$

The issue of the carbon emissions (CO_2) is particularly relevant. Hence, an assessment of the monetary value of carbon emissions emitted by the engine is appropriate. For this purpose it is necessary to calculate the mass of carbon emissions in the engine exhaust gases (G_{CO2}, kg/h). If multiplied by the price of carbon emissions futures (€/ton, converted to €/kg) traded on the international stock exchanges, this gives us the expenses for the CO_2 emissions in €/h.

$$P_{CO2} = \frac{p_{CO2}\,G_{CO2}}{1000}, \text{€/h}, \tag{19}$$

where p_{CO2} is price of CO_2 emissions, €/ton; G_{CO2} – quantity of CO_2 emissions emitted by the engine, kg/h.

4. Experimental results

An advantage of the methodology shown above is that the data from the test bench experiment could be used to make an economic assessment of the engine operation worldwide, depending on the resource price in the corresponding region. The calculations in the current article are based on fuel prices in Germany. The main reason for this approach is that hydrogen is not a fuel of mass consumption. The traded volumes of this gas are small, supply and demand for this market are of much lower volumes than the ones for the diesel fuel market. Therefore, it is not likely to find reliable information about hydrogen prices [9]. Due to scarcity of public data, the hydrogen end-customer price data for Germany is retrieved from the German website of the major fuel producer and distributor Shell Oil (https://www.shell.de/) as well as the online service H2-Mobility (https://h2.live/), a commercial webservice by AIR LIQUIDE Deutschland GmbH, OMV Deutschland GmbH, Shell Deutschland Oil GmbH, TOTAL Deutschland GmbH, Linde AG, and Daimler AG. According to the data, the average price per kilogram of hydrogen for Germany is 9.5 €/kg. Hydrogen price in hydrogen stations in USA is similar to the one in Germany, fluctuating between 12 and 16 $/kg [10-11]. Data for the hydrogen price from documents for purchases of gas storage cylinders for the experiment is also at authors' disposal (Bulgaria). In this case, the price for a kilogram of hydrogen is 127.82 €/kg. The price is correct and reliable, does not fluctuate like prices of mass consumption fuels. Yet, the application of IC engines is mostly in road vehicles so it is appropriate to use the price of hydrogen at hydrogen stations for the calculations. Apart from that, the price for hydrogen in gas storage cylinders in Bulgaria is several times higher than the one at hydrogen stations in Germany and that would twist the results of the study.

In order to eliminate the impact of short-term fluctuations in the price of diesel, its average price for Germany for April 2019 is taken. The fuel end-customer price is retrieved from the Shell Oil website for Germany (https://www.shell.de/). According to the information acquired, the average price of diesel fuel in Germany for April 2019 is 1.2975 €/l. The measured fuel density during the experiments is 0.8233 kg/l. After dividing the price per litre of diesel fuel by the fuel density, the price per kilogram of diesel fuel is obtained: 1.576 €/kg. The fuel prices noted above are used in order to calculate the total fuel expenses (P_F), the diesel (P_{DF}) and hydrogen (P_{H2}) fuel expenses. Results for the fuel expenses are shown in figures 1, 5 and 6. The weighted average fuel price (P_{FA}) as a function of the K_{H2} coefficient is given in figure 4.

Historic data for the price of carbon emission futures is gathered from the major financial portal Investing.com (https://www.investing.com/). It is also taken as a weighted average for the month of April 2019, again to eliminate the impact of the financial instrument short term volatility. The cost is

24.26 €/ton (weighted average). The price is valid not only for Germany, as carbon emissions are traded on the international stock exchanges. The weighted average price of carbon emissions in August 2018 (the period when the experiment was carried out) was 19.62 €/ton. To illustrate the upward trend in carbon emissions price, calculations were made with both prices. Still, carbon prices are several times lower than fuel prices at the current time. Calculation results for the CO_2 emission expenses (P_{CO2}) are shown in figures 3, 9 and 10.

As stated above, the operating expenses will be calculated for two separate cases. First case – as a function of variable K_{H2} coefficient with engine running at constant speed and load (1500 min^{-1}, 1.5kW power output). Second case – as a function of variable engine load (power output from 1 to 4kW), with engine running at constant speed (1500 and 2000 min^{-1}) and constant K_{H2} coefficient (10%).

The price for the entire energy P_{kW} (total energy price) obtained at the engine crankshaft is compared to the price of electrical energy in Germany (P_E) for the month of April 2019 – 0.30 €/kWh. Results for the energy prices (P_{kW}, P_{kWH2}, P_{kWDF} and P_E) are shown in figures 2, 7 and 8.

4.1. Calculations at variable K_{H2} coefficient (0-50%), constant engine load (power output 1.5 kW) and speed (1500 min^{-1}).

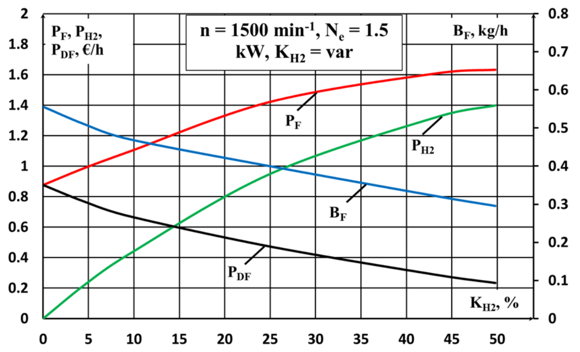

Figure 1. Variation of total fuel expenses, diesel fuel and hydrogen fuel expenses and total fuel consumption as a function of the K_{H2} coefficient.

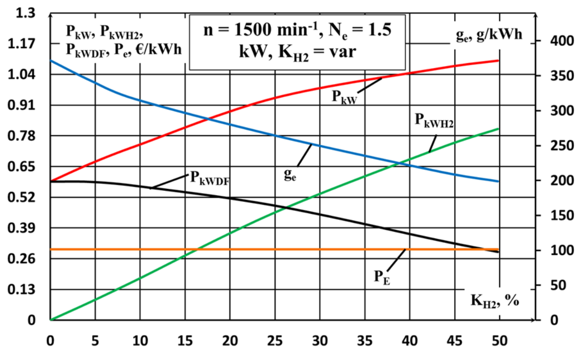

Figure 2. Variation of total energy price, diesel fuel energy price, hydrogen energy price and brake specific fuel consumption as a function of the K_{H2} coefficient; the price of electric energy in Germany for April 2019 is shown.

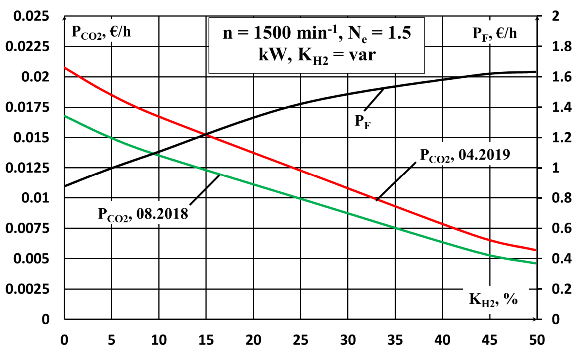

Figure 3. Variation of the expenses for CO_2 emissions at emission prices for August 2018 and April 2019 and the total fuel expenses as a function of the K_{H2} coefficient.

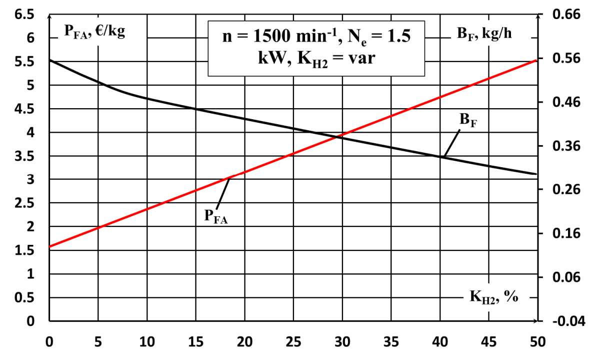

Figure 4. Variation of the weighted average fuel price and the total fuel consumption as a function of the K_{H2} coefficient.

4.2. Calculations at variable engine load (power output 1-4kW), constant engine speed (1500 min^{-1} and 2000 min^{-1}) and constant K_{H2} coefficient (10%).

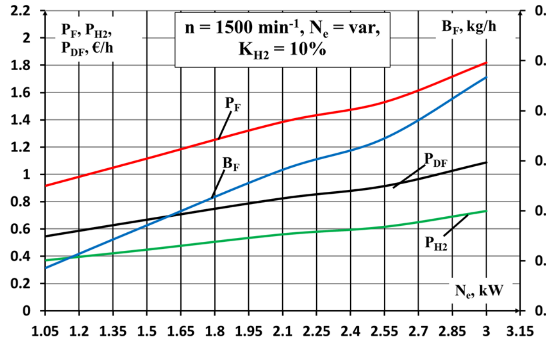

Figure 5. Variation of total fuel expenses, diesel fuel and hydrogen fuel expenses and total fuel consumption as a function of the engine load at engine speed of 1500 min^{-1}.

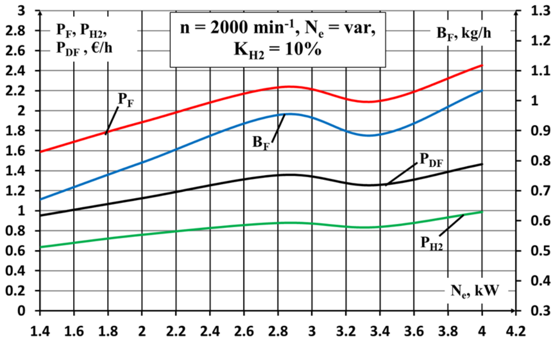

Figure 6. Variation of total fuel expenses, diesel fuel and hydrogen fuel expenses and total fuel consumption as a function of the engine load at engine speed of 2000 min^{-1}.

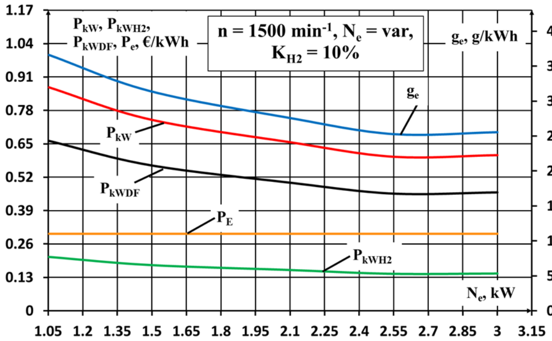

Figure 7. Variation of total energy price, diesel fuel energy price, hydrogen energy price and brake specific fuel consumption as a function of the engine load at speed of 1500 min^{-1}; the electric energy price in Germany for April 2019 is shown.

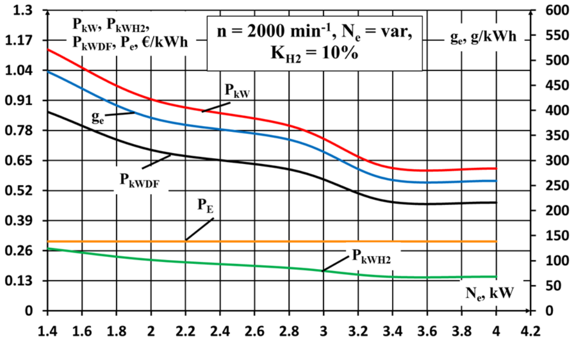

Figure 8. Variation of total energy price, diesel fuel energy price, hydrogen energy price and brake specific fuel consumption as a function of the engine load at speed of 2000 min^{-1}; the electric energy price in Germany for April 2019 is shown.

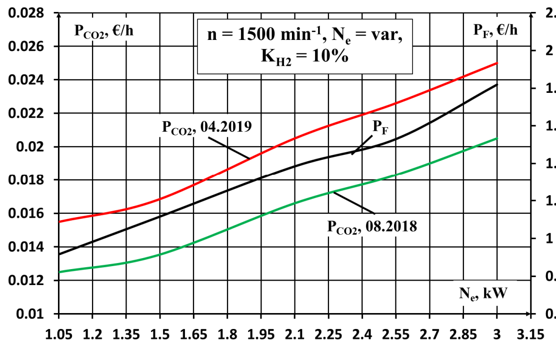

Figure 9. Variation of the expenses for CO_2 emissions at emission prices for August 2018 and April 2019 and the total fuel expenses as a function of the engine load at speed of 1500 min^{-1}.

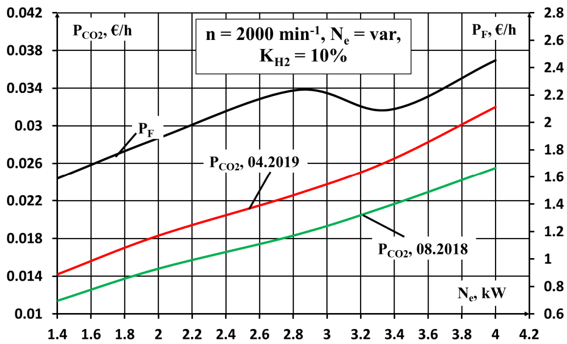

Figure 10. Variation of the expenses for CO_2 emissions at emission prices for August 2018 and April 2019 and the total fuel expenses as a function of the engine load at speed of 2000 min^{-1}.

5. Conclusions of the study

After performing an analysis of the gathered results, the following conclusions can be made:

- The total fuel consumption at a steady engine mode (constant speed and load) drops with the increase of the K_{H2} coefficient values due to the higher lower heating value of hydrogen. The curve of the total fuel expenses however rises due to the high price of hydrogen;
- The expenses for diesel fuel have an insignificant share in the total fuel expenses due to the much lower price of diesel fuel compared to the hydrogen price. The expenses for diesel fuel drop while the ones for hydrogen rise with the increase of the K_{H2} coefficient;
- The total energy price rises with the increase of the K_{H2} coefficient despite the fact that the brake specific fuel consumption drops. This is again due to the higher price of hydrogen. The diesel and hydrogen energy prices are equal for $K_{H2} = 26\%$;
- The expenses for CO_2 emissions drop almost 4 times with the increase of the K_{H2} coefficient from 0 to 50%. The rise of the price of CO_2 emission futures, traded at the international stock exchanges from August 2018 to April 2019, is significant and leads to the augmentation of the CO_2 emissions expenses;
- The weighted average fuel price, calculated in €/kg, understandably rises with the increase of the K_{H2} coefficient;
- Naturally, with constant values of the K_{H2} coefficient and constant engine speed, the fuel consumption rises with the increase of engine load. The curve of the total fuel expenses repeats the curve of the total fuel consumption;
- With the increase of engine load at constant values of the K_{H2} coefficient and at constant engine speed, the brake specific fuel consumption drops. As K_{H2} is *10%* at all engine loads, the weighted average fuel price and the weighted average lower heating value of fuel remain unchanged. Therefore, with the drop of the brake specific fuel consumption, the total energy price for the energy obtained from the engine drops;
- With the increase of engine load, the total fuel consumption and the amount of carbon emissions rise, hence the expenses for carbon emissions.

As a conclusion we can note that at this stage of hydrogen market development its use as a fuel for IC engines is not profitable. The expenses for carbon emissions drop several times, but not enough in order to compensate the drastic augmentation of the total energy price and the total fuel expenses with the increasing hydrogen share in the total fuel amount.

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