DEVELOPMENT OF MODEL FOR RUNNING DIESEL ENGINE ON RAPESEED OIL FUEL AND ITS BLENDS WITH FOSSIL DIESEL FUEL

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Abstract. Using *ExtendSim* simulation software a mathematical model is developed to determine the diesel engine operating parameters using rapeseed oil and its blends with fossil diesel fuel. The main difference of the model from other studies: developed module for determination of the ambient temperature when, using rapeseed oil fuel, fossil diesel has to be added to ensure the fuel pump operation and fuel flow through the system; developed analytical relationships to determine the residual gas molar calorific value, that provides continuous modelling process; specified empirical coefficients for constructing of engine power curves. The modelling results show that using pure rapeseed oil vehicles can be operated up to -14 ºC, with a blend RO80 (80 % rapeseed oil and 20 % fossil diesel fuel) – up to -17 ºC and so on. If the ambient temperature drops below -30 ºC, blends with rapeseed oil content of less than 30 % or pure diesel fuel have to be used. The reduction of the engine power and torque for the car *VW Golf III 1.9TD* engine is linear – each 10 % of rapeseed oil in fuel blend reduces the maximum power and torque of around 0.5 %. Using pure rapeseed oil the decrease is about 5 %.

Keywords: rapeseed oil fuel, fossil diesel fuel, modelling, engine power, engine torque.

Introduction

The aim of the research is to develop a mathematical model to determine the main diesel engine operating parameters running them on rapeseed oil and its blends with fossil diesel fuel, as well as to establish suitable rapeseed oil and fossil diesel fuel blend ratios, operating motor vehicles at different ambient temperatures, including the ones that are met in Latvian winter conditions.

Materials and methods

Analyzing the simulation tools suitable for modelling of motor vehicle operating parameters the *ExtendSim* software is selected. The developed model consists of three parts or modules (Fig. 1).

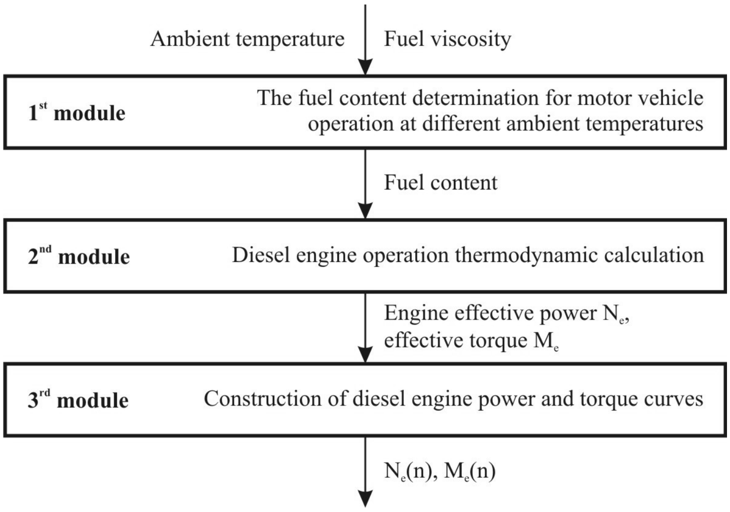

Fig. 1. **Model block diagram**

The first module depending on the ambient temperature determines if motor vehicles can be operated on pure rapeseed oil, or oil should be mixed with fossil diesel fuel. The input parameter of the second module is the fuel content and properties. Diesel engine operation thermodynamic calculation is based on the methodology approved at several doctoral theses [1; 2], in addition creating analytical relationship to determine the residual gas molar calorific value that provides a continuous modelling process. An analogue of the third module is found in the thesis “Application of bioethanol in Otto engines” [3]. While there the petrol powered engine operation is modelled, the algorithm is suitable also for diesel engines specifying the coefficients for constructing of the engine effective power and torque curves.

To ensure the fuel pump operation and the fuel flow in the fuel supply system, fuel kinematic viscosity should not exceed 500 – 1000 $\text{mm}^2\cdot\text{s}^{-1}$ [4]. In the model as a critical the lowest value is assumed to have a small margin of safety operation of the motor vehicle during the winter time.

To determine the kinematic viscosity of fuel depending on the ambient temperature, the following formula is used [5]:

$$\ln(v) = A + \frac{B}{T} + \frac{C}{T^2}, \tag{1}$$

where v – kinematic viscosity of fuel, $\text{mm}^2\cdot\text{s}^{-1}$;
T – ambient temperature, K;
A, B and C – coefficients that depend on the used fuel.

To determine the coefficients the experimental studies performed in Spain are used [6]. The coefficients for fossil diesel fuel (DF) and rapeseed oil (RO) are obtained using regression analysis (Fig. 2).

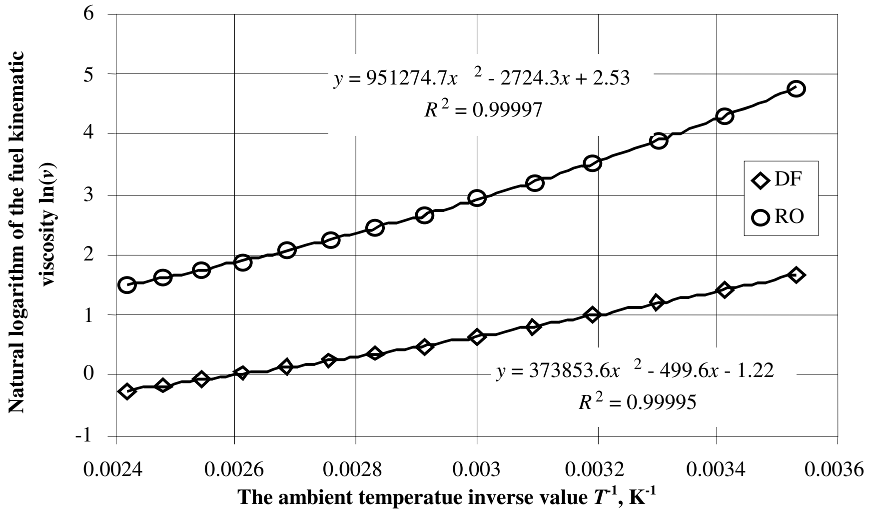

Fig. 2. **Determination of coefficients for calculating of fuel kinematic viscosity**

The values calculated using the obtained formula are compared with other studies, for example, with the measurement of the kinematic viscosity of rapeseed oil at temperature range 260...325 K (-13...+52 ºC) carried out in Germany [7]. Kinematic viscosity of this study corresponds to the values obtained by analytical methods, so the following relationships are used in the model:

$$v_i = e^{A_i + \frac{B_i}{(t+273)} + \frac{C_i}{(t+273)^2}}, \tag{2}$$

where v_i – i_{th}-fuel kinematic viscosity, $\text{mm}^2\cdot\text{s}^{-1}$;
t – ambient temperature, ºC;
A_i, B_i and C_i – i_{th}-fuel coefficients.

Depending on the fuel content the weighted average kinematic viscosity of the fuel blend is calculated. The model blocks for determination of the fuel kinematic viscosity are shown in Fig. 3.

If the fuel blend percentage is known, the content of carbon (C), hydrogen (H) and oxygen (O) content in fuel blend in fuel mass fractions can be calculated from the relationships:

$$C = \frac{\sum_{i=1}^{n} C_{sat-i} \cdot m_i}{\sum_{i=1}^{n} m_i}, \; H = \frac{\sum_{i=1}^{n} H_{sat-i} \cdot m_i}{\sum_{i=1}^{n} m_i}, \; O = \frac{\sum_{i=1}^{n} O_{sat-i} \cdot m_i}{\sum_{i=1}^{n} m_i}, \tag{3}$$

where m_i – i_{th}-fuel content in blend, mass %;
C_{sat-i} – content of carbon in i_{th}-fuel, mass parts;
H_{sat-i} – content of hydrogen in i_{th}-fuel, mass parts;

$O_{sat\text{-}i}$ – content of oxygen in i_{th}-fuel, mass parts.

The calculated C, H and O values serve as outputs to the second module of the model “Diesel engine operation thermodynamic calculation” (Fig. 4).

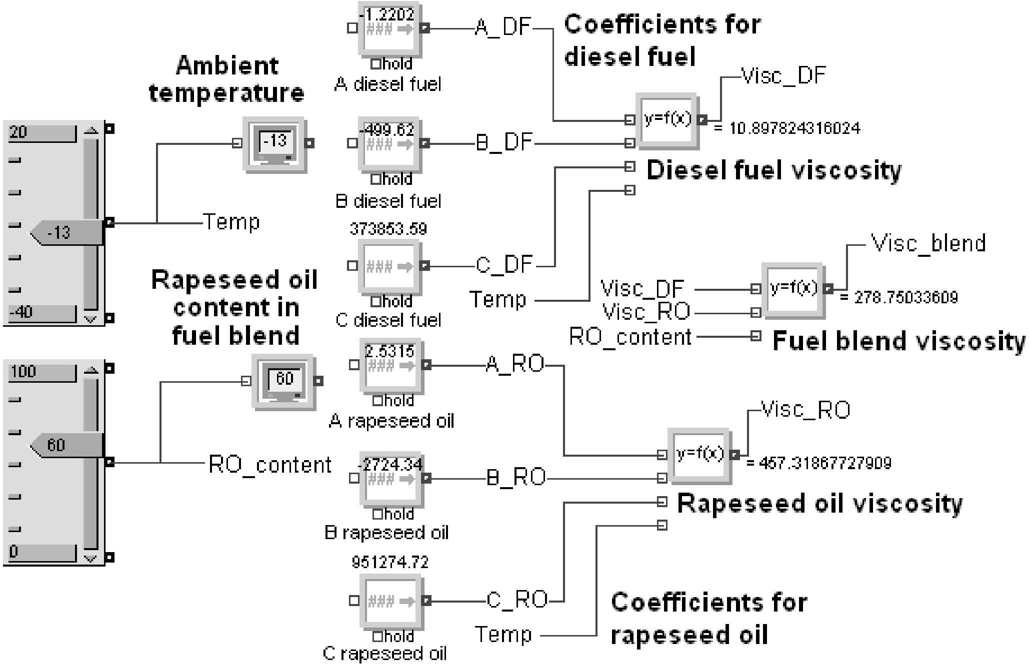

Fig. 3. **Model blocks for calculation of fuel kinematic viscosity**

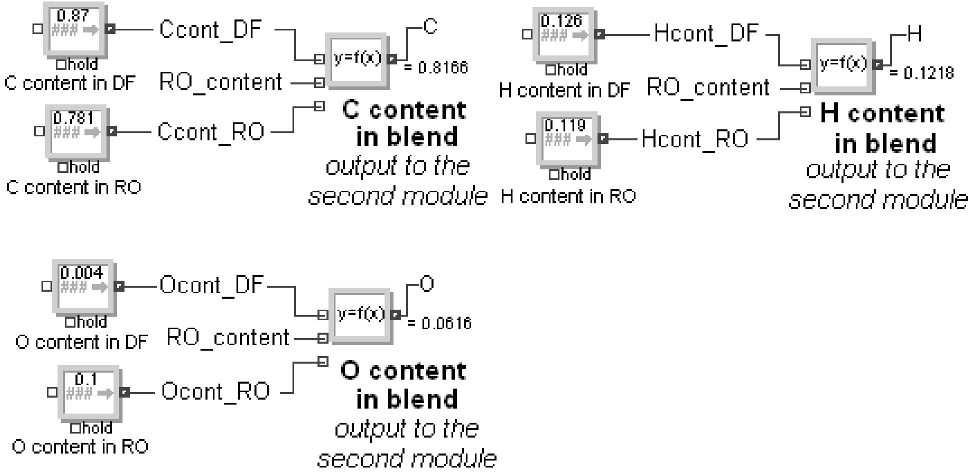

Fig. 4. **Fuel blend content determination blocks**

The thermodynamic calculation of diesel engine operation is based on the classic relationships, given in various sources of information [1; 2; 8-11]. In some of them residual gas molar heat capacity calculation depending on the temperature and air-fuel ratio is based on the interpolation method after the empirical data are read from the table. It does not provide a continuous modelling process, as at certain modelling steps a number of parameters have to be entered manually. Therefore, to get the residual gas molar calorific value analytical relationship is worked out.

Designing of residual gas temperature and molar calorific value correlation diagrams at different air-fuel ratios, regression equations and coefficients of determination are found.

However, direct introduction of these equations in the model is not appropriate, because it leads to the use of a number of logical operators. Besides, the calculation would be incorrect in the case of the air-fuel ratio intermediate values such as 1.23, 1.56, etc.

Therefore, another regression analysis is performed to determine whether there is a correlation between residual gas molar calorific value decrease with increasing the air-fuel ratio.

At each air-fuel ratio calculations were made using the formula:

$$K_{decrease} = \frac{\sum_{i=1}^{n} \frac{Q_i}{Q_1}}{n}, \tag{4}$$

where Q_1 – residual gas molar calorific value at constant temperature and air-fuel ratio 1, kJ·(kmol·K)$^{-1}$;
Q_i – residual gas molar calorific value at the same temperature and air-fuel ratio α, kJ·(kmol·K)$^{-1}$;
n – number of different constant temperatures, where the calculations were made ($n = 21$, $t = 400...2400$ ºC, step 100 ºC).

The correlation diagram of molar residual gas calorific value reduction depending on the air-fuel ratio is given in Fig. 5.

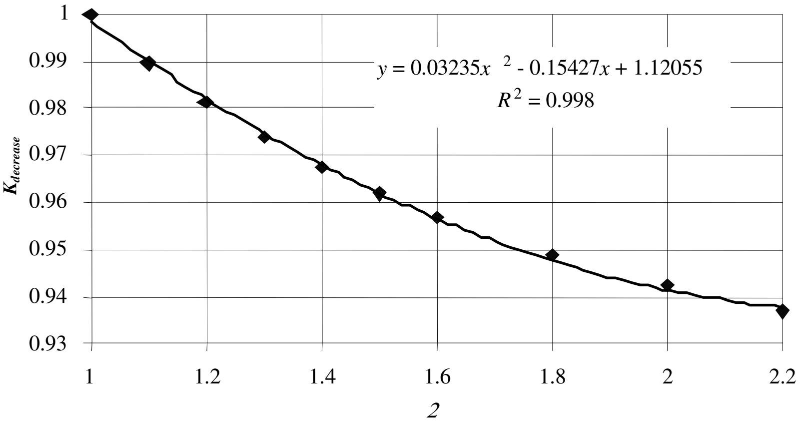

Fig. 5. **Correlation diagram of residual gas molar calorific value reduction depending on air-fuel ratio**

The final relationship introduced into the model is obtained combining both regression analyses: three coefficients are taken from the correlation diagram of the residual gas molar calorific value at different temperatures and the air-fuel ratio 1, other three coefficients – from the correlation diagram of residual gas molar calorific value reduction depending on the air-fuel ratio:

$$Q_{mol-t} = \left(A \cdot t^2 + B \cdot t + C\right) \cdot \left(D \cdot \alpha^2 + E \cdot \alpha + F\right), \tag{5}$$

where Q_{mol-t} – residual gas molar calorific value at temperature t and air-fuel ratio α, kJ·(kmol·K)$^{-1}$;
A, B, C, D, E and F – coefficients obtained from the regression equations.

Since the analytical relationship is derived from the table that represents only fossil diesel use, two correction factors K_1 and K_2 are introduced in the model. They take into consideration the fuel blend changes in the fuel heating value and molecular weight compared to diesel fuel.

The output parameters from the diesel engine thermodynamic calculation module are: maximum effective power $N_{e\max}$ (kW) at engine crankshaft rotational frequency $n_{\max}$ (min^{-1}) when the maximum power is reached, fuel consumption per hour G_T (kg·h^{-1}), and effective torque M_e (N·m) at the same crankshaft rotational frequency $n_{\max}$.

If the maximum effective engine power $N_{e\max}$ and engine crankshaft rotational frequency $n_{\max}$ at which this power is developed are known, the approximate shape of the engine effective power curve can be determined according to the empirical relationship [12]:

$$N_e = N_{e\max} \cdot \left[X \cdot \frac{n_e}{n_{\max}} + Y \cdot \left(\frac{n_e}{n_{\max}}\right)^2 - Z \cdot \left(\frac{n_e}{n_{\max}}\right)^3 \right], \tag{6}$$

where N_e – engine effective power at engine crankshaft rotational frequency n_e, kW;
n_e – engine crankshaft rotational frequency at the point to be determined, min^{-1};

X, Y, Z – empirical coefficients describing the engine type ($X + Y – Z = 1$).

Empirical coefficient values for diesel engines from the literature data are: $X = 0.53$, $Y = 1.56$ and $Z = 1.09$ [12]. However, using them, the nature of the constructed power curve may differ from actual depending on the engine type, such as turbo charged or not, with direct fuel injection or with pre-chamber etc. That is why it is necessary to correct X, Y and Z values.

Analytical calculation of the coefficients is very difficult to resolve because there are two equations with three unknowns. One of the methods is using step-by-step approximation analyzing the existing experimental power curves [13]. Since at the Research Laboratory of Alternative Fuels (Latvia University of Agriculture, Faculty of Engineering) a lot of different vehicles are tested on the chassis dynamometer *Mustang MD-1750*, this method is used to find the coefficient X, Y and Z values. As a car with indirect injection and turbo charging is adapted to run on rapeseed oil fuel in the experimental studies [14], cars with similar characteristics, but different working volumes are selected for the analysis – *Opel Astra-G 1.7TD*, *Mitsubishi Space Wagon 2.0D Turbo*, *BMW 525 TD*, *Mercedez Benz E290D Turbo*. The following power curve empirical coefficients are obtained from the analysis and entered in the appropriate model blocks: $X = 0.4$, $Y = 2.2$ and $Z = 1.6$.

If the value of the maximum engine power in the full crankshaft rotational frequency range is known, the torque can be calculated at any value of n:

$$M_e = 9549 \cdot \frac{N_e}{n} . \tag{7}$$

Since the maximum torque is achieved at different crankshaft rotational frequency than the maximum power, the additional block is placed in the model. This block outputs the maximum torque value checking the formula (7) results in the full crankshaft rotational frequency range. The model blocks for constructing of diesel engine power and torque curves are shown in Fig. 6.

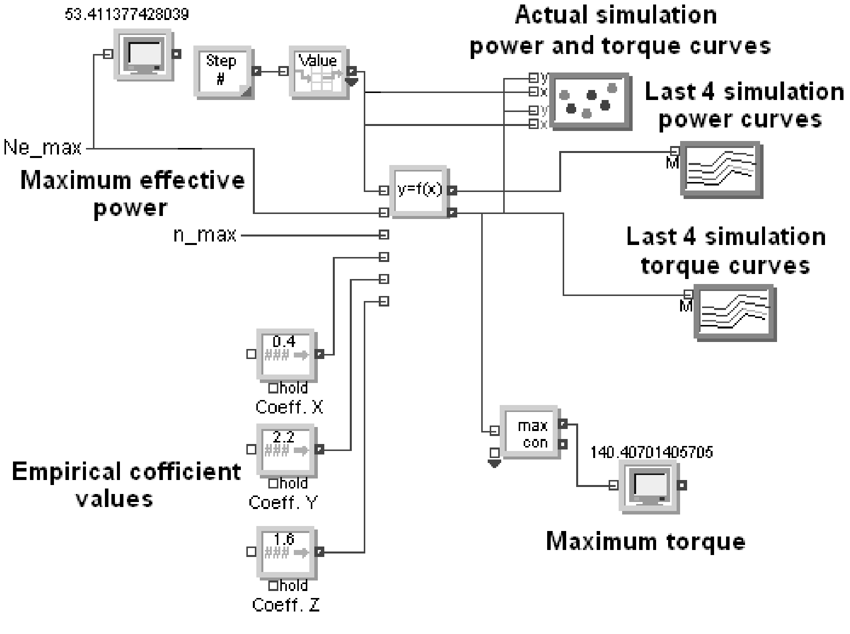

Fig. 6. **Model blocks for constructing of diesel engine power and torque curves**

Results and discussion

At the first step of the model studies the maximum percentage of rapeseed oil in the fuel blend at different ambient temperatures is estimated, providing that the fuel kinematic viscosity does not exceed 500 $mm^2 \cdot s^{-1}$.

In order to make the simulation easier, several changes are made in the first module of the model: ambient temperature slider (Fig. 3) is replaced by a number generator that changes the temperature in the range of -30...+20 ºC in increments of 1 ºC; block for creating the current blend viscosity curve depending on the ambient temperature is added, as well as *MultiSim Plotter* block that allows graphical overview of the last four simulation graphs.

The summary of simulations is shown in Fig. 7.

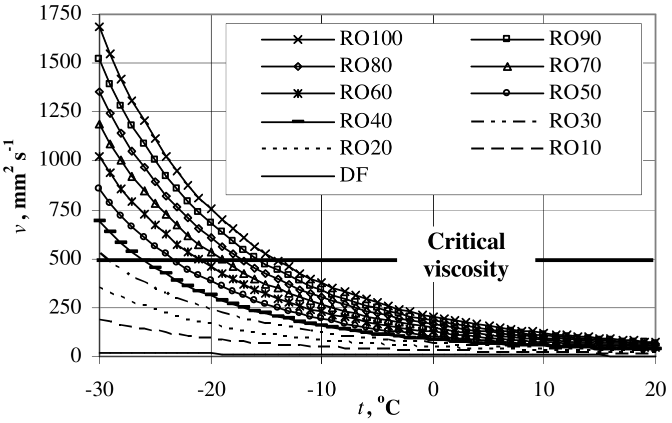

Fig. 7. **Fuel blend viscosity depending on ambient temperature**

It is established that to provide fuel pump operation and the fuel flow in the fuel supply system with pure rapeseed oil the vehicle can be operated up to -14 °C, with a blend RO80 – up to -17 °C and so on. If the ambient temperature drops below -30 °C, blends with rapeseed oil content of less than 30 % or pure diesel fuel can be used. In order to obtain an analytical correlation the first module of the model is changed again: rapeseed oil content slider (Fig. 3) is replaced by critical viscosity of the blend.

The summary of simulations is shown in Fig. 8.

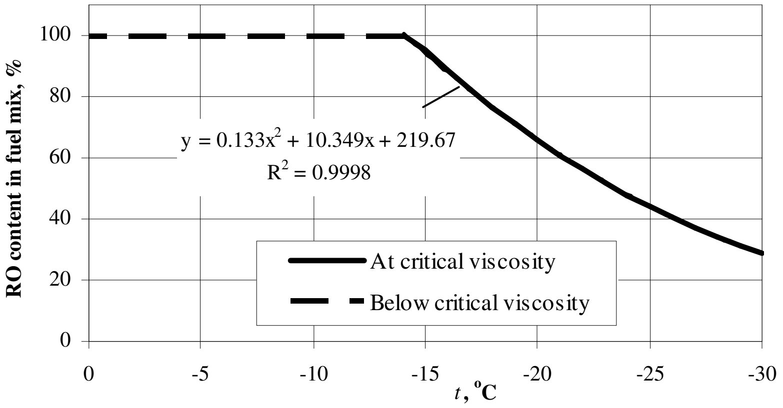

Fig. 8. **Maximum rapeseed oil content in the blend depending on ambient temperature**

Thus, the correlation to determine the maximum rapeseed content in the fuel blend if the temperature drops below -14 °C is found.

Engine power and torque modelling studies are carried out for the same vehicle that previously is used in experimental studies, i.e., car *VW Golf III 1.9TD* [14]. The simulation results show, that the car engine maximum power is reached at 4200 min^{-1}. Using diesel fuel it is 56.25 kW, using rapeseed oil – 53.35 kW. The maximum torque this engine develops at 2900 min^{-1}: running on diesel fuel – 147.9 N·m, on rapeseed oil – 140.3 N·m. Maximum power and torque difference – 5.15 %.

The power and torque reduction for the car *VW Golf III 1.9TD* engine is linear – each 10 % of rapeseed oil in fuel blend reduces the maximum power and torque of around 0.5 %. Comparing the acquired engine power and torque modelling values with the data given by the motor vehicle manufacturer operating the vehicle with fossil diesel, differences do not exceed 2.3 %. Such cut-off is permissible and does not disturb to identify differences operating motor vehicles with various fuels.

Conclusions

1. An original mathematical model suitable to predict diesel engine operating parameters running them on rapeseed oil and its blends with fossil diesel fuel is developed using *ExtendSim* software. The relationship that allows calculating the residual gas molar calorific value depending on the

temperature and air-fuel ratio is established, as well as empirical coefficients for constructing of diesel engine effective power and torque curves.

2. The modelling results show:
   - using pure rapeseed oil vehicles can be operated up to -14 ºC, with a blend RO80 (80 % rapeseed oil and 20 % fossil diesel fuel) – up to -17 ºC and so on. If the ambient temperature drops below -30 ºC, blends with rapeseed oil content of less than 30 % or pure diesel fuel have to be used;
   - reduction of the engine power and torque for unadapted car *VW Golf III 1.9TD* engine is linear – each 10 % of rapeseed oil in fuel blend reduces the maximum power and torque of around 0.5 %. Using pure rapeseed oil the decrease is about 5 % comparing with diesel fuel.
3. Comparison of the theoretical and previously carried out experimental results shows that the theoretical model can be used to determine the maximum rapeseed oil content in fuel blends at different ambient temperatures, as well as to predict the engine power and torque changes operating vehicles with different fuels. Coincidence of theoretical and experimental results is high.

Acknowledgements

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