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Simulation of fuel demand for wood-gas in combustion engine

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Abstract. In the era of the oil crisis and proceeding contamination of the natural environment, it is attempted to substitute fossil raw materials with alternative carriers. For many years, road transport has been considered as one of the main sources of the substances deteriorating air quality. Applicable European directives oblige the member states to implement biofuels and biocomponents into the general fuel market, however, such process is proceeding gradually and relatively slowly. So far, alternative fuels have been used on a large scale to substitute diesel fuel or petrol. Derivatives of vegetable raw materials, such as vegetable oils or their esters and ethanol extracted from biomass, are used to that end. It has been noticed that there is no alternative to LPG which, due to financial reasons, is more and more popular as fuel in passenger cars. In relation to solutions adopted in the past, it has been decided to analyse the option of powering a modern passenger car with wood gas - syngas. Such fuel has been practically used since the 1920's. To that end, a computer simulation created in SciLab environment was carried out. Passenger car Fiat Seicento, fitted with Fire 1.1 8V petrol engine with power of 40kW, whose parameters were used to prepare the model, was selected as the model vehicle. The simulation allows the determination of engine demand on the given fuel. Apart from the wood gas included in the title, petrol, methane and LPG were used. Additionally, the created model enables the determination of the engine power at the time of the indicated fuels supply. The results obtained in the simulation revealed considerable decrease in the engine power when the wood gas was supplied and the increased consumption of this fuel. On the basis of the analysis of the professional literature describing numerous inconveniences connected with the use of this fuel as well as the obtained results, it has been established that using the wood gas as alternative fuel is currently unjustified.

1 Introduction

Wood gas (german holzgaz, synthesis gas) is a gas produced in the process of gasification of biomass, in this case - wood. The process is carried out in special devices called "gas generators" and it has many stages [1]. The gasification consists in thermal transformation of fuel in solid form (wood) into the gaseous fuel (wood gas) [2]. The gas consists of the combination of such flammable substances as: hydrogen, carbon oxide, methane and non-flammable - carbon dioxide, nitrogen, water vapour. The composition of the gas depends on numerous factors, *inter alia*, on properties of the gasified material, e.g. humidity, or generator parameters, e.g. internal temperature of the hearth [1, 2].

Wood gas as fuel in passenger vehicles has already been used in the past. In 1920's a French engineer J. Imbert constructed a wood gas generator which could be used to power cars with gas fuel [1, 4]. In the following years, this technology was adopted by the automotive magnates like: General Motors, Mercedes-Benz or Ford. Due to the availability of the raw material and simple construction of the gas generator, the Europeans constructed the devices on their own by means of old gas cylinders, boilers and washing machines [1]. The wood gas became popular mainly during the World War II. In the warfare the petrol reserves were entirely used by the army primarily for the purpose of aviation. Therefore, it became necessary to use other fuels for remaining vehicles - trucks, passenger and delivery cars. It is estimated that the number of vehicles powered with wood gas in the said period equalled to 7 million [1, 4]. The use of syngas in motor vehicles entailed, however, numerous inconveniences.

Due to the low technology efficiency, arduous operation of the generator, the risk of poisoning oneself with carbon dioxide and the regained access to petrol as transportation fuel, wood gas has been superseded from the power systems of motor vehicles. The gas became more often used in stationary installations designed to heat residential units [4, 5]. It may seem that technologies based on wood gas powering of motor vehicles do not have any future. Nevertheless, legal conditions in respect of biofuels and biocomponents as well as strict environmental standards imposed on existing vehicles render it necessary to seek alternative solutions for present carriers.

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1.1 The aims of the study

The purpose of this thesis was the evaluation of supply modern engine with wood gas.
To fulfil the formulated objective, the following values were determined:

- Demand of a petrol engine for wood gas, as well as petrol, methane and LPG;
- Reduction of power of the engine after syngas supply in relation to other fuels (petrol, methane, LPG).

1.2 Scope of the study

The scope of the thesis comprises the preparation of the simulation of internal combustion engine operation of a selected passenger car, including:

- Preparation of the simulation presenting the demand of the selected internal combustion engine for used fuels;
- Carrying out the simulation and obtaining results in the form of diagrams of temporary values monitored during the simulation and numerical values for cumulated values of particular fuel consumption, air consumption and total consumption of air and fuel mixture;
- Preparation of the simulation concerning the assessment of changes in the maximum power characteristic of the selected engine and carrying out the simulation and obtaining results on its efficiency;
- Analysis of the achieved results.

2 Materials and Methods

2.1 The object of research

To construct the simulation model, the parameters of the passenger car Fiat Seicento with a Fire 1.1 8v petrol engine with power of 40 kW were used. It is a typical urban car with low operation costs due to low fuel consumption and exhaust emission. The manufacturer provides the following values of fuel combustion for the said unit: in the mixed cycle 5.7 l/100 km, in the urban cycle 7.2 l/100 km and in the extra-urban cycle 4.8 l/100 km [6]. Table 1 below presents basic data of engine specification:

Table 1. Specification of the Fire 1.1 8v engine with the power of 40 kW [6].

Parameter	Value
Engine code	176.b2.000
Capacity	1108 cm^3
Diameter, piston stroke	70.72 mm
Maximum power	54KM (40kW) at 5500 rpm
Maximum torque	86 N·m at 3800 rpm
Arrangement of cylinders	line
Number of cylinders	4

2.2 Prepared simulation

The simulation model was constructed in the Scilab environment. The software enables the use of numbers and structures such as matrices and vectors. It has built-in graphics features which allow the creation of graphs and diagrams in two or three dimensions. It may be widely used to perform basic and advanced calculations in many fields of science. The structure of the prepared simulation is depicted below. The model was divided into a few main units containing elements necessary to carry out specific tasks.

2.2.1 NEDC test generator

Data, which was entered in the simulation unit “NEDC test generator”, enabled the control of the simulated operation process of the selected vehicle and its engine according to the requirements of the “New European Driving Cycle” (NEDC) test. It is a current approval test for vehicles, which are to be considered roadworthy within the area of the European Community [7, 8]. Such data was entered into components “Signal Builder” which at the initiation of the simulation generate the following signals: Vehicle velocity [m/s] constituting the main element needed to determine a load for a vehicle, Clutch [-] this signal informs next simulation units about the connection of the drive to the engine (when it is turned on) or disconnection of the drive from the engine (turned off), Number of gear [-] through the change of gear the signal controls the transmission ratio between the engine and vehicle wheels in the next simulation elements, effort on wheels [N] is the result of calculations which include the vehicle dynamics and drags occurring when the car is in motion.

Then, within the module, calculations of a temporary value of the vehicle velocity [m/s] are carried out, and they are followed by determination of the distance covered by the vehicle with the use of integrating element and vehicle accelerations with the use of derivative term according to the correlations presented below [10]:

$$d = \int_0^{tc} v(t)\ dt\ [m] \qquad (1)$$

$$a(t) = \frac{dv(t)}{dt} \left[\frac{m}{s^2}\right] \qquad (2)$$

Where:
$v(t)$ - Temporary vehicle velocity in the NEDC test,
tc - Completion time of the simulation.

After that, the simulation calculates temporary load values resulting from the vehicle movement Fv [N] based on the parameters consistent with NEDC procedure and assumed for this type of vehicle (conversion mass 740 kg) according to the correlation [7, 8, 10]:

$$Fv = a + b \cdot v(t)^2\ [N] \qquad (3)$$

Where:
$v(t)$ - Temporary vehicle velocity in the NEDC test,
a - Rolling resistance coefficient (5 N),
b - Drag coefficient (0.0337 N/(km/h)^2.

Apart from the load resulting from the vehicle motion resistance, the simulation also includes the calculation of the load resulting from the motion dynamics in the

NEDC test according to the methodology on the basis of the correlations [7, 8, 10]:

$$Fa = m\frac{dv(t)}{dt}\ [\mathrm{N}] \tag{4}$$

Where:
$v(t)$ - Temporary vehicle velocity in the NEDC test,
m - Conversion mass of the vehicle 740 kg.

Then, the calculated load values are summed up and transferred to subsequent simulation modules. Fig. 1 shows a part of the developed simulation calculating vehicle parameters: acceleration, distance and load.

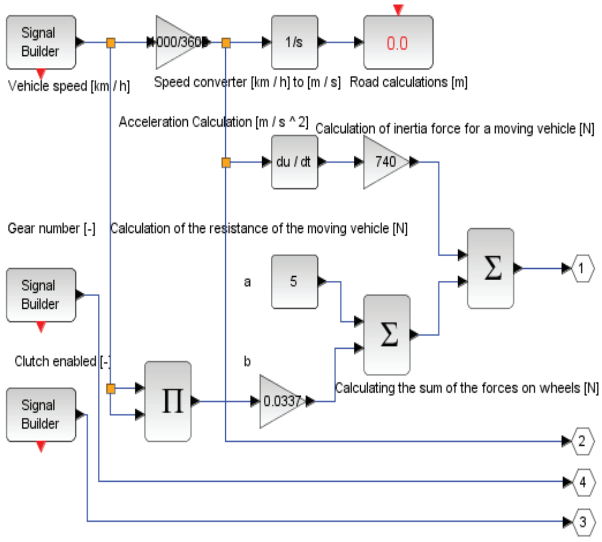

Fig. 1. Diagram of the NEDC test generator.

2.2.2 “Drive system” and “Engine” simulation units

„Drive system” unit, on the basis of temporary vehicle velocity values, vehicle wheels load, number of gear ratio and the value of signal of clutch engagement, performs calculations of the temporary values of torque of the engine Ms [N·m] and the rotational speed of the engine ω [rad/s] with the use of parameters of the selected vehicle according to the correlations [10]:

$$Ms = Fk \cdot R \ \cdot Pm \cdot S\ [N \cdot m] \tag{5}$$

$$\omega s = \frac{v(t)}{R} \cdot P\omega \cdot S\ \left[\frac{rad}{s}\right] \tag{6}$$

Where:
Fk - Temporary value of the effort on wheels [N],
R - Wheel radius [m],
Pm - Transmission ratio of the drive system for the torque (0; 0.0769; 0.137; 0.209; 0.287; 0.336 [-]),
S - Clutch engagement signal (0, 1 [-]),
$v(t)$ - Temporary vehicle velocity in the NEDC test,
$P\omega$ - Transmission ratio of the drive system for the rotational speed (0; 13.9; 7.30; 4.79; 3.48; 2.98 [-]).

Next, the “Engine” unit checks whether the calculated values are contained within the ranges of permissible changes and the values of rotational speed of the neutral gear on 83.7 rad/s (800 rpm) are determined according to the principles of engine operation in the vehicle which does not have the start/stop feature and cannot stop the engine during the longer no-load states in compliance with NEDC test.

2.2.3 “Calculations for petrol” simulation unit

Within this unit, on the basis of the assumed characteristics of the hourly fuel consumption for the selected engine in the function of the rotational speed and torque, temporary values of the fuel and air consumption necessary for operation and cumulated values are calculated. In the model was used 95 octane gasoline. In this case as well the general engine efficiency for a particular engine operation point is calculated and it constitutes a basis for further estimation of consumption of other fuels. To perform the calculations universal characteristics of the selected vehicle [9] were used which, after having been converted into digital form, were entered into the simulation component as a regular two-dimensional matrix. Such component, with the use of linear interpolation function, allows the calculation of temporary values of fuel consumption for any rotational speed values of the engine and torque. Using temporary values of the rotational speed defined previously, torque and characteristics of the hourly fuel consumption, module elements perform the calculation of the temporary value of fuel stream $p\dot{a}l$ [g/s] on the basis of the following correlation [10]:

$$p\dot{a}l = fu(\omega s,\ Ms)/3600\ \left[\frac{g}{s}\right] \tag{7}$$

Where:
fu - Function of hourly fuel consumption depending on the rotational speed and torque [g/h],
ωs - Engine rotational speed [rad/s],
Ms - Engine torque [N·m]).

After that, including the fuel stream and a stoichiometric constant, the values of the air stream are calculated and they are essential to carry out proper process of fuel and air mixture combustion in the engine combustion chamber on the basis of the correlation [10]:

$$p\dot{o}w = p\dot{a}l \cdot Ste\ \left[\frac{g}{s}\right] \tag{8}$$

Where:
$p\dot{a}l$ - fuel stream [g/s],
Ste - Stoichiometric constant for petrol (14.7 g_{pow}/g_{pal}).

Including calorific value of petrol, the energy stream $\dot{E}e$ [J/s] provided by the fuel was calculated, and, after that, the temporary value of engine efficiency η [-] was determined with the use of the correlation [10]:

$$\dot{E}e = Qe \cdot p\dot{a}l\ \left[\frac{J}{s}\right] \tag{9}$$

$$\eta = \frac{Ms \cdot \omega s}{\dot{E}e}\ [-] \tag{10}$$

Where:
$p\dot{a}l$ - fuel stream [g/s],
Qe - calorific value of petrol (42 kJ/g),

ωs - engine rotational speed [rad/s],
Ms - engine torque [N·m]).

The simulation model, based on the calculated temporary values, performs calculations of cumulated values of fuel and air consumption for the entire test, using integrating elements. Fig. 2 shows a fragment of a built-in simulation that calculates the instantaneous petrol stream to power the engine during the NEDC test, the energy flow required for the engine drive and the total fuel and air consumption values.

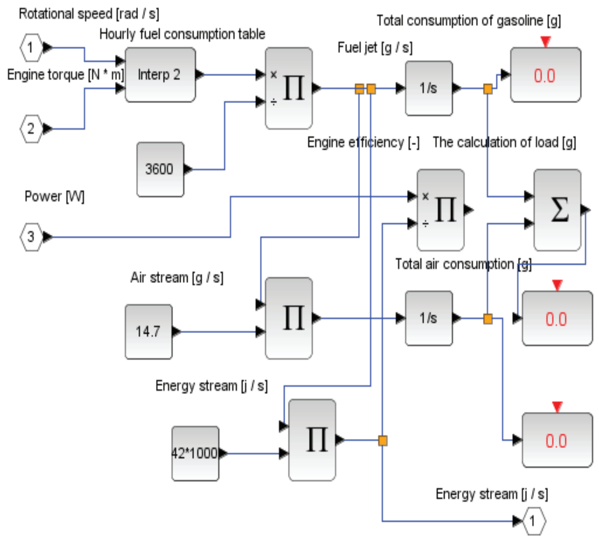

Fig. 2. Diagram of the calculations for petrol.

2.2.4 "Calculations for methane", "Calculations for LPG" and "Calculations for wood gas" simulation units

The said simulation units have the same structure enabling the calculation of the temporary values of demand for a particular fuel $\dot{pal}$ [g/s], including a required stream of energy provided by a given fuel determined in the previous module and calorific value of a given fuel as well as calculation of the temporary value of the air stream according to the correlation [10]:

$$\dot{pal} = \frac{\dot{Ee}}{Qe} \left[\frac{g}{s}\right] \tag{11}$$

$$\dot{pow} = \dot{pal} \cdot Ste \left[\frac{g}{s}\right] \tag{12}$$

Where:
$\dot{Ee}$ - stream of energy provided by the fuel [J/s],
Qe - Calorific value for fuels: methane, LPG, wood gas [J/g],
Ste - Stoichiometric constant for fuels: methane, LPG, wood gas [g_{pow}/g_{pal}].

Table 2 below summarizes the accepted calorific values and stoichiometric steady-state combustion air requirements for individual fuels. In the developed simulation, the chemical composition of the applied wood gas was assumed:

- Nitrogen (N_2) 47% Vol.;
- Carbon monoxide (CO) 23% Vol.;
- Hydrogen (H_2) 18% Vol.;
- Carbon Dioxide (CO_2) 10% Vol.;
- Methane (CH_4) 2% Vol.

Table 2. Calorific values and stoichiometric values for fuels used in the simulation.

Fuel	Calorific values [kJ/g]	Stoichiometric values [g_{pow}/g_{pal}]
Petrol	42	14.7
Methane	50	17.2
LPG	46.1	15.7
wood gas	4.9	1.39

In order to depict the effects of the simulation, the elements in the discussed modules present temporary values in the form of diagrams. The cumulated values are estimated as well. Below, Fig. 3 shows the simulation elements that calculate the value of the wood gas stream in the NEDC test.

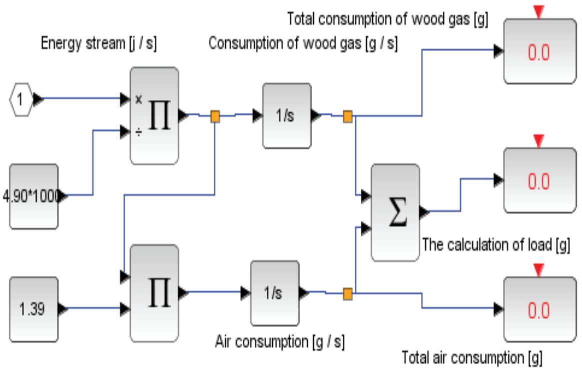

Fig. 3. Diagram of the calculations for wood gas.

2.2.5 Simulation of the estimation of changes in maximum power characteristic

Fig. 4 presents the reference diagram of the prepared simulation. The following simplification assumptions were applied in the simulation of the estimation of changes in maximum power characteristic of the selected engine for different fuels:

- Particular values on the maximum power curve in the function of the rotational speed for petrol in the case of a selected engine depend on the maximum load delivered to engine cylinders;
- The same values of the engine efficiency with the use of different fuels were assumed for a particular point of engine operation located on the maximum power curve;
- In the case of other fuels used, the volume of the fuel and air mixtures equal to the volumes of petrol and air mixture;
- Based on the maximum streams of mass of the used fuels which may be supplied to the engine and calorific values, theoretical energy streams are calculated, and subsequently, on the basis of the engine efficiency the progress of the theoretical curve of the maximum engine power is determined.

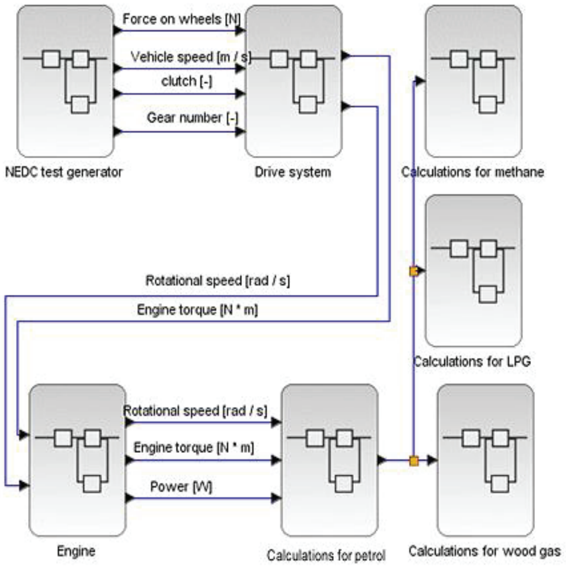

Fig 4. General diagram of the prepared simulation.

3 Results and discussion

The results were presented below as waveforms and numerical values for the included parameters.
The results of the simulation unit performance responsible for the calculation of temporary parameters of the internal combustion engine "Engine" were presented in Fig. 5 in the form of temporary waveforms of the torque values produced by the engine, engine rotational speed, including the restrictions assumed in the simulations and power produced by the engine. The parameters shown in the diagrams are key elements necessary for further calculations in the units concerning particular fuels.

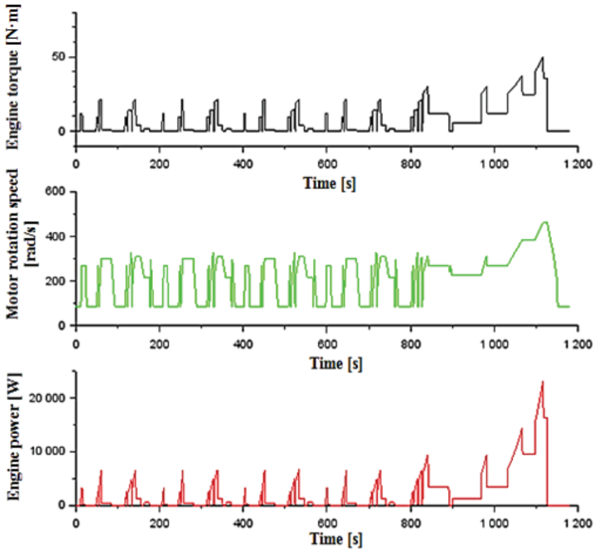

Fig. 5. The results of the simulation unit performance responsible for the calculation of temporary parameters of the internal combustion engine.

On the basis of [9], the characteristics of the hourly fuel consumption for the selected engine were adopted for the simulation. The view of the waveform of the characteristics after its conversion into numerical form is shown in Fig. 6. For technical reasons, characteristics fragments for higher maximum torque values (red line in the diagram) typical for the selected engine were extrapolated in such a manner that a regular matrix with a set of values may be obtained. It prevents calculation problems of the simulation modules for engine operation conditions near the maximum torque curve in the function of the rotational speed.

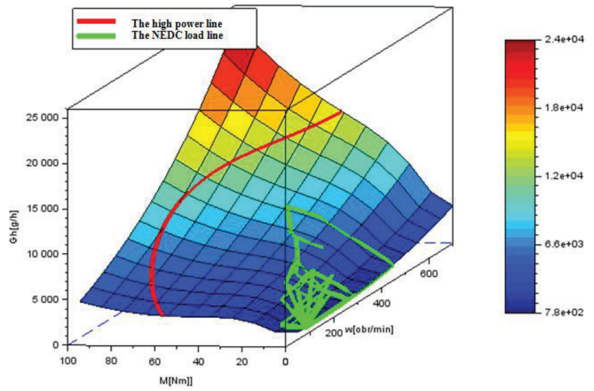

Fig. 6. Characteristics of the hourly fuel consumption in the function of the rotational speed and torque of the selected engine adopted in the simulation.

The diagram was also marked with a line (green colour) which determines the course of changes in the engine operation conditions during the simulation of the NEDC test. The form of the line confirms that the aforementioned test uses moderate ranges of the rotational speed and torque of the selected engine during the process.

Table 3 below presents the results of the cumulated values of fuel and air consumption as well as total load provided to the engine for different variants of the engine simulation in respect of the used energy sources obtained from the simulation.

Table 3. Comparison of the mass fuel and air consumption for the NEDC test for different fuels supplying the engine, calculated during the simulation.

	Petrol	Methane	LPG	Wood gas
Mass fuel consumption [kg]	0.497	0.418	0.453	4.26
Mass air consumption [kg]	7.31	7.19	7.12	5.93
Mass load consumption [kg]	7.81	7.61	7.57	10.2

In the simulation of the test, values for the engine powering with the petrol and liquefied petroleum gas are comparable due to the similarity of their energy parameters such as calorific value or stoichiometric constant. In the case of methane, the consumption of this energy source measured in grams during the test simulation is the lowest since it had the highest calorific value and stoichiometric constant.

As far as the NEDC test simulation for the wood gas is concerned, high values of its consumption were obtained, which results from its very low calorific value (4.9 kJ/g) in relation to other used fuels. Moreover, the results of the simulation confirm the information contained in the professional literature revealing considerable demand for this gas during the engine operation due to low energy values of the fuel. The values of the air consumption, however, in this type of engine supply, are lower than in the case of other analysed fuels. It is associated with the lower value of stoichiometric constant for the wood gas.

The next step in the prepared simulation was the estimation of the changes in maximum power characteristic for the selected engine when using the following fuels: petrol, methane, LPG and wood gas according to the methodology described in the thesis. Fig. 7 presents the results of performance of the prepared simulation in the form of diagrams of the maximum engine power in the function of the rotational speed [rad/s].

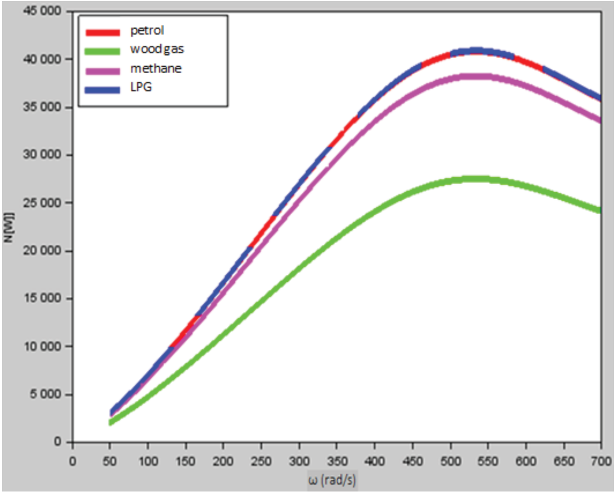

Fig. 7 Waveform of the maximum power in the function of the rotational speed for different fuels used in the simulation.

In the cases of supplying the engine with: petrol and LPG the curves of the power practically overlap. As far as methane powering is concerned, there is a slight drop of the value of the maximum power characteristic. However, a considerable decrease in the value of the maximum power characteristic was obtained in the case of powering the engine with wood gas.

4 Conclusions

The following conclusions may be drawn from the analysis of the prepared simulation model, obtained simulation results and professional literature:

- Scilab environment constitutes functional software enabling the simulation of the vehicle dynamics based on the implemented characteristics;
- The cumulated values of the engine demand for wood gas proved to be significantly higher than for other examined fuels. It results from the low calorific value of the carrier.
- The analysis of the maximum power characteristic of the engine supplied with wood gas revealed much lower values than in the case of other carriers.
- Results obtained in the simulation support data contained in the professional literature. Considering inconveniences related to the use of syngas, its low calorific value and drops in engine power, it has been established that the use of wood gas as fuel for motor vehicles is currently unjustified.

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