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On Combustion of Diesel Fuel Drops at LPG Fuelling by Diesel Gas Method

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Abstract

The Liquid Petroleum Gas can be use at diesel engine with significant reductions in nitrous oxides and smoke emissions and affects the in-cylinder mixture forming and combustion process. The paper presents the results of a thermodynamic model developed for vaporization and combustion processes simulation for an automotive diesel engine fuelled with LPG by diesel gas method. The mass flow of vaporized substance at the particle area, drops combustion time and flame position are determinate, showing a significant influence of LPG cycle dose on their characteristic parameters. The drops combustion duration decreases for dual fuelling and the flame radius increases.

Keywords: LPG dose; mixture forming speed; fuel drop combustion; flame radius; mass transfer number.

1. Introduction

In terms of pollution reduction, the Liquid Petroleum Gas (LPG) can be defined as a viable alternative fuel due to the important reductions in exhaust diesel emissions, especially nitrous oxides and smoke, aspects of real importance in the modern content of pollution legislation [1]. Nowadays, LPG is a worldwide alternative fuel used on a large scale for internal combustion engines. For a 1.5 DCI diesel engine from Dacia Logan, at diesel-LPG fuelling at full load regime and 4000 min^{-1}, the effective energetically specific fuel consumption decreases with 2% [2]. The NO_x emission decreases with 21%, the CO_2 decreases with 8%, the unburned hydrocarbon emission

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decreases with 50% and the smoke emission decreases with 50% [2]. Also at other running regimes the emissions decrease is important. The mixture forming, the heat release, the energetically and pollution performance of the engine are influenced by different vaporization and burning properties of the LPG comparative to diesel fuel.

Higher combustion rate of air-LPG mixtures leads to the increase of maximum pressure and maximum pressure rise rate. Thus, the maximum LPG cycle quantity admitted inside the cylinder can be limited for efficiency, mechanical reliability, noise, smooth running reasons. The higher autoignition temperature of the LPG, around 481...544 ^{o}C versus 225 ^{o}C for diesel fuel [1] can allows the use of excessive values for the compression ratio and required the use of a diesel pilot injection for air-LPG mixture ignition. LPG raised vapour pressure assures forming of air-LPG mixtures of higher homogeneity. Starting the combustion into a relative lean high homogeneity air-LPG mixture influences the combustion process and cycle variability. Also, wide inflamabillity limits of the liquid petroleum gas 2.1…10.4% versus 0.6…5.5% for diesel may leads to an improvement of the combustion process [1].

In a droplets vaporization-combustion model, Pimsner [3] establish in a time interval of 0.1 .... 1.0 s the temperature variation of a tetralin drop with the diameter of 1.06 mm and calculates combustion duration of almost 0,5 s in the centre of the drop and at 0.12 mm from the droplet surface [3]. During the droplet combustion the temperature rise rate at 0.12 mm from the droplet surface is more considerable comparative to centre zone, especially till the end of the first half of the combustion interval. Fenn presents the way of variation in time for the diameter of a large droplet of fuel [4]; initially, the drop dimensions varies slow due to a vaporization achieved only by heat transfer between drop and surround area at the average temperature inside the combustion chamber, followed by rapid dimensions variations due to the amplification of the substance transfer, defined by mass transfer number B, determinate by the presence next to the drop of the flame zone in the moment when the ignition occurs [4]. Thus, the diameter squared of a benzene drop, situated in an environment at 740°C temperature, decreases in a period of time, starting from 0 s (injection moment) to 0.7 s, from 1.6 mm^2 to 1.4 mm^2, and since the ignition time, in a 1.25 s time interval the droplet diameter squared significantly decreases from 1.4 mm^2 to zero [4]. The increase of the temperature in the gaseous environment of the drop at 700, 750 and 800°C, significantly reduces the processes total time from 2 s to 1.6 and 1.4 seconds, respectively. Abramovici [5] shows that in a temperature interval of 300...1700°C the combustion period of a single 45 μm diameter fuel drop decreases with 25%, from $5 \cdot 10^{-3}$ s to $1.2 \cdot 10^{-3}$s, since the oxidant environment temperature increases. Thus, the vaporization of a diesel fuel drop into a gaseous media situated nearby of other burning drops is influenced by the level of pressure and temperature reached in the closed proximity. Kadota, Hiroyasu [6, 7] and Kanury [8, 9] establish vaporization and combustion time periods for a particle of light diesel fuel with the initial diameter of 15 μm, at 20 bar and 1000 K pressure and temperature regime, obtaining period of droplets combustion of 0,304 ms. Based on a relative simple model, Law [10] establishes the vaporized substance flow and the flame radius. Spalding and others [9, 10, 11, 12, 13, 14] establish the flame position for a 40 μm initial diameter fuel particle, for many values of air-fuel ratios λ=1; 1,1; 1,5, at maximum values till $10 \cdot 10^{-1}$cm, notice that the combustion process stops in the moment of flame radius annulling [3] after a period of 1; 1.4; $1.9 \cdot 10^{-3}$s for those three air-fuel ratio values. For air-fuel ratio values of λ=1.1 ... 1.5 the combustion period is in the area of 0.0009...0.0014 s [9].

2. Setup procedure of the theoretical model

2.1. Modelling concept

To study the vaporization and combustion processes of diesel fuel drops inside the engine cylinder for a diesel engine fuelled with diesel fuel, a one-dimensional, one-zone thermodynamic model developed and calibrated by authors over the years in processes simulations was used for mathematical simulation. The vaporization and combustion of liquid diesel fuel drops study is the base for combustion study.

Following the modern concept for vaporization and combustion of the liquid fuel particle Spalding and et. al. [5, 6, 11, 12, 13, 14, 15] offer calculus relations for a spherical symmetry classic model, with a diffusive combustion developed inside the flame envelope created around the liquid particle. The liquid total mass flow, w_s, that fuels the vaporization area and the flame radius are determinate. The variation of the evacuated vapour mass flow from the vapour surface is related with the flame radius variation. The vaporization and combustion times of a diesel fuel particle are calculated with relations for a spherical symmetry classic model for vaporization and combustion of the

liquid fuel particle, considering a diffusive combustion process inside the gas flame envelope of the liquid particle. Inside the combustion chamber the liquid diesel fuel drops receive the heat from the preheated air and from the residual burned gases by convection and also absorb the radiant energy from the combustion chamber walls and the flame [3]. The heating of the fuel drop begins, it's temperature increases and the evaporation process starts. When the temperature of the diesel fuel vapours rise significantly, the combustion may starts in a diesel fuel vapours-air area which surrounds the fuel drop and where the relative rich dosage suitable for ignition starts is achieved [1, 3] and finally spreads thru immediate outskirts layers. The flame becomes stable in the area where the chemical reaction velocity is equal with the diffusion speed of the fuel into the air. This area, characterized by stoichiometric air-fuel state, is dimensionally defined by the flame radius which is the distance measured from the centre of the drop [3, 9]. The experimental research's show the influence of pressure on radiation, convection and burning mass velocity. Since the vaporized fuel flow is proportional with the quantity of heat transmitted to the drop surface, results a variation of the heat quantity similar with the pressure variation and a mutual influence of the vaporization and combustion of the drops in the nearby area of others drops, the drop vaporization constant being modified by nearby presence of other fuel drops [3, 16].

Due to higher propane vapour pressure, the air-LPG mixture admitted inside the cylinder is in a higher degree of homogeneity and assures a higher flame propagation velocity during the combustion process, when the flame nucleus is formed at the diesel fuel jet boundary. Thus in some combustion chamber areas the flame is developed in the time of mixture formation between air and diesel fuel drops, at their contact limit, with the diffusive flame character and in other combustion chamber areas a deep mixture process before combustion is possible, the flame being developed in a premixed gases environment [3].

In some combustion chamber zones, nearby the burning of air-LPG homogeneous mixtures, may exists preheated regions in which the air-LPG-diesel fuel vapours mixture may be heated to a superior temperature and from total quantity of heat released during the combustion, a part of it is consumed for heating by admixture and another part for heating by conductibility, respectively. Local increases in pressure and temperature of the nearby air-LPG mixture combustion zones leads to the increase of mass transfer number which further leads to the increasing of the vaporized substance mass flow on the nearby droplets surfaces. The modification of the in-cylinder gaseous environment density and of thermal conductibility coefficient with the increase of LPG cycle dose will leads to the modification of gaseous environmental thermal diffusivity, to the increase of vaporized substance flow at the fuel drops surface and also to the decrease of droplets vaporization duration.

If the drops vaporization is followed by combustion, the increases of in-cylinder gas thermal diffusivity with LPG cycle dose increase will assure the decreases of diesel fuel drops combustion time and increases the flame radius.

2.2. Experimental investigation and model conception

The model is developed for a 1.5 litre supercharged diesel engine at 4000 min^{-1} and full load regime for diesel fuelling and dual fuelling (diesel fuel and liquid petroleum gas) with a percentage of LPG up till 40%. The LPG cycle dose is injected inside the inlet manifold by diesel gas method and electronic controlled by a secondary electronic control unit (ECU) connected back to back with the main engine ECU. The engine characteristics are presented in the table 1.

The mathematical model for fuel drops vaporization and combustion study is developed on the following hypotheses [3, 9, 14]:

- constant radius fuel drop and flame zone are concentrically spheres
- convection and radiation of the hot gases are neglected
- the vaporization process is isobar and developed in permanent regime
- fuel drop temperature is equal with liquid diesel fuel boiling temperature
- coefficient of thermal conductivity is independent to temperature
- the air and fuel vapours are perfect gases, the values of specific heats being independent to temperature
- concentration and temperature depend on the radius measured from the drop centre.

The model use in-cylinder pressure diagrams smoothed and averaged from 50 consecutive cycles and use the general state equation applied for ideal gases in order to evaluate the global in-cylinder temperature.

Table 1. The K9K K792 diesel engine characteristics.

EURO 4 K9K K792 Engine Parameter	Values
Bore / Stroke	76 [mm] / 80,5 [mm]
Compression ratio	18.3 [-]
Swept volume	1461 [cm3]
Maximum power	50 [kW] / 4000[min-1]
Maximum torque	150 [Nm] / 2000 [min-1]
Supercharging pressure	1.8 [bar]
Injection pressure of Delphi common rail injection system	maximum 1600 [bar]
Nozzle hole diameter	0.15 [mm]

The quantity of the diesel fuel substituted by LPG is established by an energetic substitute ratio value which takes into consideration the energetically value of the both fuels, x_c [%]:

$$x_c = \frac{Ch_{LPG} \cdot Hi_{LPG}}{Ch_{DF} \cdot Hi_{DF} + Ch_{LPG} \cdot Hi_{LPG}} \cdot 100$$

(1)

where: Hi_{DF}, Hi_{LPG} represents the lower heating value of diesel fuel and LPG in [kJ/kg] and Ch_{DM}, Ch_{LPG} are diesel fuel and LPG fuel consumptions in [kg/h]. At only diesel fuelling the x_c value is zero.

From the equation of the energy conservation, the liquid total mass flow, w_s, that fuels the vaporization area is determinate. The convection process that drives the fuel vapors and the diffusion effect are controlling the evacuated vapor mass flow from the vapor surface. Assuming by the surface conditions that the fuel drop radius is equal with the gas envelope radius around the fuel drop, the mass flow of vaporized substance at the particle area, w_s [g/cm²s], in stationary regime [3, 9, 14] is determinate.

$$w_s = \frac{\alpha_g \cdot \rho_g \cdot \ln(1+B)}{r_p}$$

(2)

B is the mass transfer number which depends on in-cylinder gas temperature, ρ_g density of combustion chamber gaseous environment, α_g thermal diffusivity, r_p particle radius.

Inside the fuel jet, defined by particles with the Sauter mean diameters, the combustion process is identical for all fuel particles [1, 9, 17]. The calculated value of the Sauter mean diameter is 10 μm. If the vaporization of the fuel isolated particle is followed by combustion, in the outside space of the particle an infinitesimal flame is developed. In this zone the flame becomes stabilized and divides the fuel and oxidant areas. Its position is defined by the radius r_f, [cm] as the distance on which the fuel vapor flow and the oxidant are in stoichiometric ratios [3, 9, 14].

$$r_f = \frac{w_s \cdot r_p^2}{\alpha_g \cdot \rho_g \cdot \ln(1 + c \cdot y_{0\infty})}$$

(3)

c fuel/oxygen mass stoichiometric ratio, $y_{0\infty}$ oxygen mass fraction in a distanced area from the drop [3, 9].

Into the final reaction zone, established by r_f radius, the diffusion speed of diesel fuel vapors in air is equalized by chemical reaction speeds, the flame becomes steady and covers the fuel drop completely. The radiation heat transfer and the effects of thermal diffusion are neglected. Following the hypothesis of the boiling temperature reached at the

liquid surface, the combustion velocity is established by the vaporized fuel mass flow, w_s [3, 9, 14]. According to this hypothesis the combustion velocity doesn't take into consideration the flame temperature and depends only by mass transfer number. The flame position is established by the r_f radius and the particle combustion duration [3, 9, 14] can be determined.

$$t_a = \frac{\rho_1 \cdot d_{po}^{\;2}}{8 \cdot \alpha_g \cdot \rho_g \cdot \ln(1+B)}$$ (4)

B is the mass transfer number calculated in conditions of combustion.

The law of mass diffusive burn is determinate in correlation with the in-cylinder injected fuel mass m_{inj} and the oxygen partial pressure p_{O2} [9, 14, 17, 18]:

$$\xi_{md} = 0.017 \cdot m_{inj} \cdot p_{O_2}$$ (5)

3. Results and discussions

The acceleration of the vaporization process of the diesel fuel droplets in the presence of the nearby LPG-air burning mixtures also leads to the increase of mixture forming speed and of its quantity during the same interval of time. The injected diesel fuel is atomized, the resulted drops starts to heat, to vaporized, the formed vapours being mixed by turbulent diffusion with the air driven into the jet [3, 9]. In the areas with suitable mixture concentrations, chemical transformations are started and developed till autoignition occurs. In the presence of homogeneous air-LPG mixtures, the combustion time period of the diesel fuel drops is reduced for all substitute ratios, Fig. 1.
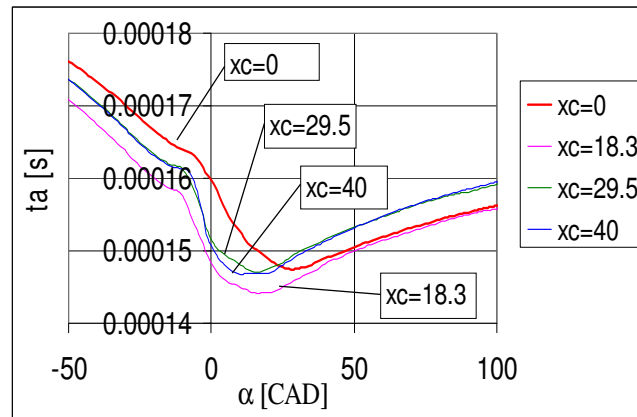

Fig. 1. Diesel fuel drops combustion time period at 4000 min-1 and full load.

Around the top dead centre (TDC) the diesel fuel drops combustion time decreases with 9% for x_c=18.3 and 3.1% for x_c=29.5 … 40. At this x_c values is also registered the most reduced vaporization time. For x_c with values up till 20, for which the maximum vaporization time also decreases, appears a ~2.4% reduction of the minimum combustion time. For bigger substitute ratios the drops combustion time tends to increase without exceeding the values registered for diesel fuelling. The moment of minimum t_a is reached sooner per cycle for all x_c comparative to diesel fuelling. The calculated values of drops combustion time period are in the same range with the values registered in the literature, for similar air-fuel ratio values [3, 6, 9, 19, 13, 14, 20]. Mass flow of vaporized substance, which also defines the combustion velocity, increases with the LPG cycle dose rise, Fig. 2(a). The values registered for dual fuelling are all superior to diesel fuelling values, the increase being correlated with the previous

observed reduction tendency for combustion time, especially for area of $x_c=0...18,3$. The most important increase of 2.1% is assured for $x_c=18.3$. For the other substitute ratio the obtaining values being around the diesel fuelling value, but the maximum of vaporized substance mass flow tends to close on TDC once with the increase of LPG dose. Thus, for $x_c=0$ the maximum of vaporized substance mass flow appears at 28 CAD, comparative to 17 CAD at $x_c=18.3$, 14 CAD at $x_c=29.5$ and 11 CAD at $x_c=40$. From the maximum values analysis is shown that the increase tendency appears for x_c values up till 20%, when is registered a decrease in the value area of diesel fuelling, with a slightly tendency of increasing. The mass flow of vaporized substance on droplet surface is equivalent with the combustion speed. The variation of the flame position is related with the variation tendency of the vaporized substance mass flow at the drop surface. At the rise of x_c, the flame is developed sooner and reaches much larger dimensions comparative to diesel fuelling, as Fig. 2(b) is shown. Flame radius increases with 2.4% for $x_c=18.3$ and remains in the same value area as for classic fueling for other x_c values. Comparative to diesel fuelling, for $x_c=30...40$ the flame radius starts to increase again. The maximum of flame radius occurs sooner per cycle, with 211% sooner for $x_c=40$ comparative to diesel fuelling. The moment per cycle for maximum value of the flame radius are $\alpha_{max}=28$ CAD at $x_c=0$, $\alpha_{max}=16$ CAD at $x_c=18.3$, $\alpha_{max}=14$ CAD at $x_c=29.5$ and $\alpha_{max}=9$ CAD at $x_c=40$.
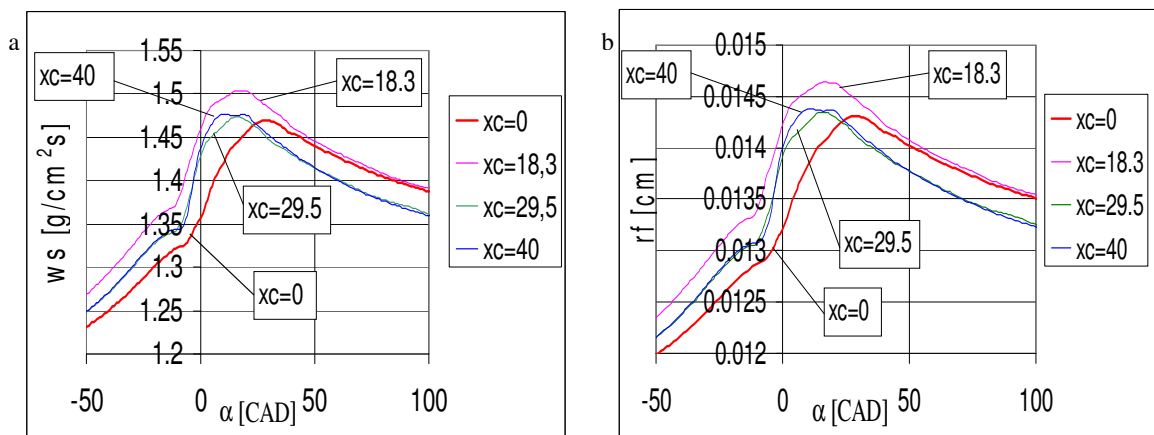

Fig. 2. (a) Mass flow of vaporized substance at the diesel fuel drop surface for 4000 min-1 and full load; (b) Flame position defined by flame radius from the drop center at 4000 min-1 and full load.

After the consummation of diesel fuel vapors, the admixture phenomenon controls the combustion process thru the mass diffusive burn law, [9, 13, 20] Fig. 3(a) and Fig. 3(b). In correlation with the increased mixture forming speed at dual fuelling, the maximum of mass diffusive speed increases with 17% for dual fuelling. Also, the moment per cycle for the maximum mass burn diffusive speed appears closer to TDC for all substitute ratios, with 50% earlier for $x_c=18...40$ ($\alpha_{max}=3$ CAD) comparative to classic fuelling ($\alpha_{max}=6$ CAD for $x_c=0$).

The diffusive burn mass laws, calculated for dual fuelling, are all superior to the law calculated for only diesel fuelling. The diffusive heat quantities increases up till 2.8% for maximum LPG dose, Fig. 3(b).

The increased quantity of in-cylinder formed mixture and raised velocity of mixture forming for dual fuelling are related with the higher values of the diffusive burned mass laws associated for $x_c=18...40$, phenomena's being controlled only by the admixture process, Fig. 3(a). Also, the increasing of the diffusive mass speed with the increase of x_c is correlated with the reduction tendency for diesel fuel drops vaporization time and with the increasing tendency for the mass flow of vaporized substance, for the droplets combustion velocity and for the flame radius, inside the study interval.

At the same operating regime the diffusive heat release law is calculated by the thermodynamic model with averaged pressure diagrams and compared to the experimental heat release law. The Fig. 4(a) and (b) presents the results for diesel fuelling and for the maximum LPG dose, $x_c=40$ at the same operating regime.
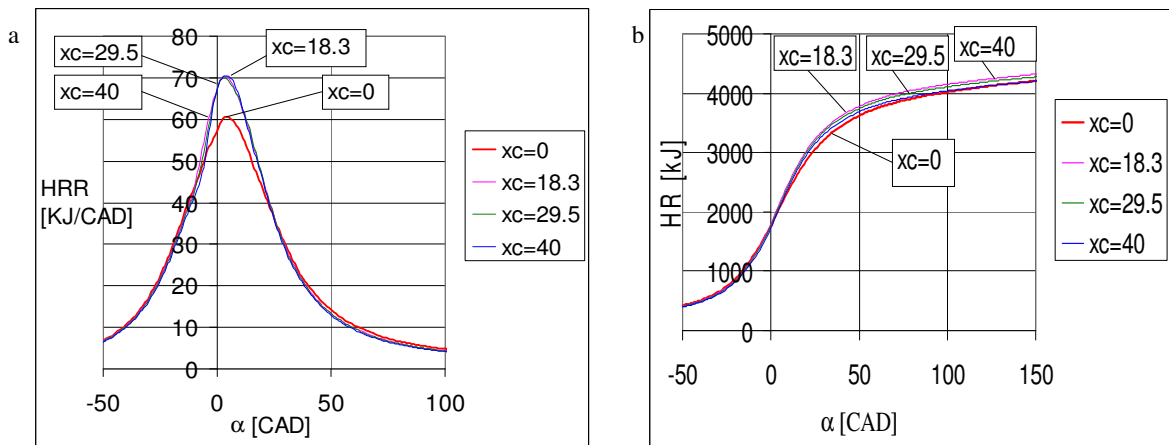
Fig. 3. (a) Mass diffusive burn rate for different xc at full load, 4000 min-1; (b) mass diffusive burn law for different xc at 100% load, 4000 min-1.
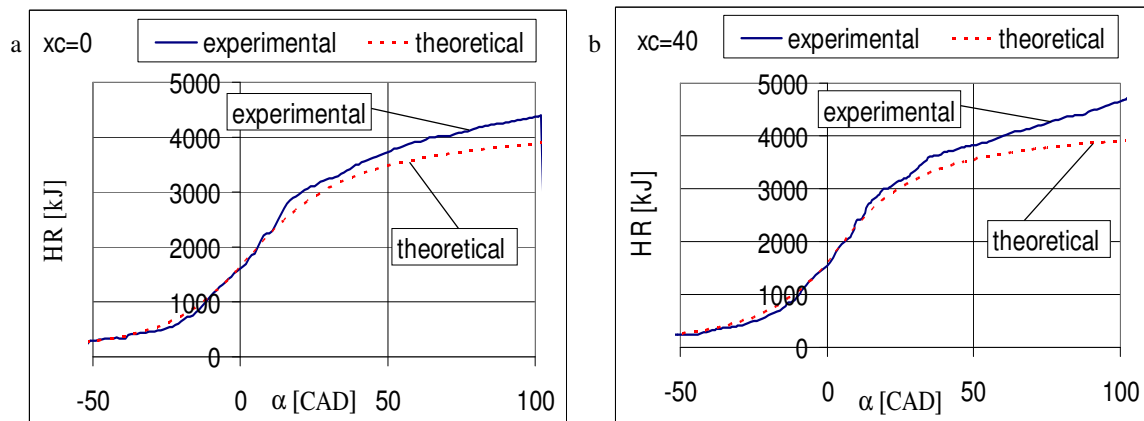

Fig. 4. Comparison between the calculated mass diffusive burn law and experimental burning law at diesel fuelling (a) and for maximum LPG cycle dose xc =40 (b) at full load and 4000 min-1.

4. Conclusions

The developed study marks out the main characteristics of in-cylinder diesel fuel drops combustion in the presence of air-LPG mixture combustion. The main conclusions of the study can be formulated:

- The mass flow of vaporized substance on the diesel fuel droplet surface which is related with combustion velocity increases up till 2.4% once with the increase of the LPG substitute ratio, the increasing being associated with the reduction of the droplets vaporization time, with 70% for xc=0…20 and with 31% for x_c=30…40, respectively.
- For all diesel fuel substitution ratios by LPG, the diesel drops ignition time decreases comparative to only diesel fuelling regime. The maximum values of ignition times are continuously decreases with 2.4% for x_c values up to 20%, and the further increases of the maximum values with xc don't exceed the area of the reference regime.
- Combustion velocity of diesel fuel drops increases for higher substitute ratios. Also the maximum values of the droplets combustion velocity increases with 2.4% for x_c=18.3, followed by a reduction to the level of diesel

fuelling. In the same interval of x_c values, this variation is correlated with the decreasing of droplets vaporization time.

- Flame radius increases for all domain of x_c and it's maximum value is reached sooner per cycle. Thus, the flame is developed sooner and much quicker with the increase of the LPG cycle dose. This phenomenon is associated with the variation of the mass flow of vaporized substance which increases and occurs much sooner per engine cycle when the substitute ratio increases. Also, these aspects are in the correlation with the tendency of variation registered for combustion time period of diesel fuel droplets.
- Mass burning diffusive speed and its associated law, controlled by the admixture process, modifies their allure and values since the LPG cycle dose increases. The mass diffusive speed increases with 17% and occurs with 50% sooner per cycle comparative to diesel fuelling. Also the diffusive heat release laws indicate an increasing in heat quantity for all dual fuelling regimes.
- Increasing of the mixture forming speed leads to the increase of the diffusive mass rate controlled by admixture process, when the substitute ratio increases. Phenomena are correlated with the increasing of heat release rate at the increasing of LPG cycle dose and fundamental influence the droplets combustion process with effects as reduction of combustion time and increases of flame radius.

Acknowledgements

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