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SIMULATION OF LIQUEFIED PETROLEUM GAS JET IN COMBUSTION CHAMBER OF SPARK IGNITION ENGINE

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ABSTRACT. Based on the mathematical model validated by experimental data, the present paper introduces the evolution of concentration and velocity fields of Liquefied Petroleum Gas (LPG) jet in combustion chamber of spark ignition engine under effects of injection conditions and surrounding environment. The results allow us to predict the development of jet for an efficient organization of mixture preparation and combustion process in LPG direct injection spark ignition engine.

1. Introduction

The Liquefied Petroleum Gas (LPG) has a lot of advantages in comparison with the conventional liquid fuels (gasoline and diesel (GDI)) in aspect of pollution emission. In actual LPG engines, fuel is injected into intake manifold by mean of carburetor or electronic controlled injectors. The power of this kind of engines is reduced normally about 10% in comparison with gasoline engines because of decreasing of volume efficiency due to gas state of fuel. Thus, for a better performance of LPG engines, fuel should be injected directly into the combustion chamber. This new technology, *LPG direct injection spark ignition engine*, presents otherwise the advantages of GDI engines which are developing recently.

A basic problem needed to be studied firstly for this new engine is the development of LPG jet inside the combustion chamber. The fundamental researches on vertical jets in steady environment using gas and liquid fuels have been mentioned in [1]. This model has been developed to calculate the combustion and pollution emission, particularly soot and NO_x, in Diesel engines [2], [5], [3]. For a better representation of different effects on jet, a general model has been established in which the gravity and moving surrounding air are taken into account [6], [7], [8].

Experimental researches on LPG jet development in the combustion chamber have been shown in [9]. However, due to technical difficulties in experimental disposition, only the influence of main factors can be studied. The simulation of jet by means of mathematical models is, therefore, necessary to predict the influence of different factors on physical fields of LPG jet. This is important for an efficient organization of mixture preparation and combustion process in LPG direct injection spark ignition engine.

The present paper introduces some results of simulation calculation of LPG jet in combustion chamber based on theoretical fundamental established in [8].

2. Experimental evaluation of the model

A general integral model describing jet under effect of different parameters such as incline angle, gravitational force, movement of surrounding air has been established in [7], [8]. The model is validated by experimental velocity field. It is now compared with experimental concentration field of vertical CO_2 jet in steady environment. The injector diameter is 3 mm with an initial mass flow of 560 litters per hour. The velocity field is given by Laser Doppler Anmometer (LDA) method. Figure 1 shows the comparison of the mass flow of carbon dioxide concentrations on jet axis given by the model and by experiments. The results have shown a good coherence between model and experimental data.

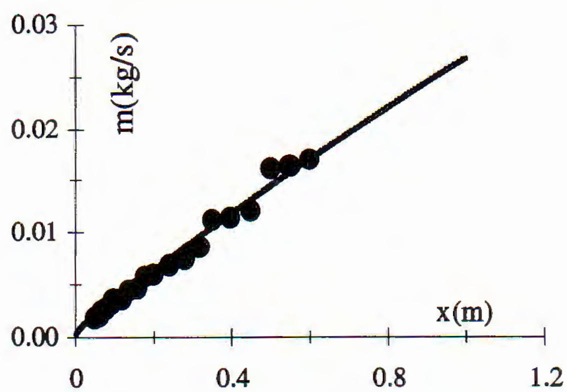


Fig. 1. Comparison of mass flows in CO_2 jet given by model and experimental data

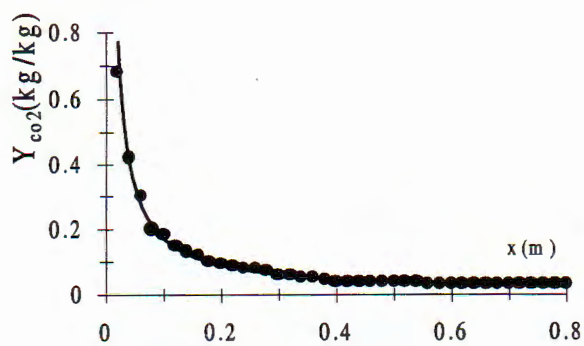


Fig. 2. Comparison of center line concentrations in CO_2 jet given by model and experimental data

The application of this model for LPG jet inside the combustion chamber requires some necessary adjustments. An experimental study of LPG jet is thus carried out. The experimental apparatus is described in [9]. The combustion chamber has two transparency windows for access of light beams of optical measurement systems (PDA and high speed camera). The injector diameter is 0.6mm. The figure 3 represents general variation of jet angle in logarithm coordinates. The analyses mentioned in [10] allow us to describe the variation of LPG jet angle by the formula:

$$\theta = 11.18 \cdot \left(\frac{p}{p_0}\right)^{0.5} \cdot \left(\frac{T}{T_0}\right)^{-0.25} \cdot t^{0.3}, \tag{2.1}$$

where p is pressure (bar), t is time (ms), T is gas temperature (°C), $p_0 = 1\,\text{bar}$, $T_0 = 25°\text{C}$.

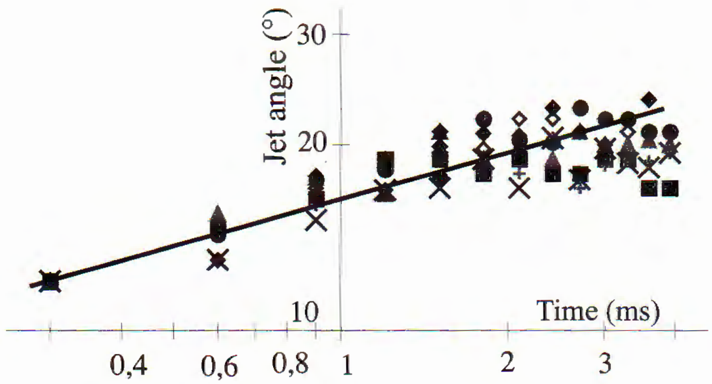


Fig. 3. Jet angle variation as function of time in different experimental conditions of LPG jet in combustion chamber

Unlike liquid jet in which jet angle is independent of time [11], the jet angle in the case of LPG increases proportionally to $t^{0.3}$.

The second fundamental parameter of jet is its penetration. In limit of small variation of air pressure and temperature in combustion chamber during the intake process, we can consider that the penetration is a function of time. The figure 4 introduces variation of the penetration of jet in semi logarithm coordinate. The penetration of LPG jet in combustion chamber can be then written as:

$$L = 55 \cdot \exp\left(\frac{-0.95}{t}\right), \tag{2.2}$$

where t (ms) is time and L (mm) is the penetration of jet.

The equation system of jet described in [8] depends on a set of coefficients. The above experimental results allow us to adjust their values corresponding to the case of jet inside the combustion chamber. The adjustement concernes essentially to the expansion radial of jet: $c_{\varepsilon_1} = 1.55$ and $c_k = 7$ instead of 1.41 and 5 respectively for jet in the air. With this new adjustment of coefficients, the axial velocity of fluid on center line of jet given by model and by experience is coherent (fig.5).

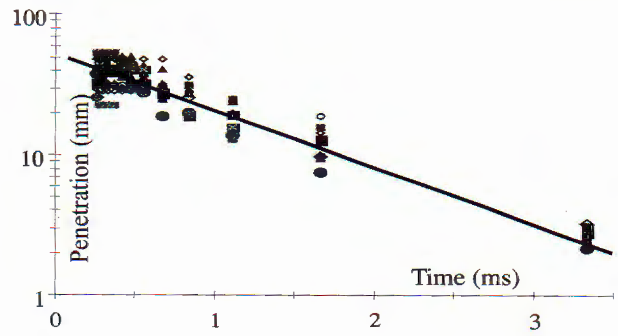


Fig. 4. Penetration of LPG jet in combustion chamber of experimental engine under effects of different conditions

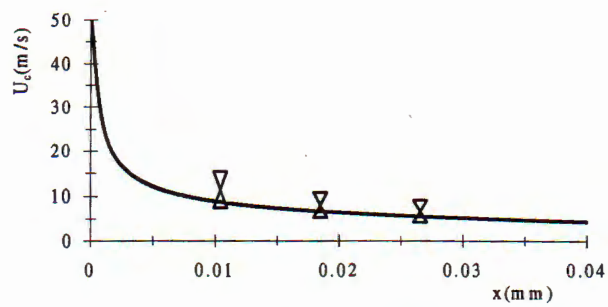


Fig. 5. Comparison of axial velocities on center line of LPG jet in combustion chamber given by model and by PDA method

Figure 6 shows a comparison of LPG jet boundary in the combustion chamber given by analyzing of experimental pictures and by calculation. The injection pressures are 40 bar, 80 bar and 100 bar. It is assumed that the fuel is totally evaporated at the injector exit. The outmost boundary shows the constant velocity line which has value of 1 percent of that on the jet axis at each cross section. Because the photograph takes only the contrast due to difference of fuel concentration in the jet, so the edge of the jet (with a very low fuel concentration) cannot be clearly seen on the film. The calculation results show the average boundary of the jet.

3. Simulation of LPG jet in combustion chamber

3.1. Fuel concentration field of LPG jet

According to the theory of diffusion, the fuel concentration can be calculated via the conserved scalar f (mixture fraction). In the integral model, the value of f, and therefore the fuel concentration, given by the model is their average values on the cross section of the jet. The radial distribution of fuel concentration is determined by affinity of profiles [1]. Figure 7 shows the concentration field in the jet corresponding to different fuels: methane, propane, butane, isooctane and LPG. In calculation, fuel is assumed to be in the gas state at the exiting of the nozzle. The results of the calculation show that the greater the masse density of fuel is, the longer the jet is; that is, the area of higher fuel concentration is farther from the nozzle.

The speed of outside air perpendicular to the initial injection speed tends to lengthen the jet and reduces the jet width. Figure 8a gives the results of calculating the concentration field in the LPG jet at the initial injection speed of 200 m/s in an environment with air speeds of 1, 5 and 15 m/s perpendicular to the jet axis. It is noted that when the speed of the outside air increases, the jet is broken downward and becomes narrower and the constant concentration line tends to be lengthened. This represents clearly the experimental jet configuration during the in-take stroke (figure 8b). When speed

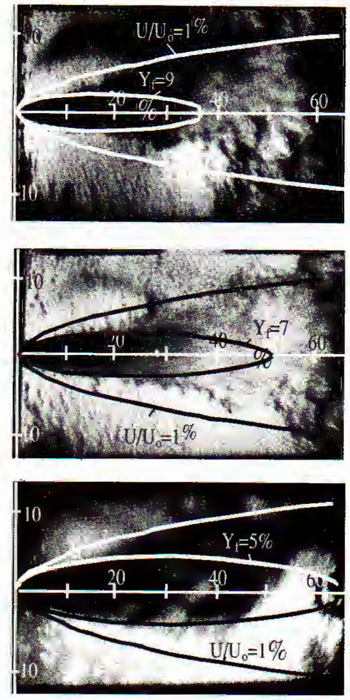


Fig. 6. A comparision of LPG jet boundary given by photo graphing and by the model ($p_{air} = 1$ bar, $U_\infty = 0$)

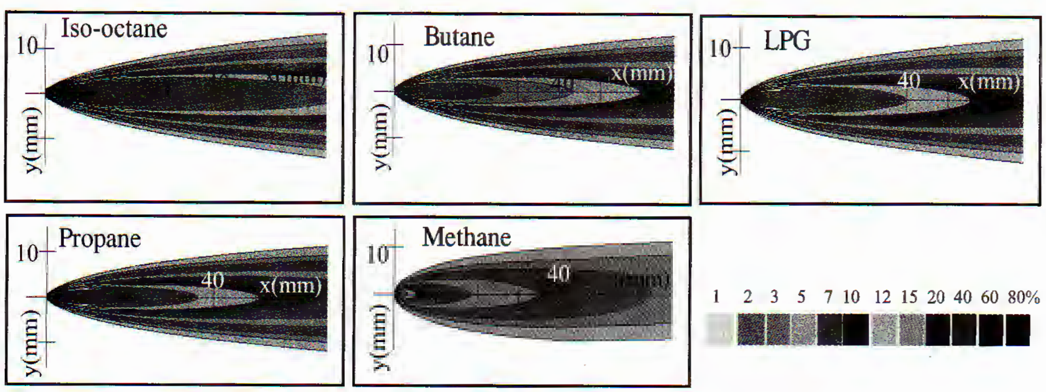


Fig. 7. Influence of fuel on the distribution of concentration in jet ($U_0 = 150$ m/s, $U_\infty = 0$, $p_{air} = 1$ bar)

of piston increases, air speed passing through the intake valve increases, bending downward jet axis.

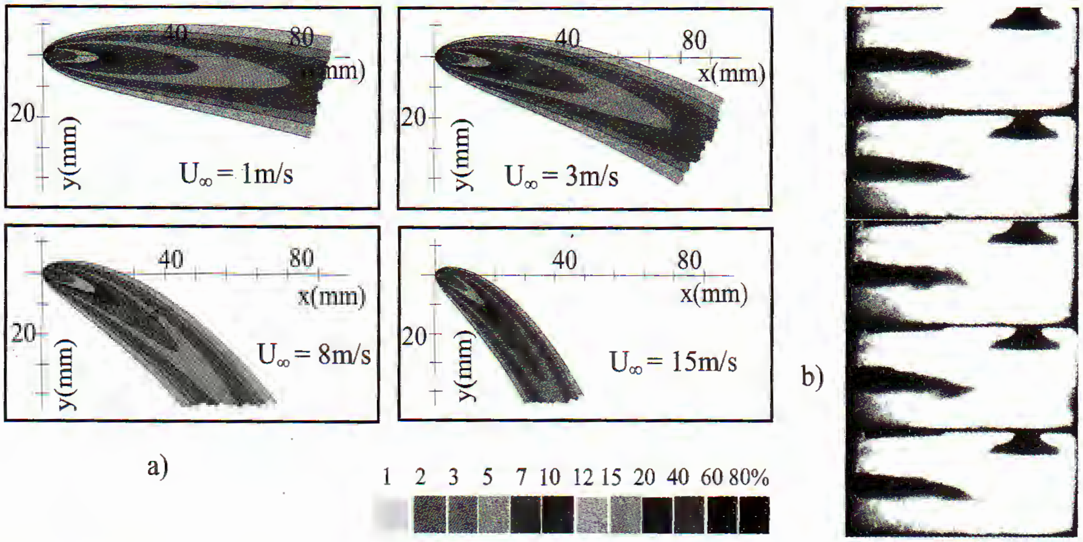


Fig. 8. Effect of moving air speed perpendicular to jet axis on fuel concentration distribution given by model (a) and by experimental data (b)

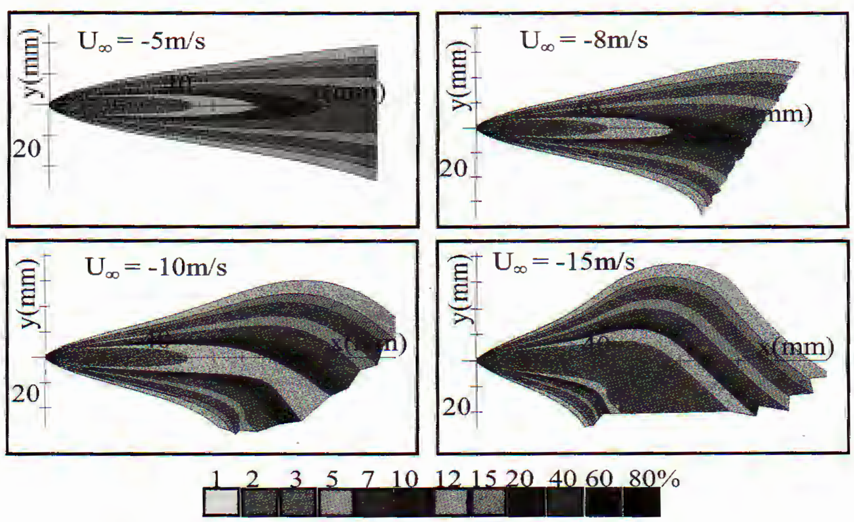


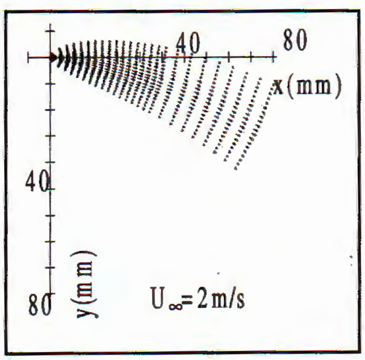
Fig. 9. Effect of opposite air moving on fuel concentration distribution of LPG jet in combustion chamber ($p_{\text{air}} = 1\,\text{bar}$, $U_0 = 150\,\text{m/s}$)

The jet boundary as well as constant concentration lines are strongly deformed under effect of air speed in the opposite direction. Figure 9 shows the concentration field of LPG jet under effect of reverse moving air at the speeds of 5, 8, 10 and 15 m/s. When air speed increases, jet head expands because of an amount of air is compressed into the jet and then the jet is pushed downward (because the density of LPG is greater than that of air).

3.2. Velocity field of jet

The velocity fields provide basic information to calculate the turbulent convection process in the diffusion jet. As shown above, according to the hypothesis "top hat profile" [1], the axial average velocity on each cross section can be determined by the integral model. The radial speed is then calculated by the affinity laws of velocity profile [1].

Figure 10 shows velocity field (U/U_{max}) of LPG jet effected by air velocity perpendicular to jet axis. This is clearly proved by experimental data (figure 10b). During injection in the in-take stroke, the jet is thruster to the piston head. When the velocity of the in-take air flows increases, the jet is bent and then disappears in the air flows.



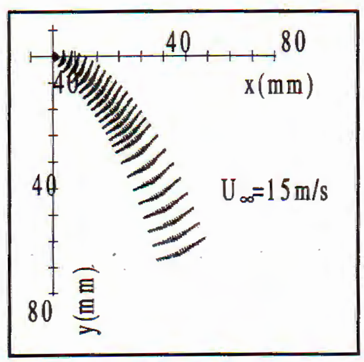


Fig. 10. Effect of moving air perpendicular to the jet axis on the velocity field of LPG jet in combustion chamber ($p_{\rm air} = 1\,$bar, $U_0 = 150\,$m/s)

As analyzed in the concentration field above, the velocity field is strongly deformed by the wind in the opposite direction. Figure 11 shows the velocity field effected by the reverse wind at 8 and 12 m/s.

3.3. Development of LPG jet

The model finally is used to predict the development of jet in combustion chamber of spark ignition engines. The figure 12 represents the development of jet in function of time given by the model. The injection velocity is 150 m/s in air environment of pressure of 1bar. The boundary of jet is determined by mass balance combined with constant concentration lines given by the model. We can find a coherence between the model and experiments given by corresponding photos of LPG jet taken in the combustion chamber of experimental engine (fig. 13) [10].

Nomenclatures

d: nozzle diameter (m)
k: turbulence kinetic energy (m^2/s^2)
m: mass flow (kg/s)
p_{air}: pressure in combustion chamber (bar)
P_j: injection pressure (bar)
U_c: velocity of air flow on the jet axis (m/s)
L: penetration of jet (mm)
U_0: initial injection velocity (m/s)
U_∞: air velocity (m/s)
x: abscissa (m)
y: ordinate (m)
Y_i: concentration of i (kg/kg)
W: momentum (N)
ε: dissipation rate of turbulence kinetic energy (m^2/s^3)
θ: jet angle (°)

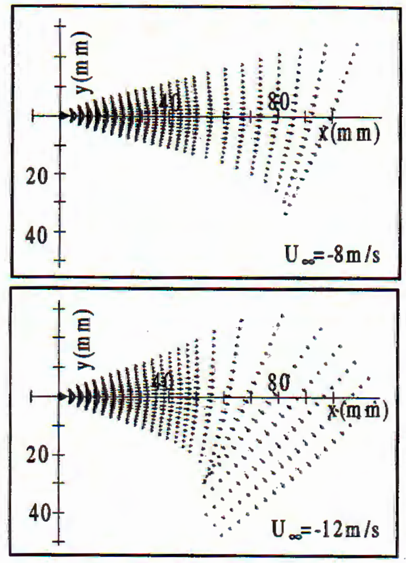


Fig. 11. Effect of opposite moving air on the velocity field of LPG jet in combustion chamber ($p_{air} = 1$ bar, $U_0 = 150$ m/s)

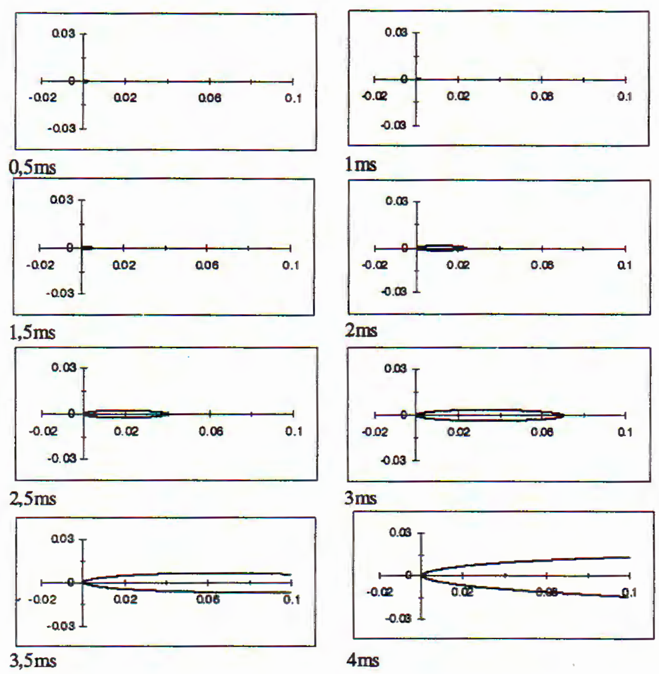


Fig. 12. Simulation of LPG jet development in combustion chamber ($p_{air} = 1$ bar, $U_0 = 150$ m/s)

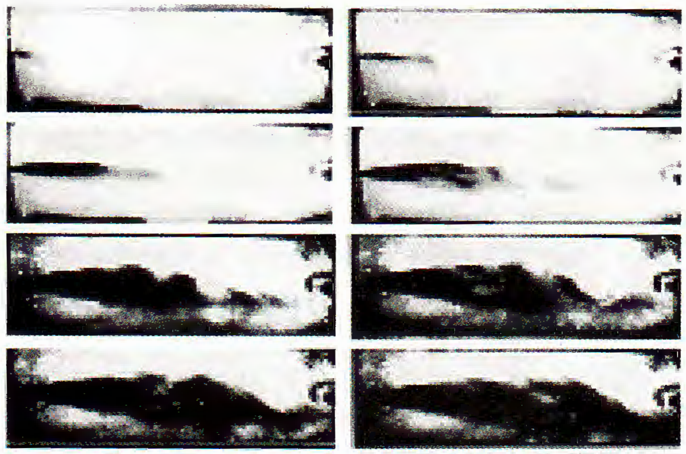


Fig. 13. LPG jet development in combustion chamber of experimental engine ($U_0 = 150\,\mathrm{m/s}$)

4. Conclusions

The model of the turbulent diffusion jet established outside the engine can be developed to predict the development of LPG jet in the combustion chamber.

The influence of fuel on the jet boundary is not considerable, but the concentration distribution of jet strongly depends on density of fuel.

Jet is very sensitive to the movement of air in the combustion chamber. The movement of air flow perpendicular to the jet axis changes the relative position of the jet in the combustion chamber but has a little influence on the length of constant concentration lines.

The movement of the air flow in the reverse direction with initial jet velocity has an important influence on geometric form as well as on constant concentration lines of jet.

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MÔ PHỎNG TIA PHUN KHÍ DẦU MỎ HÓA LỎNG (LPG) TRONG BUỒNG CHÁY ĐỘNG CƠ ĐÁNH LỬA CƯỠNG BỨC

Trên cơ sở mô hình toán học đã được kiểm chứng bằng thực nghiệm bên ngoài và bên trong buồng cháy động cơ, bài báo trình bày kết quả tính toán trường nồng độ và trường tốc độ của tia phun khí dầu mỏ hóa lỏng (LPG) chịu ảnh hưởng của các điều kiện môi trường khác nhau trong buồng cháy. Những kết quả này cho phép dự báo sự phát triển của tia phun để tổ chức tốt quá trình tạo hỗn hợp cũng như quá trình cháy trong động cơ đánh lửa cưỡng bức phun LPG trực tiếp.

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