RELATIVE IMPORTANCE OF FUEL PROPERTIES ON GDI FUEL SPRAY TIP PENETRATION

Simon Bruyère-Bergeron and Patrice Seers
TFT Laboratory, École de technologie supérieure, Montréal, Canada
E-mail: patrice.seers@etsmtl.ca

Received August 2013, Accepted November 2013
No. 13-CSME-140, E.I.C. Accession 3600

ABSTRACT
Experiments were conducted to propose correlations of fuel spray tip penetration of a direct-injection injector fed with ethanol, butanol, isooctane, gasoline, and associated blends at different injection and ambient pressures. Correlations are proposed that enable predicting spray tip penetration as a function of fuel properties. The main findings are that alcohols offer less penetration than isooctane and gasoline, which have similar behaviour at 295 K. Ambient density played a major role in spray tip penetration, while the boiling temperature and enthalpy of vaporization were important fuel properties under warmer conditions.

Keywords: fuel spray; ethanol; butanol; fuel properties; direct-injection; correlations.

IMPORTANCE RELATIVE DES PROPRIÉTÉS DE CARBURANT SUR LA PÉNÉTRATION DU JET EN INJECTION DIRECTE

RÉSUMÉ
Des mesures expérimentales de la pénétration de jet de carburant obtenues à l'aide d'un injecteur à injection directe alimenté en éthanol, butanol, isooctane, essence ainsi que leurs mélanges sont présentées. A partir de ces résultats deux corrélations sont proposées et permettent de prédire la pénétration du jet en fonction des propriétés des carburants et des conditions d'injection. Les principaux résultats démontrent que les alcools offrent une moins grande pénétration que l'isooctane et l'essence. Les principales propriétés des carburants et des conditions d'injection influençant la pénétration sont explicitées dans les deux corrélations proposées.

Mots-clés : jet de carburant; éthanol; butanol; propriétés des carburants; injection directe; corrélations.

1. INTRODUCTION

Gasoline direct-injection (GDI) technology is gaining in popularity with engine manufacturers because of its lower fuel consumption and higher power output compared to port fuelled spark ignition engines. Moreover, ethanol is now common in many countries and is used as a gasoline additive to create low-level ethanol blend such as E10 or a high-level ethanol blend such as E85. The future success of GDI technology depends upon the mixture formation process and as such single and multi-holes injectors have recently been developed. Therefore, studies pertaining to the fuel spray penetration of GDI injectors have started appearing in the literature and are briefly reviewed herein.

For example, Pielecha et al. [1] used a piezoelectric gasoline injector to study the influence of injection pressure (P_{inj}) and ambient pressure (P_{amb}) on gasoline spray penetration and cone angle. They showed that increasing P_{amb} simultaneously reduced the fuel spray penetration and cone diameter. Such observations were also reported by Martin et al. [2] with a 95% isooctane/5% n-heptane fuel. They also looked at the effect of the ambient temperature (T_{amb}) on spray penetration, concluding it was small compared to that of P_{amb}.

The influence of ethanol concentration on fuel spray has been investigated, for example, by Park et al. [3], who studied gasoline, pure ethanol, and E85 spray characteristics. They found that, with a P_{inj} of 8 MPa and a P_{amb} of 0.1 MPa, the spray penetration was slightly higher for pure ethanol, followed by E85 and then gasoline, which offered the least penetration. Park et al. observed that the effect of P_{inj} on fuel spray tip penetration was more pronounced on pure ethanol than the other two fuels. On the other hand, Aleiferis et al. [4] reported that isooctane offered a greater penetration than E85 at a temperature of 393 K and a P_{amb} of 0.05 MPa by nearly 5 mm after 1 ms. Their study was conducted with a 6-hole GDI injector. They observed that with a P_{amb} of 0.1 MPa and a T_{amb} of 293 K, isooctane and gasoline offered the same spray tip penetration. When the T_{amb} was increased to 393 K, however, isooctane had a greater penetration than gasoline by nearly 10 mm after 1 ms. Zigan et al. [5] also reported this change in behavior as a function of T_{amb} but for different fuels. They showed that n-hexane was slightly more sensitive to T_{amb} change (from 298 K to 348 K, in their case) than n-decane, which could be explained by the fact that the boiling temperature of n-hexane was below their highest temperature. Their experiments were conducted with a 6-hole gasoline solenoid injector fed at a pressure of 10 MPa. Finally, Gao et al. [6] measured the fuel spray tip penetration of different gasoline-ethanol blends and found a slight reduction in penetration with increasing ethanol content in the blend when the fuels were injected at a pressure of 5 MPa and a P_{amb} of 0.1 MPa. The increase in P_{amb} to 0.5 MPa further reduced the differences among the different blends.

From this survey, it can be concluded that fuel spray tip penetration is dependent upon fuel pressure, P_{amb}, and fuel properties, since Zigan et al., [5] identified fuel boiling temperature as a property playing a role in a warm environment. It thus appears important to quantify the influence of fuel's physical properties on the spray tip penetration of GDI injector. The main objective of this paper is to propose correlations that enable prediction of fuel spray tip penetration, taking into account the effects of P_{inj}, P_{amb} and temperature, and, more importantly, fuel properties. To achieve this main objective, fuel spray tip penetrations were measured experimentally with different fuels so as to cover conventional fuels such as isooctane and gasoline, since the former is often considered a substitute for the latter in fuel spray and combustion experiments. The experiments also cover biofuels such as ethanol, which is widely used, and butanol, which has spurred interest recently because its low heating value falls between that of ethanol and gasoline. The paper presents the influence of P_{inj}, P_{amb}, T_{amb}, and injection duration. It shows that spray tip penetration can be divided in two phases, and a correlation is proposed for each of them, making it possible to characterize the influence of fuel properties on spray tip penetration. A transition time between both phases is also defined based on the correlations.

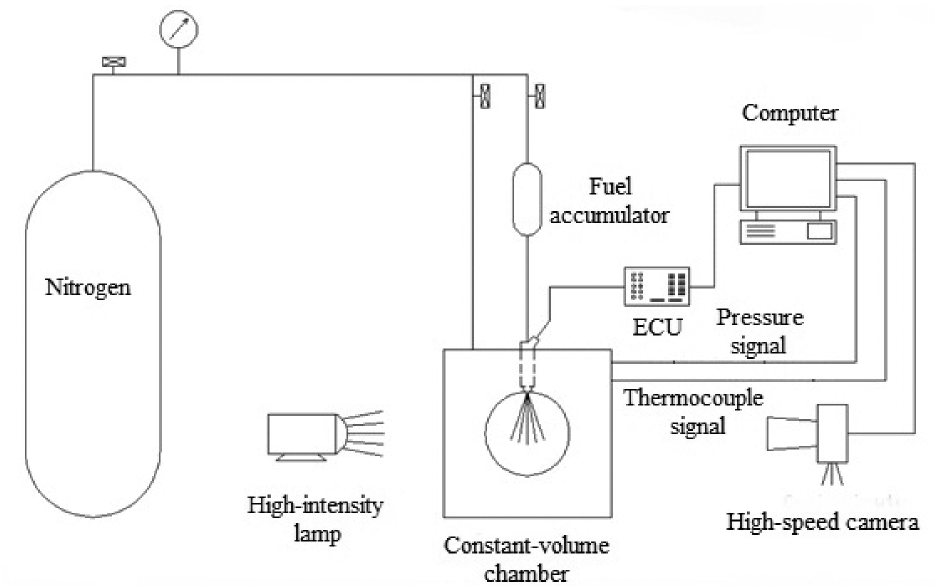

Fig. 1. Experiment setup.

2. EXPERIMENTAL METHOD

The experimental setup consisted of a constant volume chamber; a Siemens single-hole, first-generation GDI injector; a fuel system; and visualization instrument. The constant volume chamber had a diameter of 15 cm and a height of 21 cm, while the fuel spray tip could be viewed through a sapphire window. The chamber was pressurized with bottled air. The single-hole injector (Siemens Deka II), centrally located in the chamber has a 0.5 mm nozzle diameter while the needle was activated by a solenoid. The injector was energized by an electronic control unit that allowed pulse-width duration of 1 to 4 ms. The fuel system comprised an accumulator that was pressurized with nitrogen up to a fuel pressure of 10 MPa. A Photron Fastcam APX high-speed camera at 4,000 frames/sec was used with direct lightning. The experimental set-up is similar to the one used by Delacourt et al. [7] and Roisman et al. [8]. Figure 1 shows the experimental setup; Table 1 presents the fuel properties used herein. The density and boiling temperature of gasoline were taken as being the average density and the temperature at which 50% of the mass evaporates (T50) on a distillation curve, respectively. After data acquisition by the high-speed camera, images were post-treated with NASA's Spotlight-16 Image Analysis Software [9] to measure the liquid fuel spray tip penetration which is defined as the farthest liquid length on the axis below the fuel injector nozzle. From the software, a database was generated and provided the coordinate of the pixel where the fuel spray tip is located for each image. The coordinate were then converted into a distance in mm.

The influence of fuel P_{inj} was studied by varying it from 5 to 10 MPa by increments of 1 MPa for a constant P_{amb} of 0.5 MPa. The tested P_{inj} corresponds to the range of normal operating pressure of the injector. The influence of P_{amb} (0.1, 0.25, 0.5, and 1 MPa) is similar to the range of in-cylinder pressure encountered in unthrottled GDI under homogenous and stratified injection strategies and was studied at a P_{inj} of 8 MPa. Pulse-width durations of 2, 2.5, 3, 3.5, and 4 ms were also tested, while the influence of T_{amb} was studied at 295, 350 and 400 K which are representative of GDI in-cylinder temperature at injection timing. Overall, more than 100 different experiments were run.

The repeatability of the fuel spray tip penetration was assessed by comparing under the same conditions (P_{inj} of 8 MPa, P_{amb} of 0.1 MPa and injection duration of 2 ms), 3 different injection events with gasoline. The results showed a very good repeatability as shown in Table 2 which presents the average spray tip

Table 1. Fuel properties.

	ρ (kg/m^3)	Tboil, fuel (K)	hfg @ Tboil (kJ/kg)	MW (g/mol)
Gasoline [10]	750 (720-780)	T50:403 (300-498)	Average 350	Average 100-105
Isooctane [11]	688	372	271.45	114
Ethanol [11]	781	351	725.69	46
Butanol [11]	779	390	491.75	74

Table 2. Repeatability of spray tip penetration.

Time (ms)	Average spray tip penetration (mm)	Standard deviation (mm)	Coefficient of variation (%)
0.25	11.9	1.0	8.2
0.50	26.5	1.8	7.0
0.75	41.3	2.6	6.2
1.00	54.7	3.0	5.5
1.25	65.6	3.2	4.8
1.50	73.7	3.2	4.4
1.75	79.0	3.3	4.2
2.00	81.9	3.5	4.2
2.25	83.6	3.4	4.0
2.50	85.7	3.3	3.9

penetration as a function of time along with the standard deviation and coefficient of variation. Furthermore, a global uncertainty of 8.6% was calculated for the different experiments following the method proposed by Devries et al. [12].

3. RESULTS

This section presents each parameter that was studied experimentally. As will be shown, the fuel spray tip penetration can be divided into two distinctive phases with different slopes. Based on these results, correlations of the fuel spray tip penetration are presented, putting into evidence the relative weight of fuel properties. A transition time between both phases is then proposed and expressed as a function of fuel properties.

3.1. Fuel effects

Figure 2 presents the fuel spray tip penetration as a function of time for all fuels at two different injection pressures and from which a linear relationship with time can be observed during the first 2 ms, approximately. This linear relationship between fuel spray tip and time is driven by the fuel jet momentum and corresponds approximately to the injector's pulse-width duration. This linear part of the fuel spray tip penetration is followed by a nonlinear penetration of changing slope that flattens with time. This change in the spray behavior between both phases will be defined more precisely in the discussion section that follows.

The second observation is the difference of fuel spray tip penetration as a function of fuel that shows this order, from the deepest to shallowest penetration: gasoline $\geq$ isooctane $>$ butanol $>$ ethanol. These results are in accordance with Gao [6], who reported a reduction of fuel spray tip penetration for ethanol compared to gasoline, and the results of Alefeiris et al. [4], who reported similar fuel spray tip penetration for gasoline and isooctane at 293 K and a P_{amb} of 1 bar. The results differ from Park et al. [3], however, who observed a longer penetration for ethanol than for gasoline in the first spray of a double-injection strategy with a swirl DI injector. The greater fuel spray tip penetration of gasoline with respect to butanol and ethanol is likely due to the heavy molecules in gasoline, which take longer to evaporate [3, 6]. Similarly with the pure

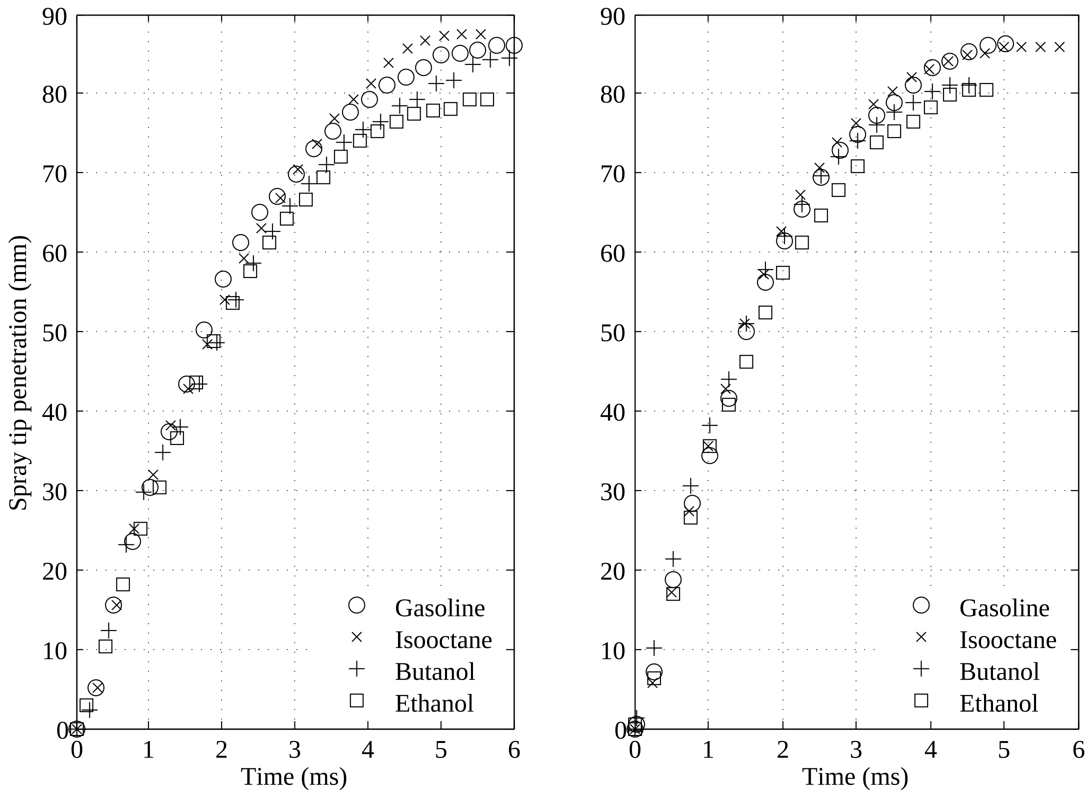

Fig. 2. Fuel spray tip penetration (T_{amb} = 295 K and injection duration of 2 ms) of gasoline, isooctane, butanol, and ethanol at P_{inj} of 5 MPa and P_{amb} of 0.5 MPa (left) and at P_{inj} of 8 MPa and P_{amb} of 0.5 MPa (right).

substances herein, the results show that the higher the molecular weight, the deeper the spray tip penetration. However as it will be shown later (see section ambient temperature) fuel droplet evaporation, through fuel properties, is a determining factor for spray tip penetration.

3.2. Injection Pressure

Figure 3 illustrates the influence of P_{inj} for isooctane (left) and butanol (right) only, as the difference reported in spray tip penetration between all fuels in Fig. 2 still holds true. The first observation is that the increase of P_{inj} provides an increasing slope in the fuel spray tip for the momentum-driven part of the injection process (injector open). This can be explained by the fact that increasing P_{inj} translates into higher initial fuel spray tip velocity, as was shown by Delacourt et al. [7] for diesel spray. This increased velocity, in turn, increases the slope during injector opening time, regardless of fuel.

3.3. Ambient pressure

Figure 4 (left and right) depicts the influence of the P_{amb}, which varied between 0.1 MPa and 1 MPa, on spray tip penetration for isooctane and butanol, respectively. Again, the difference observed in fuel spray tip penetration between all fuels (Fig. 2) still holds true for the influence of P_{amb}. As shown in Fig. 4, the increasing P_{amb} translated into a slight decrease of the slope during the momentum-driven part of the injection process and a decrease of maximum fuel-spray-tip penetration. This spray behavior is in accordance with the results reported by Martin et al. [2]. The influence of P_{amb} was twofold. First, it influenced the difference of initial fuel-spray momentum, as characterized by the difference between P_{inj} and

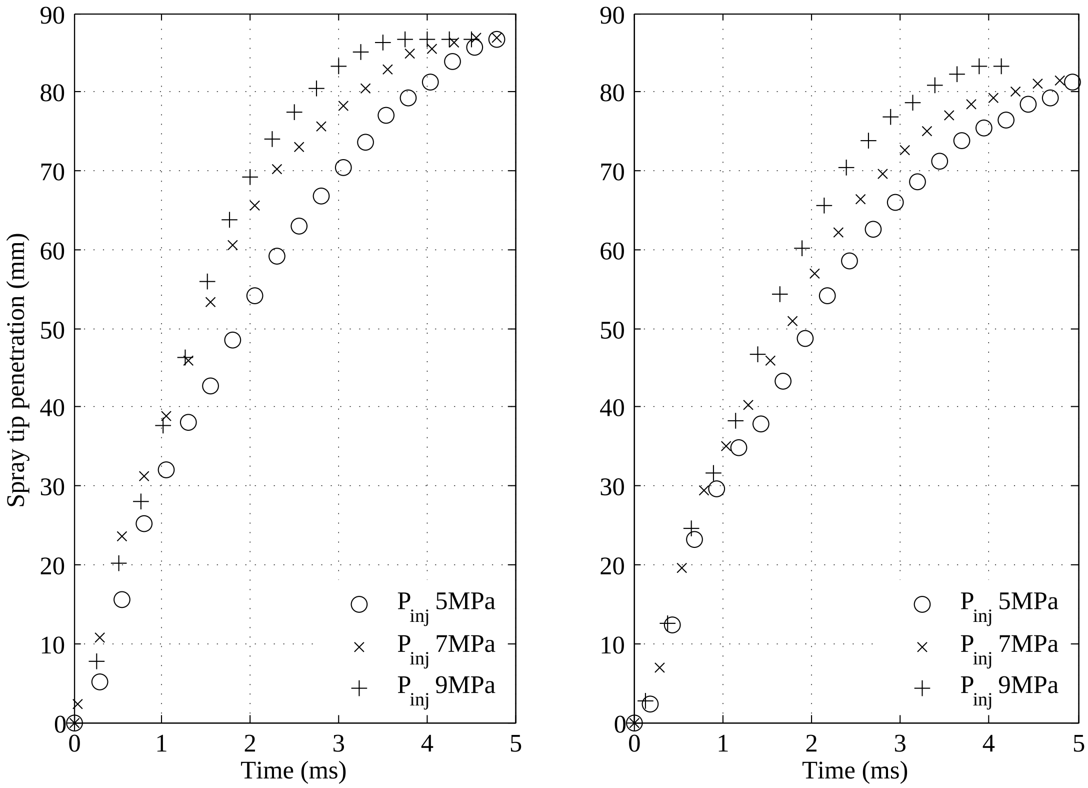

Fig. 3. Fuel spray tip penetration for P_{amb} = 0.5 MPa and T_{amb} = 295 K for an injection duration of 2 ms. Left: isooctane; right: butanol.

P_{amb}. Second, the P_{amb} changed the environment density in which the spray propagated, thereby affecting fuel droplet drag, which decreased fuel spray velocity and spray penetration.

3.4. Ambient Temperature

Figure 5 presents the influence of T_{amb} on the fuel spray tip penetration for temperatures of 295, 350, and 400 K for a P_{inj} of 6 MPa, an P_{amb} of 0.5 MPa, and an injection pulse-width duration of 2 ms. Ambient temperature has a twofold effect. First, spray tip penetration is dependent upon fuel vaporization, which depends on fuel properties such as boiling temperature and enthalpy (h_{f_g}) of vaporization. Figure 5 compares butanol (left) and ethanol (right), which have different fuel properties. Butanol evidenced a greater reduction in fuel spray tip penetration than ethanol when the temperature was increased from 295 K to 400 K. The greater impact of the T_{amb} for butanol can be explained by its lower h_{f_g} than ethanol as the boiling temperature of ethanol is lower than the boiling temperature of butanol as was presented in Table 1. The second influence of increasing the T_{amb} at constant pressure is a decrease in ambient density which influences the linear slope of the spray tip penetration as was observed previously in the section on ambient pressure. This latter phenomenon is more visible in Fig. 5 (right) for ethanol where a greater linear slope is observed with increasing T_{amb} as it is less prone to evaporation compared to butanol. If one compares the reduction of fuel spray tip penetration between 295 K and 400 K and considering that the latter temperature is above the boiling temperature of both fuels considered in Fig. 5, it appears that the h_{f_g} plays a major role in the fuel spray tip penetration. Ethanol demonstrated a lesser reduction of fuel spray tip penetration than butanol when the temperature was increased from 295 to 400 K. This observation is also supported by experimental

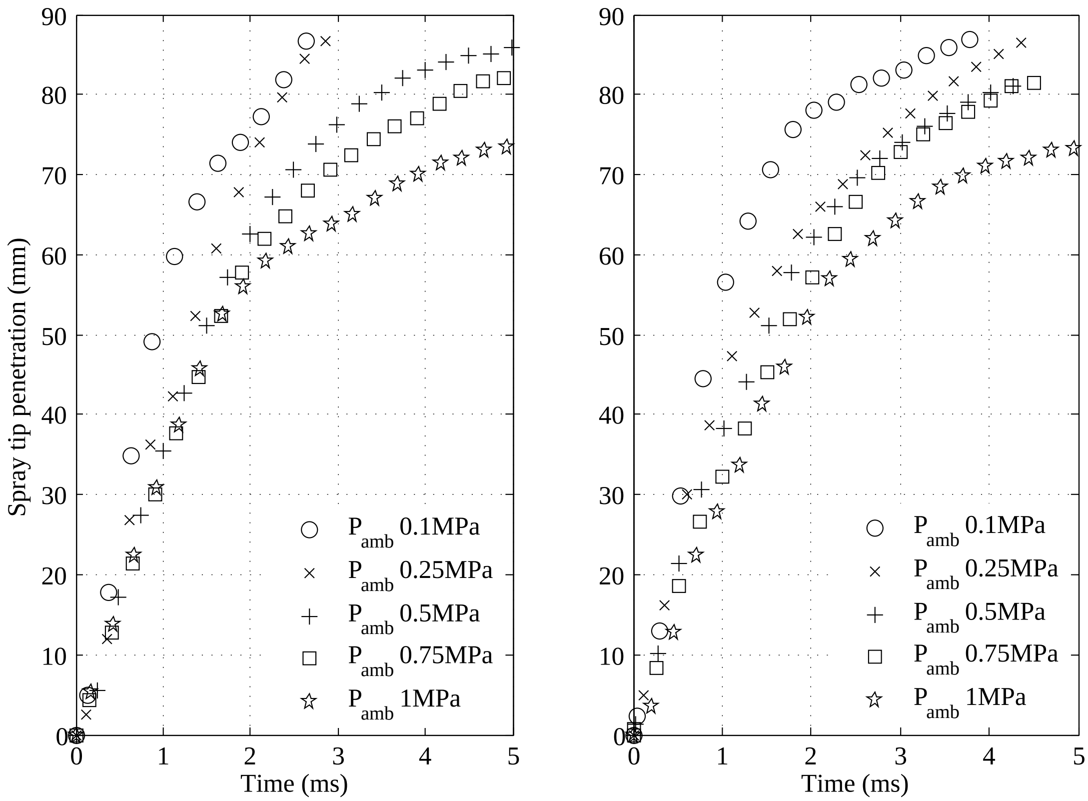

Fig. 4. Influence of P_{amb} on fuel spray tip penetration for a P_{inj} of 8 MPa, T_{amb} = 295 K and injection duration of 2 ms. Left: isooctane; right: butanol.

results of Knorsch et al. [13] who observed for different fuels that droplet evaporation is mainly controlled by h_{f_g} under high P_{amb} and temperature while the boiling temperature is the dominant properties at low P_{amb}.

3.5. Injection Duration

Lastly, Fig. 6 gives the influence of the pulse-width duration on the isooctane spray tip penetration for injection durations of 1.5 ms to 4 ms. Injector activation increased the duration of the linear slope of spray tip penetration, which is dependent on the momentum provided by the pressure difference between P_{inj} and P_{amb}. Figure 6 shows a constant linear slope for all pulse-width durations during the first phase of the spray. For the shorter injection (1.5 ms), the observed initial non-linear behavior in fuel spray tip penetration is probably due to the transient opening and closing of the injector's needle which represent, based on manufacturer data, a total time of more than 0.8 ms which is non-negligible with respect to the injection pulse-width.

4. DISCUSSION

Some general conclusion can be drawn from the results above. First, fuel spray tip penetration can be divided into two different phases. The first phase is characterized by a linear behavior of the fuel spray tip as a function of time that lasts approximately the duration of the injector's pulse-width. During the second phase, the fuel spray tip slows down, which translates into a slope that flattens with time. Second, the fuel spray tip penetration is dependent upon the fuel properties (as shown, for example, in Fig. 2), since different fuels evidenced different fuel spray tip penetrations at equal P_{amb} and P_{inj}. The ambient conditions

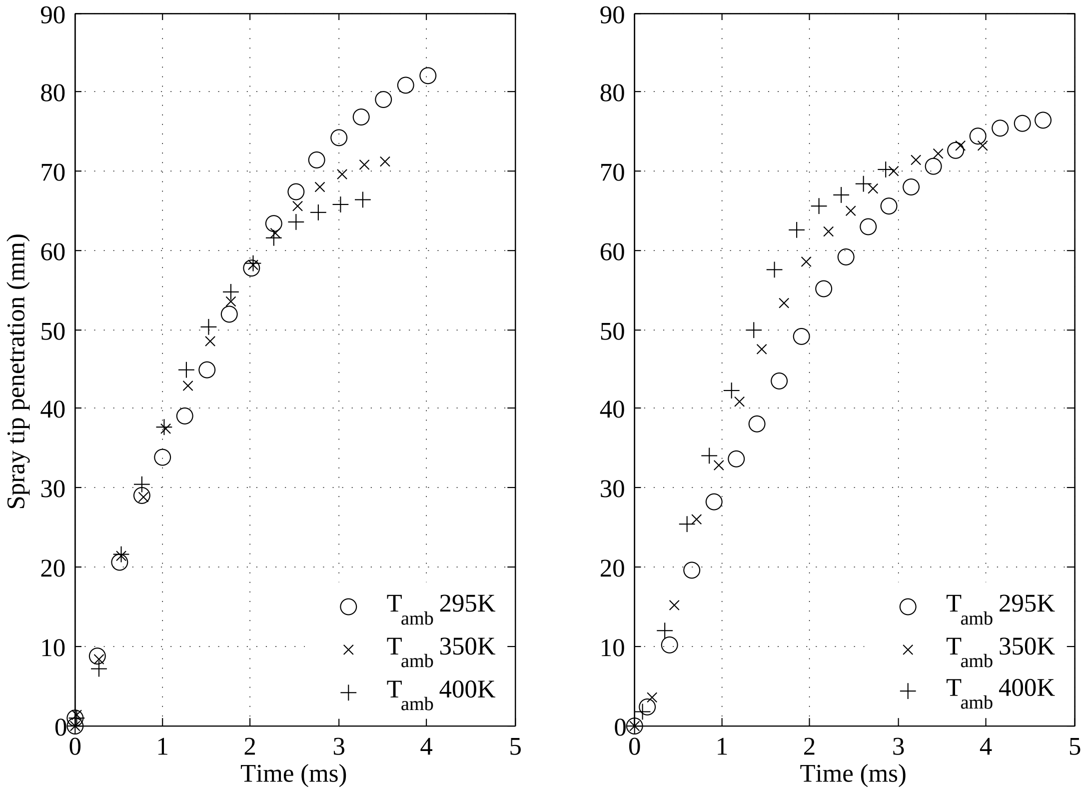

Fig. 5. Influence of T_{amb} on fuel spray tip penetration with a P_{inj} of 6 MPa and P_{amb} of 0.5 MPa for an injection duration of 2 ms. Left: butanol; right: ethanol.

(temperature and pressure) impact the spray by influencing ambient density, droplet's drag and fuel droplet evaporation, such as in Fig. 5, because of the fuel's properties. Based on these observations, two correlations are proposed for each phase of the spray tip penetration that take into account the physical conditions of the injection process (P_{inj}, P_{amb}, and T_{amb}) and the fuel's physical properties.

The general form of the proposed correlations follows that of Kostas et al. [14], Hiroyasu et al. [15], and Borman and Ragland [16] and is presented by

$$S(t) = K_{\text{fuel}} \left(\frac{\Delta P}{\rho_{\text{amb}}} \right)^{x} t^{y} \left(\frac{T_{\text{amb}}}{T_{\text{ref}}} \right)^{z}, \tag{1}$$

where S (mm) is the fuel spray tip penetration; t the time in ms; K_{fuel} a constant associated with the injector geometry and behavior, and fuel properties; ΔP (in MPa) the pressure difference between P_{inj} and P_{amb}; ρ_{amb} (in Kg/m^3) the ambient air density, and T_{ref} the reference temperature (295 K). Lastly, x, y, and z are the relative weight of the parameters to fit the correlation to the experimental data with a least-squares method using Statgraphics [17] and the Levenberg–Marquardt algorithm.

Equation (2) is proposed to allow determining K_{fuel} of Eq. (1) to be expressed as a function of fuel properties. The main fuel properties that were identified based on the experimental results as influencing the fuel spray tip penetration are fuel density (f_{fuel} in Kg/m^3), enthalpy of vaporization (h_{f_g} in KJ/kg), and fuel boiling temperature ($T_{\text{boil,fuel}}$ in K). The fuel properties, namely ρ_{fuel} and h_{f_g}, were evaluated at a temperature of 295 K and at $T_{\text{boil,fuel}}$ respectively and were taken from Yaws [11]. The exponents a, b, and c in Eq. (2) are the relative weights of the fuel's physical properties on the spray tip penetration and were found with the

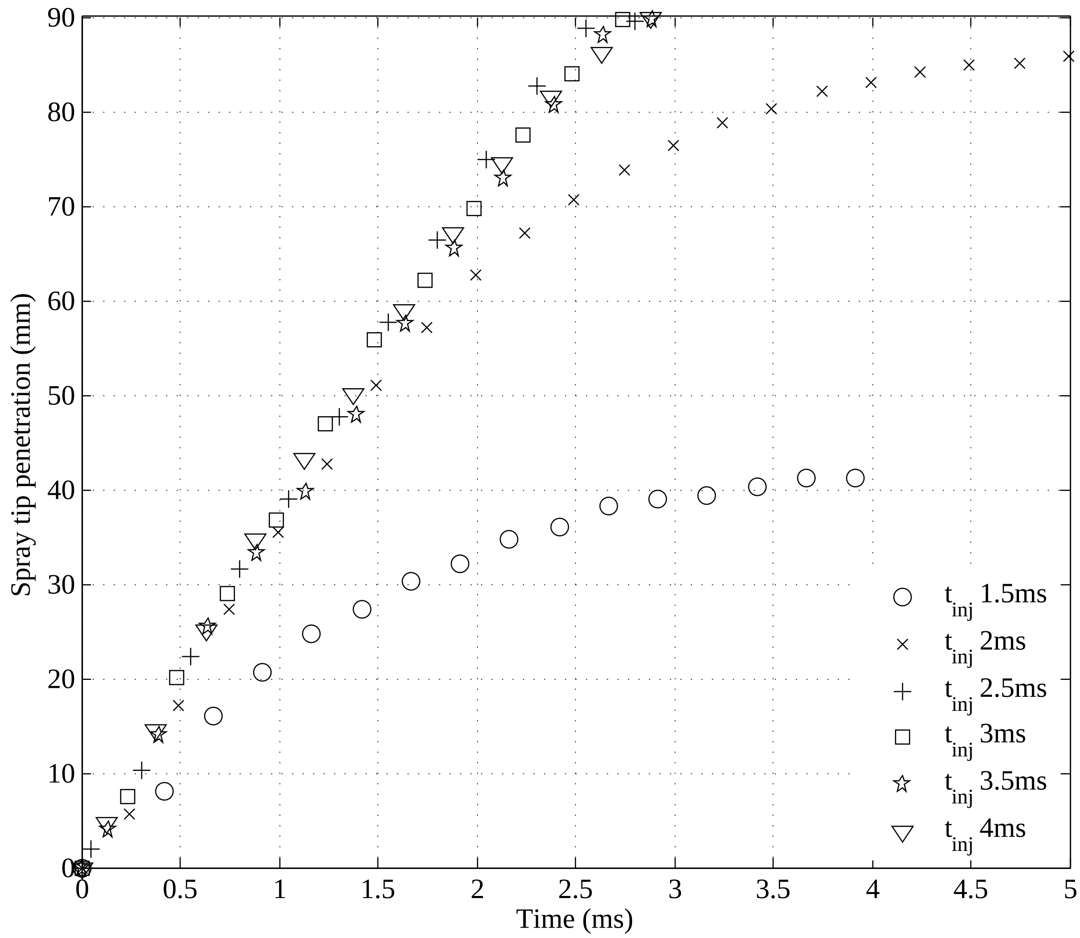

Fig. 6. Influence of the injection duration on isooctane spray penetration for a P_{inj} of 8 MPa, P_{amb} of 0.5 MPa, and T_{amb} of 295 K.

same method as above.

$$K_{\text{fuel}} = K\rho^{a}_{\text{fuel}}\, h^{b}_{f_g\text{fuel}}\, T^{c}_{\text{boil,fuel}}. \tag{2}$$

The experimental data for isooctane, butanol, ethanol, and a 50/50 mixture of ethanol and isooctane by volume were used to identify the variables of the correlations for both phases of the spray-tip penetration. Inserting Eq. (2) into Eq. (1) yields Eq. (3) for the prediction of fuel spray tip penetration in mm and the values of the constants K, a, b, c, x, y and z are presented in Table 3.

$$S(t) = K\rho^{a}_{\text{fuel}}\, h^{b}_{f_g\text{fuel}}\, T^{c}_{\text{boil,fuel}} \left(\frac{\Delta P}{\rho_{\text{amb}}}\right)^{x} t^{y}. \tag{3}$$

The transition from the momentum-driven phase to the nonlinear phase of the spray is obtained by equating the linear phase equation to the non-linear phase equation, yielding Eq. (4), where t_{inj}, in ms, is the duration of the pulse-width for which the transition time (t_t) is evaluated.

$$t_t = 3.64\rho^{1.18}_{\text{fuel}}\, h^{-0.31}_{fg,\text{fuel}}\, T^{-1.22}_{\text{boil,fuel}} \left(\frac{\Delta P}{\rho_{\text{amb}}}\right)^{-0.13} t_{\text{inj}}. \tag{4}$$

Table 3. Values of the exponents of Eq. (3) for both phase of the spray.

Variables	K	a	b	c	x	y	z
Linear phase	7.25 ± 6.08	0.07 ± 0.75	-0.05 ± 0.17	0.23 ± 0.65	0.20 ± 0.006	1	0
Non-linear phase	27.96 ± 17.87	0.87 ± 0.77	-0.26 ± 0.18	-0.60 ± 0.66	0.11 ± 0.004	0.32 ± 0.01	0

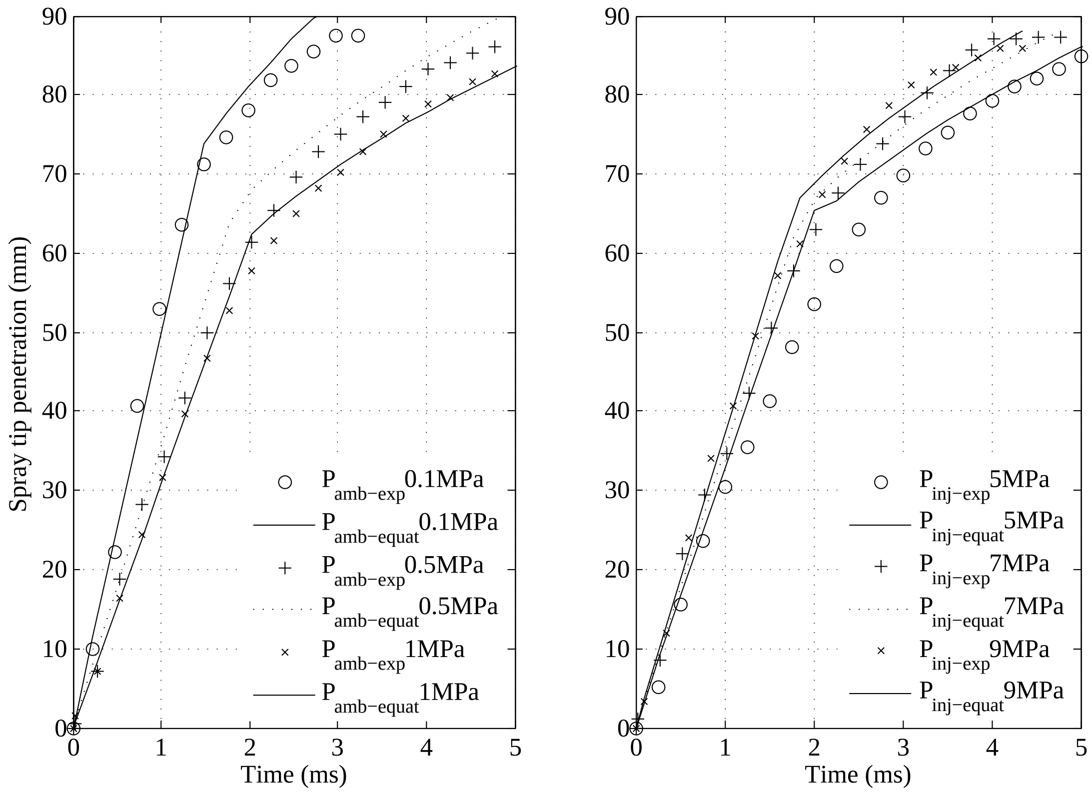

Fig. 7. Comparison between predicted gasoline spray tip penetration and experimental results for an injection duration of 2 ms. Left: P_{inj} of 5 MPa and different P_{amb}; Right: P_{amb} of 0.5 MPa and different P_{inj}.

Figure 7 compares the predicted spray tip penetration for a 2 ms injection according to Eqs. (3) and (4) with the experimental results obtained with gasoline, which was not considered in determining the correlation coefficients. On the left side of Fig. 7, P_{inj} was held constant at 8 MPa and P_{amb} was varied, while, on the right side, P_{inj} was varied at a constant P_{amb} of 0.5 MPa. As can be seen, the correlations successfully reproduce the trend observed experimentally, such as the small difference in fuel spray tip penetration for changes in P_{inj}. In Fig. 7, the maximum error between the experimental results and the predicted values for times greater than 0.5 ms after the beginning of the injection process is 14% in the case at a P_{inj} of 5 MPa and a P_{amb} of 0.5 MPa. Otherwise, the error is only a few percentage points, except at the very beginning (less than 5 mm) of spray tip penetration.

Lastly, Fig. 8 shows a graph of the predicted penetration lengths from Eq. (3) as a function of all the available experimental data and for all fuels tested herein. The correlations are able to predict the fuel spray tip penetration with a R-squared of 98.4% obtained over 1100 data points. The two dash lines of Fig. 8 are the prediction bounds with a 95% confidence.

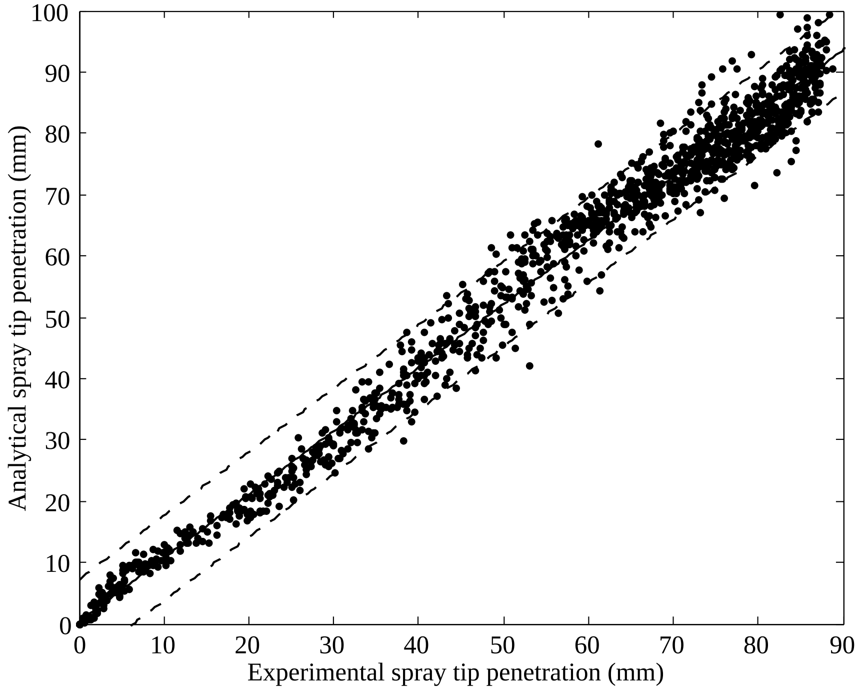

Fig. 8. Predicted fuel spray tip penetration as a function of measured penetration.

5. CONCLUSION

The main objective of this work was to propose correlations to predict fuel spray tip penetrations putting in evidence the relative importance of the fuel's physical properties. Thus, experiments were conducted using a pressurized vessel with isooctane, gasoline, ethanol, butanol and E50 for different P_{inj}, P_{amb}, T_{amb}, and pulse-width durations. Correlations were proposed for the linear (momentum driven) and the nonlinear phases of the spray. Fuel density played a more prominent role during the non-linear phase of the spray. On the other hand, the fuel's enthalpy of vaporization is the property that varies the most between each fuel and this large variation impacts significantly the fuel spray tip penetration. Finally, the driven force of the spray in the correlation is expressed as the difference between the injection pressure and ambient pressure divided by the ambient density.

ACKNOWLEDGEMENT

The authors thank AUTO21 for providing financial support for this work.

REFERENCES

1. Pielecha, I., Wislocki, K., Czajka, J. and Maslennikov, D., "The qualitative spray characteristics of high-pressure gasoline injection system", in *Proceedings of ILASS – Europe 2010, 23rd Annual Conference on Liquid Atomization and Spray Systems*, Brno, Czech Republic, September 2010.
2. Martin, D., Pischke, P. and Kneer, R., "Investigation of the influence of multiple gasoline direct injections on macroscopic spray quantities at different boundary conditions by means of visualization techniques", *International Journal of Engine Research*, Vol. 11, pp. 439–454, 2010.
3. Park, S.H., Kim, H.J., Suh, H.K. and Lee, C.S., "Atomization and spray characteristics of bioethanol and bioethanol blended gasoline fuel injected through a direct injection gasoline injector", *International Journal of Heat and Fluid Flow*, Vol. 30, No. 6, pp. 1183–1192, 2009.

4. Aleiferis, P.G., Serras-Pereira, J., van Romunde, Z., Caine, J. and Wirth, M., “Mechanisms of spray formation and combustion from a multi-hole injector with E85 and gasoline”, *Combustion and Flame*, Vol. 157, No. 4, pp. 735–756, 2010.
5. Zigan, L., Schmitz, I., Wensing, M. and Leipertz, A., “Effect of fuel properties on primary breakup and spray formation studied at a gasoline 3-hole nozzle”, in *Proceedings of ILASS – Europe 2010, 23rd Annual Conference on Liquid Atomization and Spray Systems*, Brno, Czech Republic, September 2010.
6. Gao, J., Jiang, D. and Huang, Z., “Spray properties of alternative fuels: A comparative analysis of ethanol-gasoline blends and gasoline”, *Fuel*, Vol. 86, Nos. 10–11, pp. 1645–1650, 2007.
7. Delacourt, E., Desmeta, B. and Besson, B., “Characterisation of very high pressure diesel sprays using digital imaging techniques”, *Fuel*, Vol. 84, Nos. 7–8, pp. 859–867, 2005.
8. Roisman, I.V., Araneo, L. and Tropea, C., “Effect of ambient pressure on penetration of a diesel spray”, *International Journal of Multiphase Flow*, Vol. 33, No. 8, pp. 904–920, 2007.
9. Klimek, R. and Wright, T., Spotlight-16 Image Analysis Software, 16-bit, version 2004.4.27.
10. U.S. Department of Energy, Alternative Fuels & Advances Vehicles Data Center, Web site: `http://www.afdc.energy.gov/afdc/pdfs/fueltable.pdf` Consulted June 18, 2012.
11. Yaws, C.L., *The Yaws Handbook of Thermodynamic Properties for Hydrocarbon and Chemicals.* Online version `http://www.knovel.com/web/portal/browse/%20display%20?_EXT_%20KNOVEL%20_DISPLAY_bookid=667&VerticalID=0` Consulted April 2011.
12. deVries, J., Lowry, W.B., Serinyel, Z., Curran, H.J. and Peterson, E.L., “Laminar flame speed measurements of dimethyl ether in air at pressures up to 10 atm”, *Fuel*, Vol. 90, pp. 331–338, 2011.
13. Knorsch, T., Heldmann, M., Hagedorn, T., Wensing, M. and Leipertz, A., “Influence of key biofuels on the DISI spray evaporation rate by phase Doppler anemometry”, in *Proceedings of 16th International Symposium on Applied Laser Techniques to Fluid Mechanics*, Lisbon, Portugal, July 9–12, 2012.
14. Kostas, J., Honnery, D. and Soria, J., “Time resolved measurements of the initial stages of fuel spray penetration”, *Fuel*, Vol. 88, No. 11, pp. 2225–2237, 2009.
15. Hiroyasu, H., Kadota, T. and Arai, M., “Supplementary comments: Fuel spray characterization in diesel engines”, in J.N. Mattavi and C.A. Amann (Eds.), *Combustion Modeling in Reciprocating Engines*, pp. 369–408, Plenum Press, 1980.
16. Borman, G.L. and Ragland, K.W., *Combustion Engineering*, WCB McGraw-Hill, New York, 1998.
17. StatPoint Technologies Inc. Statgraphics centurion XVI.I. Warrenton, VA, USA, `http://www.statgraphics.com/`