

On the Main Factors Governing Auto-Ignition Phenomenon of Alcohol Spray – A Study from the View Point of Fuel Properties –

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ABSTRACT

This study deals with the development of compression ignition DI alcohol engine with higher efficiency and lower emissions comparing to the conventional internal combustion engines. In order to establish such high performance alcohol engines, development of controlled ignition technology is required. This paper focuses on the main factors that govern auto-ignition phenomenon of alcohol spray from the view point of fuel properties. The reason of poor auto-ignition quality of alcohol spray was theoretically and experimentally revealed. That is difficulty of simultaneous attainments of ignition-suitable concentration and temperature in a spray mixture formation due to their smaller stoichiometric air/fuel ratio and larger latent heat for evaporation in comparison with conventional diesel fuels.

INTRODUCTION

Present life especially in developed countries depends on energy consumption in the both meaning of its high quality and huge quantity. Most of energy required in the affluent society is based on petroleum combustion in heat engines except for nuclear power plants. As the results of such life style and industrial activities, various kinds of energy and environmental problems such as petroleum exhaustion, air pollution and global warming have been appeared. Under such situations, development of alternative-fuel engines has been demanded.

Alcohol fuels especially methanol and ethanol are understood as one of the promising candidates replacing from petroleum derivatives. Although alcohol is generally recognized as the most feasible alternative fuel for premixed SI (Spark Ignition) engines, several companies

gave an attention for the development of direct injection CI (Compression Ignition) alcohol diesel engines with the support of their government R&D programs in the past. In the USA many researchers and engineers focused on the clean burning characteristics of alcohol fuels in order to prepare the upcoming strict regulations of emission due to air pollution problems in 1980's. DDC (Detroit Diesel Corporation) paid a big attention for the development of CI methanol engine under US DOE's alternative fuels utilization program. In 1990 and 1991, they reported technical papers^{[9]-[14]} intensively on the development of methanol-fueled engines and the results of field tests of methanol buses. From the middle of 1980's to the beginning of 1990's, methanol vehicle feasibility were studied extensively and the new technologies applied to conventional diesel engines for the use of methanol were reported^{[1]-[19]}. Several companies such as GM^[1], Caterpillar^[8], MAN^[7], AVL and Daimler Benz^{[2],[4]} also developed their own original methanol diesel engines as well as DDC. Within this period, most researchers and engineers focused on the use of methanol produced from natural gas, not ethanol produced from biomass judging from availability, costs of raw materials and the costs of production process.

Nowadays, biomass-based alternative fuels such as bio-diesel fuel (FAME: Fatty Acid Methyl Ester) and bio-ethanol have been highlighted due to their recyclable and carbon neutral characteristics as taking measures against global warming. Therefore, at present, use of ethanol is recognized more feasible than that of methanol produced from natural gas. Although methanol also can be technologically produced from biomass, production of bio-ethanol has an advantage in its infrastructure at present compared with methanol production. Researches on ethanol use in a diesel engine have been also conducted and reported^{[21]-[26]}.

Sweden is the leading country for the utilization of ethanol to diesel engines. The Swedish government showed the project of the development of heavy-duty vehicles fueled by ethanol produced from biomass in the middle of 1970's (before the research trend of methanol vehicles above introduced). Under the government project, Scania Truck & Buses has during many years manufactured ethanol driven trucks for Brazil and based on their experiences a diesel fueled bus engine was converted for ethanol use. Finally the feasibility tests including durability of ethanol buses have been conducted in Stockholm in the period from 1980 to 1990's^{[24]-[26]}.

This is the outline of the history of alcohol engine developments. Recently it is generally recognized that the trend of R&D for the utilization of biomass-based fuels in progress is on the use of BDF (Bio-Diesel Fuel) or BDF & diesel fuel blends for diesel engines and bio-ethanol or bio-ethanol (or ETBE: Ethyl Tertiary Butyl Ether) & gasoline blends for gasoline engines. However, methanol and ethanol not only still have potential as the alternative fuels for CI spray combustion engine enough to compete BDF but also have advantages of a number of practical know-how stored in the above introduced history of alcohol engine R&D.

Most challenging technology in the development of alcohol diesel is ignition control due to their poor auto-ignition quality as well known. Approaching way of ignition improvement is categorized by the two points of view. One is on the engine side measures as employing ignition-assist devices such as glow plug^{[3],[6],[8],[13],[15],[17],[22]}, spark plug^{[2],[6],[23],[28]} or heating surface^[20] etc. The other is on the fuel side measures as adding of small amounts of ignition improver^{[2],[4],[6],[21],[26]}. Almost all of studies listed in the references on engine side measures just concerns to seek the optimum configurations within each examined engine and their performance. While for the researches of additives, although the effect of each examined additive on ignition characteristics is introduced, what content improve the ignition is still at question. Therefore a united view for the development of ignition-improvement-technology is not obtained yet; at least alcohol diesel passenger cars have not been commercially developed yet. During such R&D history Siebers and Edwards^[29] pointed out the one fundamental knowledge and they showed an important direction that researchers and engineers should pay an attention in the design process. They concluded that auto-ignition in an alcohol spray is dominated by temperature of surrounding air regardless air pressure, and they also suggested more than 1100K of air at the fuel injection timing in order to obtain acceptable ignition delay. However, even in their research, spray mixture formation process up to auto-ignition is not revealed as physical and chemical phenomena. The authors think that it is necessary for engine designers to have the correct understanding of the complicated phenomena in spray mixture formation process including atomization and evaporation with flow behavior of entrained gas. This knowledge must be required to realize the ignition control as the key technology for the development of high performance DI alcohol engines. In the mixture formation process, two kinds of factors that govern auto-

ignition phenomenon of alcohol spray have to be considered. One can be called internal factor relating fuel properties. The other can be called external factor corresponding to the surrounding gas conditions such as pressure, temperature and oxygen concentration. As the first step, we focused on the internal factor.

This paper introduces the reason of poor auto-ignition quality of alcohol fuels revealed from the view point of fuel properties by the theoretical analysis and experimental results as actual proofs.

THEORETICAL ANALYSIS

CONDITIONS OF AUTO-IGNITION - This study employs two fundamental factors of mixture on auto-ignition in a spray. One is concentration factor; mixture has to be in its mixing ratio enough to advance chemical reactions. The other is temperature factor; temperature of mixture has to exceed a certain value that chemical reactions are promoted up to combustion. Based on this recognition, predictions of mixture formation of alcohol sprays were theoretically performed. According to the theory of momentum for the spray penetration by Wakuri et al.^[32], reaching distance of spray tip "X" depends on time from fuel injection and is expressed as equation (1)

$$X = \left(\frac{2C\Delta P_{inj}}{\rho_a} \right)^{0.25} \cdot \left(\frac{t \cdot d_N}{\tan \theta} \right)^{0.5} \quad (1)$$

Cross sectional mean excess air ratio of a spray at X location and the injection angle (2θ) are represented as equations (2) and (3), respectively

$$\lambda_x = \frac{2 \tan \theta}{L_{th} \cdot C^{0.5}} \cdot \left(\frac{\rho_a}{\rho_f} \right)^{0.5} \cdot \frac{X}{d_N} \quad (2)$$

$$\tan \theta = 0.427 \left(\frac{\rho_a}{\rho_f} \right)^{0.325} \quad (3)$$

If the concentration factor is assumed to be satisfied as $\lambda_{tip}=1$, situation of the spray suitable for auto-ignition can be predicted from the viewpoint of probability, because the location of $\lambda(X,r)=1$ must exists in any cross section along the axis of a spray. Reaching distance of spray tip, volume of spray and the time when $\lambda_{tip}=1$ are shown as equations (4), (5) and (6), respectively.

$$X_{\lambda_{tip}=1} = \frac{d_N}{\left(\frac{2 \tan \theta}{L_{th} \cdot C^{0.5}} \right) \cdot \left(\frac{\rho_a}{\rho_f} \right)^{0.5}} \quad (4)$$

$$V_{\lambda_{tip}=1} = \frac{1}{3} \pi \cdot X_{\lambda_{tip}=1}^3 \cdot \tan^2 \theta \quad (5)$$

$$t_{\lambda_{tip}=1} = \frac{X_{\lambda_{tip}=1}^2}{\left(\frac{2C\Delta P_{inj}}{\rho_a} \right)^{0.25} \cdot \frac{d_N}{\tan \theta}} \quad (6)$$



At the time indicated by equation (6), stable auto-ignition can be obtained if mean temperature of a spray is higher than fuels minimum ignition point ($T_{spm} > T_{ig}$). Required heat that increase the temperature of the spray up to T_{ig} is expressed as follows;

$$Q = G_f [c_{fl}(T_b - T_o) + \gamma_f + c_{fg}(T_{ig} - T_b)] \quad (7)$$

First and third terms of equation (7) correspond to apparent heat in liquid and gas phase, respectively, and the second term means latent heat of evaporation. Compression gas has to supply this heat into the spray by the time as equation (6) in order to obtain stable ignition. Temperature factor, therefore, has to be evaluated by the required-heat per unit volume. This is defined as equation (8).

$$Q_v = \frac{Q}{V_{\lambda_{tip}=1}} = \frac{3 \cdot Q}{\pi \cdot X_{\lambda_{tip}=1}^3 \cdot \tan^2 \theta} \quad (8)$$

PREDICTION OF MIXTURE FORMATION - Table 1 shows thermal and fuel properties of five kinds of normal-alcohols (Methanol, Ethanol, Propanol, Butyl-alcohol and Amyl-alcohol) with those of gas-oil. Comparison of stoichiometric air / fuel ratio (L_{th}) between methanol and gas-oil indicates that L_{th} of methanol is less than half of gas oil's one. Contrary, latent heat of evaporation (γ_f) of methanol is more than six times larger than that of gas-oil.

Evaluations of concentration and temperature factors of mixture on auto-ignition for normal alcohols and gas-oil were conducted based on equations (4), (6) and (8) with the value of fuel properties listed in the table 1. Results of the evaluation are shown in fig.1. For methanol, the concentration factor represented as $\lambda_{tip}=1$ is satisfied much earlier than gas-oil. Normalized required time to $\lambda_{tip}=1$ of methanol (t_M/t_G) is equal to 0.18. This is caused by the difference of L_{th} . While for the temperature factor, on the contrary, required heat per unit volume by the time represented as t_M of methanol (Q_{VM}) is 6.4 times larger than that of gas-oil (Q_{VG}) attributed much larger γ_f of methanol. The ratios of t/t_G and Q_v/Q_{vG} for other normal-alcohols also are obtained from fig. 1 as below:

$$t_E/t_G=0.36, t_P/t_G=0.48, t_B/t_G=0.57 \text{ and } t_A/t_G=0.64 \\ Q_E/Q_v=3.80, Q_P/Q_v=3.50, Q_B/Q_v=2.70 \text{ and } Q_A/Q_v=2.20$$

We can understand from this theoretical approach that it is difficult for normal-alcohols to realize auto-ignition compared with gas-oil, because the large amount of heat-supply into a small sized spray is required in shorter time. This means that it is more difficult for the fuels with larger Q_v/Q_{vG} and smaller t/t_G to occur auto-ignition. Estimations of a spray mixture formation for ethanol and gas-oil were also performed. Results are shown in fig.2 as the histories of mean temperature of a spray (T_{spm}) and mean excess air ratio of a spray tip (λ_{tip}) after fuel injection. Value of λ_{tip} was calculated based on equation (1) and (2). Mean temperature (T_{spm}) was obtained from equation (9) as instantaneous heat balance assumed to be satisfied.

$$G_f [c_{fl}(T_b - T_o) + \gamma_f + c_{fg}(T_{spm} - T_b)] \\ = G_a c_{ac}(T_c - T_{spm}) \quad (9)$$

Table 1 Thermal and fuel properties of normal-alcohols

Fuel notation	CH ₃ OH (M)	C ₂ H ₅ OH (E)	C ₃ H ₇ OH (P)	C ₄ H ₉ OH (B)	C ₅ H ₁₁ OH (A)	gas-oil
Molecular weight	32.0	46.0	60.1	74.1	88.1	—
L_{th}	6.45	9.01	10.3	11.1	11.8	14.6
ρ_f	787	785	800	806	812	825
c_{fl}	2.72	2.72	2.74	2.75	2.36	2.37
c_{fg}	2.14	2.33	2.45	2.55	2.37	1.92
T_b	338	352	370	391	411	443 ~ 663
γ_f	1190	854.8	786.6	619.2	593.1	187.2
T_{ig}	658	636	685	616	573	530
H_u	19.9	26.8	30.7	33.1	34.7	44.4

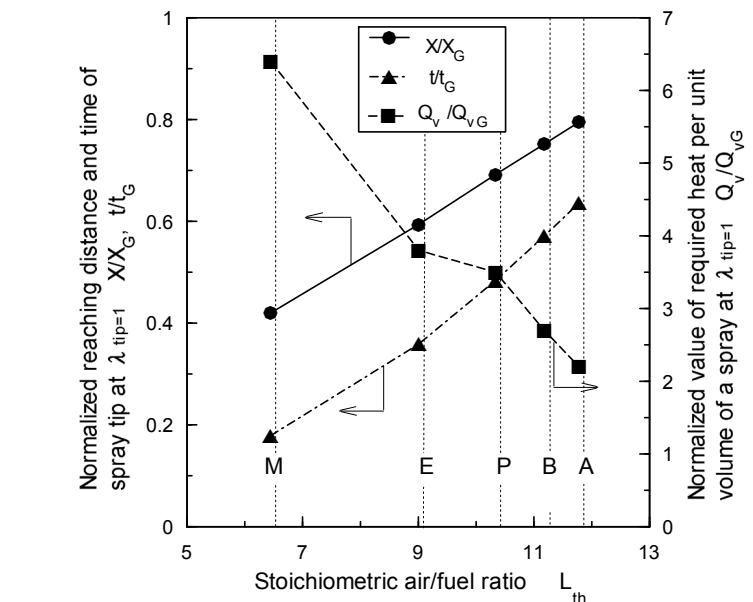


Fig. 1 Evaluations of thermal and concentration factors on auto-ignition for normal-alcohols in a form of normalized values as X/X_G , t/t_G and Q_v/Q_{vG}

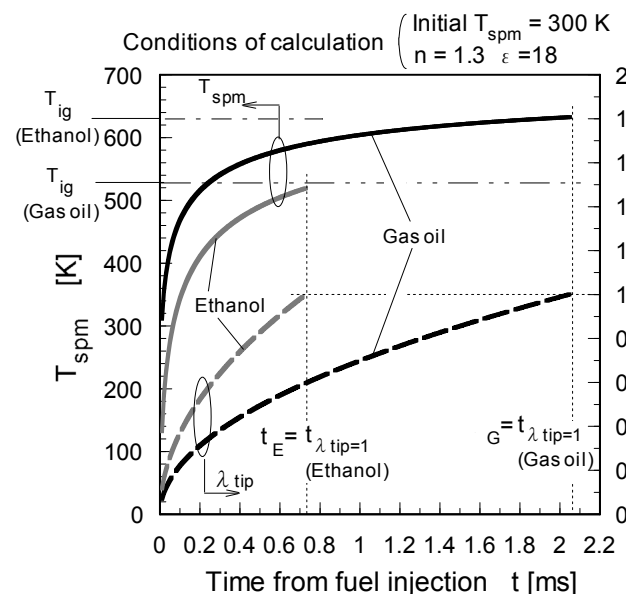


Fig. 2 Estimations of λ_{tip} and T_{spm} histories after fuel injection for ethanol and gas oil