Investigation on thermal properties of a novel fuel blend and its diesel engine performance

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Abstract: It is widely recognized that characteristics of fuel are strongly related with engine performance and exhaust emission. In this paper, a novel fuel blend is developed by adding carbon coated aluminium into diesel. Nanoparticles are blended with diesel in terms of different mass ratios, which are used for optimal selection. Thermo-physical properties of fuel blends are investigated at different testing temperatures. It is indicated that carbon coated aluminium is quite conducive to thermal conductivity but has little influence on viscosity. The highest thermal conductivity by using carbon coated aluminium could reach $0.23 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ which is improved by 15% when compared with neat diesel. Then a series of experimental tests are conducted by using a heavy duty engine. Results show that at 1810 rpm speed, brake specific fuel consumption is in the range from $0.1 \text{ kg} \cdot \text{kWh}^{-1}$ to $0.41 \text{ kg} \cdot \text{kWh}^{-1}$. By using carbon coated aluminium, brake specific fuel consumption could be reduced by up to 13.3%. The maximum emission reduction by using novel fuel blend could reach 16.7%, 48.8% and 33.5% in terms of nitrogen oxides, hydrocarbon compound and carbon monoxide. Based on improved thermos-physical properties, positive effect of carbon coated aluminium on engine performance and emissions has been demonstrated.

Keywords: Diesel, Carbon coated aluminium, Engine performance, Emission

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21 Nomenclature

Al@C	Carbon coated aluminium
A	Pre-experimental factor (Pa·s)
BSFC	Brake specific fuel consumption
B0	Diesel
B0E4	Diesel with 4% ethanol
B0E4N30	Diesel with 4% ethanol and 30ppm Al@C
C_p	Specific heat capacity ($J \cdot g^{-1} \cdot ^\circ C^{-1}$)
CO	Carbon monoxide
d	Thickness of sample (m)
E	Activation energy ($kJ \cdot mol^{-1}$)
EDX	Energy Dispersive X-ray
ESC	European Stationary Cycle
Fe@C	Carbon coated iron
HC	Hydrocarbon compound
NO _x	Nitrogen oxides
Ni@C	Carbon coated nickel
P	Power (kW)
R	Gas constant ($J \cdot mol^{-1} \cdot K^{-1}$)
SCR	Selective catalysts reduction
T	Temperature ($^\circ C$)
TEM	Transmission electron microscope
t_{50}	Half time

22 Greek letters

α	Thermal diffusivity ($mm \cdot s^{-1}$)
β	Mass ratio of diesel with regard to mass of fuel blend
γ	Mass ratio of ethanol with regard to mass of fuel blend
λ	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
ρ	Density ($kg \cdot m^{-3}$)

μ Dynamic viscosity (mPa·s)

23 Subscripts

Al@C Carbon coated aluminium

di Diesel

en Ethanol

ex Exhaust

fb Fuel blend

24 1. Introduction

25 Since the issue of high energy consumption and environmental pollution, an increasing number of attentions
26 has been paid to energy efficiency improvement and pollutant emission reduction in the past decades [1]. In order
27 to decrease pollutant emission of vehicles, strict standards have been proposed and come into force all over the
28 world [2]. To deal with this problem, renewable alternative fuels [3], engine modification [4] and exhaust gas
29 treatment e.g. selective catalysts reduction (SCR) [5] are characterized as main methods. Considering cost and
30 feasibility, alternative fuels still take a leading role since it could reduce pollutant emissions with relatively small
31 impact on engine performance [6].

32 A variety of researches on alternative fuels have been widely investigated. The blended renewable biofuels
33 by using various additives have been regarded as effective approaches to exhaust emissions reduction [7]. One
34 remarkable fact is that alcohol has potentials to be adopted as oxygenated fuel additives for fossil-based fuels,
35 which could control soot emissions [8, 9]. Among alcoholic additives, methanol is the most oxygenated, which
36 may increase the amount of nitrogen oxides (NO_x) under some operation conditions due to the increase of oxygen
37 content in fuel [10]. Ethanol is known as a renewable fuel, which is often used as an additive in clean fuel blends
38 [11]. It is indicated that carbon monoxide (CO) can be reduced significantly at high engine load and hydrocarbon

compound (HC) and NO_x emission are determined by different mass ratios [12, 13]. Butanol could be added to diesel fuel without incorporating other additives due to high cetane number and great molecular weight of n-butanol [14]. Moreover, a two-phase composition does not form in case of blending with diesel fuel at any temperature. Compared with the alcoholic additive, other vegetable oils e.g. sunflower oil [15], coconut oil [16] and bio diesel [17] are attempted to be added to the oil-based fuels for diesel engines. Nevertheless, when blending the oxygenated fuels with diesel fuels, the basic fuel properties e.g. density, flash point, viscosity and cetane number may be varied, which may have an influence on engine performance [18]. Emission reduction and engine power are required to be balanced when alcohol is added to diesel for an optimal selection. Under this scenario, fuel blends are often jointly used with tertiary additives e.g. nitro methane, methyl ester and octyl nitrate [19, 20].

Despite various advantages e.g. preventing formation of a two-phase blend and viscosity enhancement, tertiary additives inevitably result in the increase of brake specific fuel consumption (BSFC) and the decrease of brake power [21]. To overcome these disadvantages, nanoparticles are selected as alternative additives to improve thermo-physical properties, e.g. diffusivity, viscosity and thermal conductivity [22]. The most commonly used nanoparticles are composed of ceramics and metal oxides, e.g. zinc oxide, titanium oxide, cerium oxide and carbon nanotubes as additives [23, 24]. Metal oxides are generally able to improve chemical reaction process while carbon based materials could enhance heat transfer performance [23, 25]. Combining advantages of these additives may be more desirable to further improve engine performance with less pollutant emissions. Thus carbon coated metal with core-shell structure reveals vast potentials in developing novel fuel blends. Carbon coating is able to protect the external condition for the metal core, and the metal core can take a promoting effect while maintaining the excellent thermo-physical properties in the working process [26]. One striking fact is that carbon coated metal has been successfully applied into chemical sorbents for sorption thermal energy storage, which accelerates the chemisorption reaction process [27, 28]. It is expected to have a positive effect on fuel blends due to the fact that

thermal conductivity and lipophilicity could be improved which is superior to that using metal oxide and carbon based material, respectively. Combustion inside engine is then more complete, and emissions of NO_x, HC and CO will be reduced to some extents.

Less research is reported for fuel blends by using carbon coated metal as additive. The objective of this paper is to demonstrate the positive effect of carbon coated aluminium on neat fuel. The improved thermo-physical properties result in an efficient engine performance and cleaner emissions. Thus the overarching framework of this paper could be elaborated as follows: novel fuel blends are first developed by using Al@C with different mass ratios. Thermo-physical properties of fuel blends using Al@C i.e. thermal diffusivity, thermal conductivity and viscosity are then tested and compared with that not using Al@C. Based on thermo-physical properties of fuel blends, performance is analysed in terms of BSFC, exhaust temperature, NO_x, HC and CO emission.

2. Materials

2.1. Carbon coated metal

As a type of nanoparticles, carbon coated metal is characterized with core-shell structure. Metal core is protected by carbon coating as external condition for maintaining its excellent properties inside. The commonly used metal cores are Al, Ni, Fe and Cu which could play different roles. Al@C is selected as an example for illustrating their similar structures. Fig.1 indicates transmission electron microscope (TEM) image of Al@C with different magnitudes, which could refer to our previous work [29]. The encapsulated structure of Al@C is observed. It is worth noting that aluminium cores are completely surrounded by carbon shells with a thickness ranging from 2 nm to 4 nm. Core-shell structure of nanoparticles with metallic core and carbon shell could protect metal core due to the fact that carbon based materials have a high thermal stability even in severe conditions. Also carbon shell could improve suspension stability of the nanoparticle when it is dispersed in fuel since metal tends be hydrophilic.

Fig.1 TEM image of Al@C with different magnitudes (a) 50 nm; (b) 20 nm [29].

2.2. Preparation of novel fuel blends

The detailed developing processes of novel fuel blend by using carbon coated metal is indicated in Fig.2, which are described as follows: carbon coated metal is first mixed with ethanol as surfactant in ultrasonic bath for 2 hours (a₁ process). This process aims to disperse the aggregated particle and have a good distribution in surfactant. Simultaneously, diesel is measured as a set volume (a₂ process). Then the mixture will be combined with diesel in ultrasonic bath for 30 minutes (b process). After that, fuel blends become darker, which indicates homogeneously distribution in diesel (c process). Finally, fuel blends will be poured into small bottles for observing their precipitation (d process).

Fig.2 Developing processes of novel fuel blends by using carbon coated metal.

Other carbon coated metals e.g. carbon coated nickel (Ni@C) and carbon coated iron (Fe@C) tend to precipitate after one night, which are not suitable for developing fuel blends. Difference of fuel blends by using Al@C and other carbon coated metals is probably related with Van der Waals force between nanoparticles and oil molecules. Van der Waals force of Al@C is stronger than its gravity whereas other carbon coated metals have a stronger gravity than their van der Waals force [30]. That is the main reason for selecting Al@C as fuel additive

in this paper. Different mass ratios of Al@C, i.e. 30 ppm, 60 ppm and 90 ppm are selected for further comparison which are shown in Fig.3. It is demonstrated that sample with a ratio of 30 ppm remains stable during two weeks whereas sample with 60 ppm precipitates partially on the bottom of the bottle. Comparably, sample with 90 ppm shows a significant deposit. Phase separation becomes obvious with the increase of mass ratio of Al@C due to the fact there is a weak gel structure of nanoparticles in ethanol. This structure results in a strong van der Waals force for particles in suspension. Thus fuel blend with 30 ppm of Al@C is selected for testing thermos-physical properties and engine performance in the rest of this paper, which is compared with that without using Al@C. The detailed parameters of fuel blends are shown in Table 1.

Fig.3 Comparison of fuel blends with various mass ratios of Al@C (a) just finished; b) two weeks later.

Table 1 Fuel blends developed for testing thermo-physical properties and diesel engine.

Fuel blends	Specific composition
B0	100% Diesel
B0E4	100% Diesel & 4% Ethanol
B0E4N30	100% Diesel & 4% Ethanol & 30 ppm Al@C

3. Thermo-physical properties testing

Thermal conductivity of fuel blend is investigated by laser flash method, and the concerning testing equipment, i.e. LFA467 instrument. Structure and testing procedures of the unit could refer to the reference [31]. The testing temperature is monitored by means of an infrared detector, which is first calibrated by liquid nitrogen. Thermal diffusivity could be determined through the curve of temperature vs. time. Sample holder for liquids is specially used in the experiment which is shown in Fig.4. The liquid is filled into the holder by using syringe and then the hole is blocked by locking pins.

Since the width of optical pulse is infinitely small, heat conduction of testing sample is considered to be one-dimensional heat transfer process. Thermal diffusivity could be evaluated by equation 1:

$$\alpha = 0.1388 \cdot d^2 / t_{50} \quad (1)$$

where α is thermal diffusivity ($\text{mm}^2 \cdot \text{s}^{-1}$), d is thickness of the testing sample (mm), t_{50} is semi-heating time (s).

Thermal conductivity could then be calculated by equation 2:

$$\lambda = \rho(T) \cdot C_p(T) \cdot \alpha(T) \quad (2)$$

where $\lambda(T)$ is thermal conductivity at a testing temperature ($\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$), $\alpha(T)$ is thermal diffusivity ($\text{mm}^2 \cdot \text{s}^{-1}$), C_p is specific heat ($\text{J} \cdot \text{g}^{-1} \cdot \text{K}^{-1}$), $\rho(T)$ is density of the sample ($\text{kg} \cdot \text{m}^{-3}$). The random error of the testing equipment is less than 0.1%, and the largest relative error of thermal conductivity is 5%.

Specific heat and density of novel fuel blends are calculated by equation 3 and 4, which are according to their respective mass ratios of mixture.

$$\rho_{\text{fb}} = \beta \cdot \rho_{\text{p,di}} + \gamma \cdot \rho_{\text{p,en}} + (1 - \beta - \gamma) \cdot \rho_{\text{p,Al@C}} \quad (3)$$

$$C_{\text{p,fb}} = \beta \cdot C_{\text{p,di}} + \gamma \cdot C_{\text{p,en}} + (1 - \beta - \gamma) \cdot C_{\text{p,Al@C}} \quad (4)$$

where β is mass ratio of diesel with respect to total mass of novel fuel blend, γ is mass ratio of ethanol with respect to total mass.

Fig.4 Sample holder for low-viscous liquid (a) schematic; (b) photo.

Before testing thermal properties of fuel blends, thermal diffusivity of pure water is first tested which is compared with the corresponding literature value for calibration as shown in Fig.5. The reference result of water is $0.147 \text{ mm}^2 \cdot \text{s}^{-1}$ at 30°C . The relative error is no more than 3%, which is within acceptable range. It is demonstrated

that laser flash method is suitable to be applied for testing thermal diffusivity of fuel blends. The standard error is also calculated according to equation 5. The error bars are added in the rest of paper. Fig.6 shows thermal diffusivity of fuel blends when testing temperature varies from 25°C to 90°C. It is worth noting that thermal diffusivities of different fuel blends increase with the increase of testing temperature. Thermal diffusivity of B0E4N30 is higher than that of B0 and B0E4. B0E4 has a similar thermal diffusivity with B0, which indicates that 4% ethanol almost has no influence on thermal diffusivity. The highest thermal diffusivity of B0E4N30 could reach 0.161 mm²·s⁻¹ at 25°C, which is 18% higher than that of B0. For different fuel blends, thermal diffusivity is in the range between 0.081 mm²·s⁻¹ and 0.161 mm²·s⁻¹ when temperature ranges from 25°C to 90°C. Based on thermal diffusivity, thermal conductivities of various fuel blends are then calculated which are shown in Fig.7. According to equation 3 and 4, specific heat capacity and density are also combined results of diesel, ethanol and Al@C. Due to the largest mass ratio, diesel still takes a leading role. Density decreases with the increase of temperature whereas specific heat increases with the increase temperature. The decrease of density of diesel is around -0.0017 g·cm⁻³ per Celsius whereas increment of specific heat is around 0.0037 J·g⁻¹·°C⁻¹. Similar with trend of thermal diffusivity, thermal conductivities of fuel blends increase with the increase of testing temperature. Thermal conductivity of B0E4N30 is higher than that of other two, but the difference becomes close with the increase of testing temperature. It is indicated that ethanol also has little influence on thermal conductivity of fuel blends. With the increase of temperature, thermal conductivity of B0 is almost the same with B0E4. This could be attributed to small mass ratio and limited higher thermal conductivity of ethanol e.g. 0.126 W·m⁻¹·K⁻¹ for B0 and 0.16 W·m⁻¹·K⁻¹ for ethanol at environmental temperature. Comparably, Al@C strongly enhances thermal conductivity due to its unique characteristic. The highest thermal conductivity of B0E4N30 could reach 0.23 W·m⁻¹·K⁻¹ at 90°C testing temperature which is improved by 15% when compared with B0. With temperature increasing from 25°C to 90°C, thermal conductivity ranges from 0.124 W·m⁻¹·K⁻¹ to 0.23 W·m⁻¹·K⁻¹ in terms of different fuel blends.

$$\sigma = \sqrt{\frac{\sum_{i=1}^n (x_i - \mu)^2}{N}} \quad (5)$$

where σ is standard error, μ is average testing value, N is sample times.

Fig.5 Thermal diffusivity of pure water vs. different testing temperatures.

Fig.6 Thermal diffusivity of fuel blends vs. different testing temperatures.

Fig.7 Thermal conductivity of fuel blends vs. different testing temperatures.

Viscosities of oleic acid are also tested at different temperatures by a viscometer, which are shown in Fig.8. Results show that viscosities of different fuel blends are quite close. B0 has a relatively high viscosity than the other two when temperature increases from 25°C to 75°C. Viscosity of B0E4 is a bit higher than that of B0E4N30 with temperature ranging from 25°C to 40°C whereas almost no difference could be observed when temperature is higher than 40°C. With regard to viscosities of fuel blends, ethanol has a more positive influence than that of Al@C. Al@C could further improve the viscosity of B0E4 in low temperature range. When testing temperature increases from 25°C to 75°C, dynamic viscosity decreases from 3.67 mPa·s to 1.062 mPa·s in terms of different fuel blends. In order to comprehensively analyse the performance of viscosity, Arrhenius relationship is used to correlate the viscosity with different testing temperatures as shown in equation 6 [32]. It could be transformed and linearly fitted by equation 7. Then activation energy and pre-experimental factor of fuel blends are obtained as indicated in Table 2. Results demonstrate that B0 has the highest activation energy and the lowest pre-experimental factor whereas B0E4N30 reveals the reverse results. It is generally acknowledged that activation energy is within 15-30 kJ·mol⁻¹ and natural logarithm of pre-experimental factor ranges from -17 Pa·s to -10 Pa·s in terms of low and moderate viscous fluids. Thus the fitting results of testing viscosity are in a reasonable range, and average absolute deviation of dynamic viscosity is no more than 5% when compared with ideal value calculated by each pure material according to Eyring equation [33].

$$\mu = A \cdot \exp(E/RT) \quad (6)$$

where E is activation energy, A is pre-experimental factor of fuel blends.

$$\ln\mu = \ln A + E/RT \quad (7)$$

Table 2 Activation energy and pre-experimental factor of fuel blends.

Fuel blends	Ln(A) (Pa·s)	E (kJ·mol ⁻¹)
B0	-14.577	21.35
B0E4	-14.234	21.29
B0E4N30	-14.156	21.05

Fig.8 Viscosity of fuel blends vs different testing temperatures.

4. Diesel engine testing

Fig.9 indicates diesel engine bench for fuel and exhaust testing, and its schematic and photo are presented in Fig.9a and Fig.9b, respectively. The diesel engine bench is mainly composed of a diesel engine, an oil tank, a dynamometer, an intercooler, an air flow meter, a turbo charger and exhaust gas analysers. A heavy-duty diesel engine is adopted for testing which is produced by Cummins, and detailed information is indicated as in Table 3. A common rail fuel injection system has four solenoid injectors for each cylinder with a maximum pressure of 1800 bar. Through intake system and fuel control system, fuel enters the combustion chamber of diesel engine. Exhaust turbocharger and intercooler are also equipped in the intake and exhaust system to control flowrate and temperature during the combustion process. Eddy current dynamometer is able to achieve multipoint of choice and control. Testing apparatus with their accuracies is listed in Table 4. All exhausts are measured and assessed by HORIBA MEXA 1600D gas analyser. The rest of this part is relevant to engine performance and emissions, and more details could refer to our previous work [34].

Fig.9 Diagram of engine test bench (a) schematic; (b) photo [35].

Table 3 Specification of diesel engine ISBe 5.

Specification	Explanation
Cylinder	4
Chamber	ω type
Peak torque	760 N·m
Displacement	4.5 L
Governed speed	2500 rpm
Stroke	124 mm
Bore	107 mm
Compression ratio	17.3
Emission standard	Euro V

Table 4 The main testing apparatus for testing bench.

Apparatus	Type	Testing scope	Accuracy
Dynamometer	Eddy current	0-230kW	$\pm 0.3R$
Temperature sensor	K	0-1200°C	$\pm 0.1^\circ C$
Pressure sensors	PTX	0-10 bar	$\pm 0.1\%$
HORIBA	1600D	0-500 g·kW ⁻¹ ·h ⁻¹	$\pm 0.2\%$

Fig.10 demonstrates engine exhaust temperature of different fuel blends at a fixed speed of 1810 rpm. Under this scenario, operation load of engine corresponds with the power, e.g. 25% load accounts for 32 kW while 100% load accounts for 119.4 kW. Results show that diesel exhaust temperature increases with the increase of the load. The highest exhaust temperature could reach 614°C at 100% load. When load increases from 25% to 100%, exhaust

temperature ranges from 321°C to 614°C by using different fuel blends. One remarkable fact is that addition of Al@C could reduce engine exhaust temperature. The exhaust temperature of engine by using B0E4 is lower than that of B0. This is mainly because ethanol has a lower energy density and a higher enthalpy of vaporization than diesel. Also exhaust temperature by using B0E4N30 is lower than the other two fuels without using Al@C due to the improved thermal diffusivity and reduced viscosity. When compared with exhaust temperature of B0, average reduction is about 4.3%, in which 1.8% and 2.5% come from ethanol and Al@C, respectively. Also worth noting that engine combustion performance is improved when exhaust temperature is reduced. The more complete combustion is achieved, the less engine energy is consumed, which improves combustion reaction of fuel and thermal efficiency.

Fig.10 Exhaust temperature by using three fuel blends vs different operation loads.

Brake specific fuel consumption (BSFC) is a significant parameter for assessing engine performance. It is generally acknowledged that the desirable BSFC of heavy-duty diesel engine is about 200 g·kWh⁻¹ [36]. Fig.11 demonstrates experimental BSFC by using different fuel blends. At engine speed of 1810 rpm, BSFC decreases with the increase of the load, and the results are in the range from 0.1 kg·kWh⁻¹ to 0.41 kg·kWh⁻¹. Similar with exhaust temperature, Al@C has a positive influence on improving fuel economy of the engine. BSFC of B0E4N30 is always lower than that of B0 at different loads. When the load is higher than 25%, BSFC of B0E4 is higher than that of B0, which reveals that adding ethanol to diesel is not conducive to BSFC. This is mainly because ethanol has a relatively low energy density which results in more fuel consumptions at a same load. Comparably, BSFC of B0E4N30 is reduced by up to 16.8% when compared with B0E4. Also the gap between these two fuel blends

becomes large with the increase of load due to the fact that fuel-air mixture in the cylinder is more homogeneous when thermal diffusivity of fuel blend is higher, which results in more complete combustion.

Fig.11 BSFC by using three fuel blends vs different operation loads.

Fig.12 demonstrates specific emissions of engine by using different fuel blends in terms of NO_x , HC and CO, which are shown in Fig.12a, Fig.12b and Fig.12c, respectively. The results are converted into specific value according to equation 8 to 10, and standard error at various loads are also presented.

Considering NO_x emission, it is demonstrated that the specific results decrease with the increase of load due to the reduced fuel consumption. NO_x emission of B0E4 at 25% load becomes a bit higher when compared with B0. When load is higher than 25%, NO_x emission of B0E4 is slightly lower than that of B0 due to the relatively low combustion temperature of ethanol. Also emission characteristic by using B0E4N30 is similar to B0E4 within the low-load range. However, when load is higher than 25%, Al@C is quite conducive to NO_x emission which is reduced by up to 16.8% in comparison with B0 due to the improved heat transfer performance. The highest NO_x emission could reach $14.7 \text{ g} \cdot \text{kWh}^{-1}$ by using B0E4 whereas B0E4N30 reveals the lowest NO_x emission of $3.52 \text{ g} \cdot \text{kWh}^{-1}$ in terms of different loads. The reasons are elaborated as follow: It is widely acknowledged that NO_x emission is mainly determined by combustion temperature. Fuel blend by mixing Al@C has the lowest combustion temperature, which results in the least NO_x emission.

In regard of HC emission, it could be observed that specific HC emission also decreases with the increase of load. HC emissions from B0E4 and B0E4N30 are higher than those from B0 under low load conditions, because the in-cylinder temperature is not quite high at low load and existence of ethanol contributes to lower combustion

temperature, which promotes HC production. However, with the increase of load, HC emission of B0E4 surpasses that of B0E4N30 and becomes almost the same with B0. This is mainly because the in-cylinder temperature is much higher at high load and the effect of ethanol becomes ignorable. Moreover, Al@C is demonstrated to reduce HC emission at most engine operation loads because it can promote the oxidation of HC. The reason that B0E4N30 produces slightly higher HC than B0 at low load is that the effect of ethanol exceeds that of Al@C.

CO emissions from B0E4 and B0E4N30 are significantly lower than those from B0 at 25% load. The effect of ethanol on reducing CO emissions is mainly caused by oxygen in its molecule which can oxidise CO generated during combustion. In contrast, Al@C is more likely to accelerate the reaction rate of combustion and produce less CO. With the increase of the load, CO emissions from B0E4 are almost the same as those of B0 whereas CO emissions by using B0E4N30 are relatively lower than the other two. This could be mainly attributed to the role of Al@C. CO emission of B0E4N30 could be reduced by up to 33.5% when compared with B0 due to the better combustion.

It is recognised that Al@C as an oxidation catalyst leads to a higher heat transfer rate, promoting complete combustion that reduces the emission levels of NO_x, HC and CO. At low loads, the emissions are quite low, which reduce the effect of nanoparticles or even have a negative influence. This could be observed from error bars, which are overlapped partially. At high loads, effect of Al@C becomes obvious and almost no overlapping happens. It is demonstrated that large surface contact area of Al@C increases chemical reactivity, which consecutively shortens the ignition delay. Fuel-air mixing and uniform burning are improved. Also worth noting that fuel atomization is improved due to a higher thermal diffusivity, which brings about complete combustion.

$$sNO_x = 0.001587 \cdot NO_x(\text{ppm}) \cdot m_{ex}/P \quad (8)$$

$$sHC = 0.000478 \cdot HC(\text{ppm}) \cdot m_{ex}/P \quad (9)$$

$$sCO = 0.000966 \cdot CO(\text{ppm}) \cdot m_{ex}/P \quad (10)$$

(a)

(b)

(c)

Fig.12 Specific emissions by using three fuel blends vs different operation loads (a) NO_x; (b) HC; (c) CO.

307

308 In order to have a comprehensive evaluation of different fuel blends, European Stationary Cycle (ESC) is
309 conducted to measure engine performance and pollutant emissions at Euro 5 stage [37]. Different testing modes
310 are divided into four groups from low loads to high loads. Average BSFCs and emissions in ESC testing modes
311 are compared between B0E4 and B0E4N30, which mainly aims to analyze the effect of Al@C. It is worth noting
312 that Al@C is advantageous to BSFC in all operation modes. Under full load condition, BSFC of B0E4N30 is
313 reduced by about 15.7% when compared with that of B0E4. Also worth noting that NO_x reduction caused by
314 Al@C could reach up to 16.6%. As for HC emission, a large reduction could be obtained by individual effect of
315 Al@C. It is generally recognized that HC is mainly caused by uneven mixing of fuel and gas. Thus the higher
316 thermal diffusivity by using Al@C indicates the even distribution of fuel in the combustion chamber, i.e. mixture
317 with too rich or low concentration is avoided, and reaction could be accelerated with more oxygen. The average
318 reduction of HC emission by using Al@C reaches 22.7%. Similar with HC emission, B0E4N30 has a lower CO
319 emission than the B0E4 which could be attributed to the fact that reaction could proceed with more oxygen for
320 complete combustion. When considering the testing errors, the reductions at high loads i.e. above 25% still could
321 reach up to 18% within the confidence interval.

322 The combustion residues are further investigated to explain positive effect of Al@C on engine performance
323 and emission. The more details e.g. testing procedures and methods could be refer to our previous work [38].
324 Fig.13 compares energy dispersive x-ray (EDX) results before and after combustion. It is indicated that combustion
325 residues contain the elements of copper, aluminium, oxygen, carbon and silicon. Compared with values of Al@C
326 before combustion, peak intensity of oxygen increases whereas aluminium and carbon peak decrease. The
327 enlargement of Si could be mainly attributed to the fuel residue. According to atomic ratio of aluminium and
328 carbon, it is demonstrated that aluminium atoms exist in the form of oxide rather than metal after combustion.

Al@C nanoparticles have been transformed into alumina particle during combustion process in engine. And this transition may have a positive impact on both engine performance and emissions. With higher diffusivity and viscosity, atomisation is also improved by using Al@C. When fuel blend is injected into the combustion chamber, nanoparticles are dispersed homogeneously and react with the oxygen predominately to form alumina and CO₂. Some of these reactions surpass that forming nitrogen with oxygen during the combustion process.

Table 5. Comparison of BSFC and engine emissions in ESC testing modes.

Load%	Mode	B0E4N30 vs. B0E4 (%)			
		BSFC	NO _x emission	HC emission	CO emission
25	6, 8, 10	-4	-3.8	-10.2	-20.7
50	2, 4, 12	-6.9	-3.9	-20.1	-20.7
75	3, 5, 11	-12.4	-10.5	-26.2	-20.1
100	1, 7, 9	-15.7	-16.6	-34.4	-24

Fig.13 EDX results before and after combustion.

5. Conclusions

A novel fuel blend is developed by adding Al@C into diesel. Nanoparticles are adopted with diesel in terms of different mass ratios for optimal selection. Thermo-physical properties of fuel blends are investigated at different

testing temperatures. Based on testing properties of fuel blends, performance is analysed in terms of exhaust temperature, BSFC, NO_x, HC and CO emission. Conclusions are yielded as follows:

[1] Thermal diffusivities of different fuel blends increase with the increase of testing temperature. Thermal diffusivity of B0E4N30 is higher than that of B0 and B0E4. The highest thermal diffusivity of B0E4N30 could reach 0.161 mm²·s⁻¹, which is 18% higher than that of B0. Thermal conductivity of B0 is also higher than that of other two, but their difference becomes close with the increase of testing temperature. When temperature increases from 25°C to 90°C, thermal conductivity ranges from 0.124 W·m⁻¹·K⁻¹ to 0.23 W·m⁻¹·K⁻¹.

[2] Viscosities of different fuel blends are quite close. B0 has a relatively high viscosity than the other two. Ethanol has a positive influence on B0 whereas Al@C has no impact on fuel blends. When testing temperature increases from 25°C to 75°C, dynamic viscosity decreases from 3.67 mPa·s to 1.062 mPa·s in terms of different fuel blends. B0 has the highest activation energy and the lowest pre-experimental factor whereas B0E4N30 reveals the reverse results.

[3] At 1810 rpm speed, BSFC decreases with the increase of the load, and the results range from 0.1 kg·kWh⁻¹ to 0.41 kg·kWh⁻¹. BSFC of B0E4 is higher than that of B0E4N30 when the load is higher than 25%. Specific emissions i.e. NO_x, HC and CO decrease with the increase of load. NO_x emission by using B0E4N30 is similar with B0E4 at 25% load. When load is higher than 25%, NO_x emissions by using B0E4N30 is reduced by up to 16.8% in comparison with B0. When the load increases from 25% to 100%, HC emission of B0E4N30 is reduced by up to 48.8% in comparison with B0. CO emission of B0E4N30 could be reduced by up to 33.5% when compared with B0.

The proposed novel fuel blend by using Al@C may be an alternative approach in the near future, which is quite conducive to engine performance and emission. Ethanol has a positive influence on NO_x emission while its effects on BSFC, HC and CO emission are not always obvious. It is desirable to seek for another surfactant, which may further improve overall performance. Or try to develop fuel blends without using surfactant by other methods e.g. long-term ultrasonic.

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