# EFFECT OF BUTANOL-DIESEL-BLENDED FUEL IN COMMON RAIL DIESEL ENGINE

SAKDA THONGCHAI

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENT FOR THE DEGREE OF
MASTER OF ENGINEERING IN AUTOMOTIVE ENGINEERING
(INTERNATIONAL PROGRAM)
INTERNATIONAL COLLEGE
KING MONGKUT'S INSTITUTE OF TECHNOLOGY LADKRABANG
2010

KMITL-2010-IC-M-004-002

**Thesis Title** Effect of Butanol-Diesel-Blended Fuel in Common Rail Diesel Engine
**Student** Mr. Sakda Thongchai
**Student ID.** 50061924
**Degree** Master of Engineering
**Program** Automotive Engineering (International Program)
**Year** 2009
**Thesis Advisor** Asst. Prof. Dr. Chinda Charoenphonphanich
Dr. Nuwong Chollacoop
Prof. Dr. Katsunori Hanamura

# ABSTRACT

With a recent energy crisis, many alternative fuels have been explored, especially for transportation. For fuel consumption distribution in Thailand, diesel fuel consumption is twice as much than gasoline. Natural gas for vehicles (NGV) and biodiesel have been successfully promoted to reduce this uneven diesel-gasoline consumption pattern; whereas, diesohol (10% ethanol blend in diesel) was tested for performance and emissions with acceptable results. However, ethanol-diesel blend still faces challenges in finding suitable emulsifier to prevent water absorption from ambient environment and adapting existing distribution infrastructure to cope with low flash point. Hence, this research aims to explore possibility of using a new mixture of diesohol, diesel/butanol instead of diesel/ethanol, as an attempt to solve the miscibility problem in diesel/ethanol blend and the water absorption in ethanol. The present study evaluated feasibility of using butanol to be blended with diesel called "BDx", "x" is %butanol, due to no need for emulsifier, less water absorption and less difference in physical/chemical properties in the blends. Butanol and diesel were blended at the butanol concentrations of 10, 20, 30 and 40% by volume without any emulsifier additive to observe solubility and stability. Relevant physical and chemical properties were measured and compared to the specification of Thai diesel. Then, butanol-diesel blends of 5, 10, 15, ... , 35 and 40% by volume were tested with unmodified common rail engine (ISUZU, model 4JJ1) in order to assess engine performance, fuel consumption and emissions, with comparison to commercially available diesel in the market. The physical/chemical properties of the blends revealed acceptable values except flash point; whereas, the engine testing results suggested that BD15/20 can be used in common rail engine without any modification to the engine. Nonetheless, if BDx were higher than BD15/20, it would deteriorate engine performance and fuel consumption.

# ACKNOWLEDGEMENT

This thesis could not be completed without assistance from many persons, whom I would like to express my sincere appreciation here with.

First of all, I would like to sincerely thank Dr. Nuwong Chollacoop and Dr. Subongkoj Topaiboul, who has given me many helpful suggestions, useful advices and fruitful discussions during the undertaken research. Also I would like to sincerely thank Asst. Prof. Dr. Chinda Charoenphonphanich, Prof. Dr. Takeyuki Kamimoto and Prof. Dr. Katsunori Hanamura for kind advising, suggestion and helping.

I really appreciate National Science and Technology Development Agency (NSTDA), which provided the full scholarship for studying in the master program and National Metal and Materials Technology Center (MTEC), especially the bioenergy laboratory, for providing the laboratory equipments and instruments as well as financial supporting. Moreover, I would like to thank to laboratory's members for helping me during the experiment.

Finally, I am very grateful to my family for all love, caring, understanding and motivation throughout my life.

**Sakda Thongchai**

# CONTENTS

Page

# CONTENTS (CONT.)

Page

CHAPTER 3 EXPERIMENTAL PROCEDURES

CHAPTER 4 EFFECT ON PHYSICAL AND CHEMICAL PROPERTIES

CHAPTER 5 EFFECT ON ENGINE PERFORMANCE

# CONTENTS (CONT.)

CHAPTER 6 CONCLUSIONS AND SUGGESTIONS

APPENDIX

# CONTENTS (CONT.)

# LIST OF TABLES

# LIST OF FIGURES

# LIST OF FIGURES (CONT.)

# LIST OF FIGURES (CONT.)

# NOMENCLATURE

Acronym

ABE = Acetone, Butanol, and Ethanol

ASTM = American Society for Testing and Materials

AFR = Air/Fuel Ratio

A/C = Air Condition

A/T = Automatic Transmission

BA = n-Butyl Alcohol

BD = Butanol/diesel blend

BDs = Butanol/diesel blends which "s" are various %butanol

BDx = Butanol/diesel blend which "x" is %butanol

BP = Brake power

BSFC = Brake Specific Fuel Consumption

CEC = Coordinating European Council

CI = Compression Ignition

DEDE = Department of Alternative Energy Development and Efficiency

DOEB = Department of Energy Business

ECM = Electric Control Module

EGR = Exhaust Gas Recirculation

FFV = Flexible-Fuel Vehicle

GHG = greenhouse gas

GREET = Greenhouse Gases, Regulated Emissions and Energy Use in Transportation

GV = gasoline Vehicles

HFRR = High Frequency Reciprocating Rig Test

IDI = Indirect Injection

M/T = Manual Transmission

NGV = Natural Gas Vehicles

PTT = Petroleum Authority of Thailand

RBOB = Reformulated Blendstock for Oxygenated Blending

RPM = Revolution per minute

RTD = Resistance Temperature Difference

# NOMENCLATURE

Acronym

SIDS = Sudden Infant Death Syndrome

THC = Total Hydrocarbons

US EPA = US Environmental Protection Agency

VOC = Volatile Organic Compound

WTW = well-to-wheels

WS1.4 = Wear scar diameter normalized to a standard vapor pressure of 1.4 kPa

OEM = Original Equipment Manufacturer

Symbols

C = Carbon

H = Hydrogen

HC = Hydrocarbon

$H_2O$ = Water

$N_2$ = Nitrogen

CO = Carbon monoxide

$CO_2$ = Carbon dioxide

$NO/NO_X$ = Nitric Oxide/Oxides of Nitrogen

$O_2$ = Oxygen

$\lambda$ = Air/fuel ratio (actual) per air/fuel ratio (stoichiometric)

# CHAPTER 1

# INTRODUCTION

## 1.1 Significance and Background

Nowadays, petroleum diesel oil has been used in numerous industries in order to drive economic growth. Especially, transportation sector has consumed petroleum diesel oil, which was approximately 53 million liters per day in the first quarter year 2009 (Ministry of Energy, 2009). Therefore, Thailand has been trying to find alternative fuel source especially for diesel. Both biodiesel and diesohol (diesel/ethanol blend) have been considered and subjected to many years of research and development in Thailand. For diesel/ethanol blend, even though they seem to have conflicting properties like high cetane in diesel and high octane in ethanol, the rationale behind diesel/ethanol blend is the following. Thailand has surplus of domestic ethanol production, and ethanol-blended gasoline has already been adopted in national strategic plan since 2003 (DEDE, 2003). If ethanol can be blended with diesel at small fraction, the amount of crude oil import would decrease due to lower domestic demand of diesel. At the present, only biodiesel is adopted nationwide as 3% mandatory blend to diesel fuel with optional B5 (DOEB, 2008) while diesohol (diesel/ethanol blend) still faces some technical issues such as a need for emulsifier additive, a water-absorption nature of ethanol and a rather low flash point (Chollacoop *et al.*, 2005). The flash point issue cannot be solved for diesel/alcohol blend due to the chemical property of alcohol but the need for additive and the water-absorption nature of ethanol can be avoided by the use of butanol. However, the major drawback in diesohol with ethanol is that ethanol changes the fuel characteristics of the blend, especially by causing instability and reducing the cetane number (Leelanoi, 2007). The use of butanol in diesohol could solve the problem of fuel instability at low temperatures because of its higher solubility in diesel fuel. Moreover, butanol has both lower vapor pressure and lower water solubility, i.e., there is no need for emulsifier additive, unlike diesohol with ethanol or methanol (Chotwichien, 2007). In addition, the fuel properties of diesohol with butanol indicate closer properties to diesel than those with ethanol. As a result, this research has demonstrated a concept of blending butanol (instead of methanol or ethanol) in diesel and testing with common rail diesel engine.

## 1.2 Objectives

1.2.1 To study the physical and chemical properties of butanol/diesel blends in comparison with conventional diesel fuel.

1.2.2 To investigate the performance of common rail diesel engine when using butanol/diesel blend fuel and its influence on emission.

1.2.3 To study the limitation of using various butanol/diesel blends in unmodified common rail diesel engine.

## 1.3 Scopes

This experiment prepared various samples by blending the fuel between commercial grade butanol and conventional diesel fuel without emulsifier and additive. Conditions of physical and chemical tests, and engine tests were included in order to observe and determine the highest concentration of butanol that can be used in this engine type.

1.3.1 The first part focused on important physical and chemical properties that can affect the engine performance. Butanol/diesel blend ranged from 10% to 40% (v/v) were analyzed according to ASTM and CEC standards. All of the results were compared with the original diesel fuel.

1.3.2 The second part focused on performance and emission of common rail diesel engine by using various concentrations of butanol/diesel blends ranged from 5% to 40% by volume. The common rail diesel engine was tested under full load and partial load condition. The tested results were analyzed and compared with most of commercial diesel fuel.

## 1.4 Expected Benefits

1.4.1 Knowledge of the physical and chemical characteristics of butanol/diesel blends.

1.4.2 Knowledge of the behaviors of common rail diesel engine when using various butanol/diesel blends fuels.

1.4.3 Capability building with basic scientific equipment and characterization instruments for chemistry science and engineering study.

1.4.4 Knowledge, which can be applied to the practice as an alternative way to reduce consumption of petroleum import.

# CHAPTER 2

# THEORY AND LITERATURE REVIEWS

## 2.1 Principle of Common Rail Diesel Engine

A common rail diesel engine is principally comprised of three systems in order to control the engine activity. There are fuel system, injector unit and electric control module (ECM). Understanding these systems, it can facilitate the understanding of engine operation.

In this system, pressure generation and injection functions are decoupled from each other. Fuel for individual cylinder is drawn from a common accumulator, which is constantly held at high pressure. Accumulator is generated by a high-pressure radial plunger pump and may be altered independently of operations (Braess and Seiffent, 2005). The injection pressure is generated independent of engine speed and injection fuel quantity. The fuel is stored under pressure in the high-pressure accumulator (in the rail) ready for injection. Each cylinder is fitted with a solenoid-actuated injector. The injected fuel quantity is defined by the driver, the injector discharge cross section, solenoid open duration, accumulator pressure and the start of injection. The injection pressures are calculated by the ECM on the stored maps. The ECM then triggers the solenoid valves so that injector (injector unit) at each engine cylinder injects accordingly (Bosch, 1999).

### 2.1.1 Fuel and Injection System

The fuel system in a "common rail" fuel injection system engine consists of low-high pressure stage to delivery fuel that the most important component are fuel tank, pre-supply pump with filter, low-pressure fuel lines for supply and return, fuel filter and low-pressure area of high-pressure pump. In high pressure stage provides high-pressure fuel for injector unit. The high-pressure generation, fuel distribution and fuel-metering take place in this stage and the most important component is high pressure pump with element shutoff valve and pressure control valve, high pressure accumulator, rail-pressure sensor, flow meter and injector.

In addition, the high pressure pump is an interface between the low-pressure and the high-pressure stages. Under all operating conditions, it is responsible for providing adequate high-pressure fuel. This also includes the provision of extra fuel as needed for rapid starting and for rapid build-up of pressure in the rail. The high-pressure pump continually generates the system pressure as needed in the high-pressure accumulator. Therefore, this means that in contrast to conventional systems, the fuel does not have to be specially compressed for each individual injection process. For the high pressure accumulator, the rail stores the fuel at high pressure. At the same time, the pressure oscillations, which are generated due to the high-pressure pump delivery, and the injection of fuel are damped by the rail volume. This high pressure accumulator is common to all cylinders, hence its name "common rail". Even when large quantities of fuel are extracted, the common rail maintains its pressure practically constant. This ensure that the injection pressure remain constant from the moment the injector opens.

The functions of injector units are to inject and atomize the fuel into the combustion chamber at the correct instant in the engine's operation cycle. The start of injection and the injected fuel quantity are adjusted by electrically triggered injectors form ECM. They are mounted on the cylinder head and are triggered off by a predetermined pressure rise in the high-pressure pipelines (Heisler, 1999).

### 2.1.2 Engine Control Module (ECM)

The electronic control module is the brains of common rail injection system. It contains a memory element, engine control microprocessor and a solenoid drive element. The engine control microprocessor receives and processes information signaled from the various sensors, which monitor the engine such as crankshaft position, engine speed and load, boost pressure and temperature, coolant temperature, accelerator pedal position, common rail pressure, etc. This data is then compared to the pre-stored memory. It is then computed and the resulting outcome is used to predict the necessary injection timing and the quantity of fuel delivery to the cylinder during each power stoke for the prevailing operating condition at any one time. This information is then converted into electrical signals, which are then sent to solenoid drive circuit accordingly. The electrical pulses are relayed to each injector control solenoid in turn to activate the respective injectors. The ECM comprises basically five functions to control the engine (Jurgen, 1999):

First is fuel quantity and Timing. The ECM determines the correct length of delivery time using performance maps based on engine speed and calculates fuel quantity and signal of engine speed, temperature, and turbo charger boost pressure are used to modify the delivery time.

Second is speed control. The engine speed information is provided by an RPM sensor that monitors the periods of angular segments between the reference marks on the engine's flywheel or in the in-line injection pump for ECM calculation. On an electronically controlled engine speed, governors are also used for low idle control to maintain a constant engine or vehicle speed and verify the correct fuel for cold-start. Therefore, the governor's functions are controlled by the fuel delivery system and fuel is controlled as a function of speed and boost pressure to limit smoke levels, engine torque, and exhaust gas temperatures.

Third is exhaust gas recirculation (EGR) control to reduce the amount of oxygen in the fresh intake charge while increasing its specific heat. This lowers combustion temperature and results in lower $NO_x$ emission. However, excessive amount of EGR result in higher emission of soot (particulate), CO, and HCs all due to insufficient air. Also, the introduction of EGR can have an adverse effect on drivability during cold-engine operation, full-load operation, and at idle. Therefore, it is best to control the EGR valve with ECM, which determines when and how much EGR will occur, based on engine temperature and accelerator position.

Fourth is turbocharger boost pressure control. ECM uses information on engine speed and accelerator position to reference a data table, and the proper boost pressure (actually, duty cycle of the control valve) is determined. On systems using intake manifold pressure sensor, a closed loop control system can be developed to compare the specified value with the measured value.

Fifth is glow plug control, electronic control of the glow plug duration can be handled by the ECM or a separate control unit in order to warm the combustion chamber. Input for determining glow time is from an engine coolant temperature sensor.

## 2.2 Physical and Chemical Property of Fuel

### 2.2.1 Butanol Characteristic

Butanol or n-Butyl alcohol (BA) is a liquid at standard temperature (SIDS Initial Assessment Report, 2001) and pressure, with a boiling point of approximately 117.6°C and a melting point of approximately –89.9°C (Union Carbide Corporation, 1992a). It is less dense than water with a specific gravity of 0.8098 g/cm$^3$ at 20°C (Weast and Astle, 1985). The solubility limit in water is approximately 77 g/L at 20°C (Merck, 1983). This value indicates BA is little soluble in water when compare with ethanol. The vapor density of BA is approximately 2.6-times that of air, with a vapor pressure of 0.56 kPa at 20°C (Union Carbide Corporation, 1992a). Given its solubility limits and its molecular weight of 74.14 g/mole, a Henry's law constant (at 25°C) can be calculated to be approximately 0.63 Pascal·m$^3$/mole ($6.3 \times 10^{-6}$ atm-m$^3$ /mole). In general, chemicals with a Henry's law constant greater than $1.0 \times 10^{-5}$ atm-m$^3$/mole, and a molecular weight less than 200 g/mole are considered volatile chemicals (US Environmental Protection Agency (USEPA), 1991). By this measure, BA is not considered to be a volatile chemical. BA does, however, meet the definition of a volatile organic compound (VOC), and does have appreciable volatility. Therefore, it can summarize properties in Table 2.1 and identification of the substance as below;

Chemical Name: n-Butyl Alcohol

Molecular or Structural Formula: CH3-CH2-CH2-CH2OH

Molecular Weight: 74.12 g/mol

Synonyms: 1-butanol, butan-1-ol, n-butyl alcohol, butyl alcohol, butyl hydroxide, butyric alcohol, 1-hydroxy butane, hydroxybutane, methylolpropane NBA, normal primary butyl alcohol, BA, propylcarbinol, propyl methanol

**Table 2.1** Physic/chemical butanol properties (SIDS Initial Assessment Report, 2001)

| Property | Value |
|---|---|
| Physical form of marketed product | Neat Liquid |
| Melting point | -89.9°C |
| Boiling point | 117.6°C |
| Relative density | 0.809-0.811 g/cm$^3$ |
| Vapor pressure | 0.56 kPa at 20°C |
| Water solubility | 77 g/l at 20°C |
| Partition coefficient n-octanol/water (log value) | 0.88 |
| Odor threshold | 15 ppm (average) |
| Conversion factor | 1 ppm=3.03 mg/m$^3$ at 25°C |
| Flash point | 98°F (37°C) |

### 2.2.2 Diesel Fuel Characteristic

Petroleum diesel is refined from crude oil with a boiling range between 172 - 370°C. Diesel fuel must be able to burn by itself in the combustion chamber, cleanly and quickly. Its general properties are showed in Table 2.2. Diesel fuel sold in Thailand is divided into two types: (1) High speed diesel is suitable for diesel engines with speed above 1,500 rpm, such as truck, bus and pickup. (2) Low speed diesel is suitable for the slow speed engine such as marine and generator.

**Table 2.2** General diesel fuel properties

| Test Item | Specification |
|---|---|
| 1. API Gravity @ 60°F | - |
| 2. Specific Gravity @15.6/15.6°C | 0.81-0.87 |
| 3. Calculated Cetane Index | Min 47 |
| Or Cetane Number | Min 47 |
| 4. Kinematic Viscosity @40°C, cSt. | 1.8-4.1 |
| 5. Pour Point, °C | Max 10 |

| | |
|---|---|
| 6. Sulphur Content, %wt. | Max 0.05 |
| 7. Copper Strip Corrosion ( 8 hrs, @ 50°C) | Max No.1 |
| 8. Micro Carbon Residue, %wt. | Max 0.05 |
| 9. Water and Sediment, %vol. | Max 0.05 |
| 10. Ash, %wt. | Max 0.01 |
| 11. Flash Point, (P.M.), °C | - |
| 12. Distillation: (Correct Temp.) | - |
| Initial Boiling Point, °C | - |
| 10 % Vol.Recovered, °C | - |
| 50 % Vol. Recovered, °C | Min 52 |
| 90 % Vol.Recovered, °C | Max 357 |
| 13. Color (Number) | Max 4.0 |
| 14. Lubricity by HFRR, µm | Max 460 |

## 2.3 Engine Performance

The parameters used for indicating the engine performance in this study is explained as follow:

### 2.3.1 Engine Power and Fuel Consumption

Torque (*T*) is a good indicator of engine's ability. It is defined as force acting at moment distance. Torque is related work by (Pulkrabek, 1997).

$$2 \times \pi \times T = W_b \ (\text{N·m}) \qquad (2.1)$$

where: $W_b$ = brake work of one revolution

For calculate engine power, brake power (BP) is defined as the rate of work of the engine by.

$$BP = \frac{2 \times \pi \times N \times T}{60 \times 1{,}000} \qquad (\text{kW}) \qquad (2.2)$$

where: $N$ = engine speed (rev/sec)

$T$ = torque from tested results (N·m)

For calculated Fuel Consumption, $\dot{m}_f$ is defined by

$$\dot{m}_f = \frac{w_f}{t} \qquad \text{(kg/s)} \tag{2.3}$$

where: $w_f$ = mass of fuel (kg)

$t$ = time (s)

Brake Specific Fuel Consumption (BSFC) is amount of fuel consumption used in one unit of time per brake power, as defined by.

$$BSFC = \frac{Fuel\ Consumption}{Power} = \frac{\dot{m}_f \times 1{,}000 \times 3{,}600}{BP} \qquad \text{(g/kW·hr)} \tag{2.4}$$

where: $\dot{m}_f$ = mass flow rate of fuel (kg/s)

$BP$ = break power from tested results (kW)

Generally, a quantity in the analysis of combustion process to quantify the amount of air and fuel is called "air/fuel ratio" (AFR). It is a parameter expressed on a mass basis and defined by a ratio of mass of air and fuel for a combustion process (Cengel and Boles, 1994), as shown in equation 2.5. For diesel engine, AFR ranges from 18 to 80 (Stone and Ball, 2004). The Stoichiometric air/fuel ratio formula is determined by.

$$AFR = \frac{m_a}{m_f} = \frac{\dot{m}_a}{\dot{m}_f} \tag{2.5}$$

where: $m_a$ = mass of air (kg)

$m_f$ = mass of fuel (kg)

$\dot{m}_a$ = mass flow into engine (kg/sec)

$\dot{m}_f$ = mass flow rate of fuel (kg/sec)

As know, the CI engine uses high pressure and temperature to ignite the combustible air/fuel ratio. To achieve this, the CI engine compression ratio is in the range of 21:1 and the fuel injected directly into the cylinder near the top dead center of the combustion stroke. Therefore, diesel engines always operate with excess air (lambda, $\lambda > 1$), which reduces the amount of soot (particulates), THC and CO emissions (Jurgen, 1999), as show in Figure 2.1. Lambda is determined by.

$$\lambda = \frac{Quantiy\ of\ airsupplied}{Theoretical\ reuirment} = \frac{AFR_{actual}}{AFR_{stoichiometric}} \qquad (2.6)$$

where: $AFR_{actual}$ = air/fuel ratio measured form the engine

$AFR_{stoichiometric}$ = air/fuel ratio calculated from theory

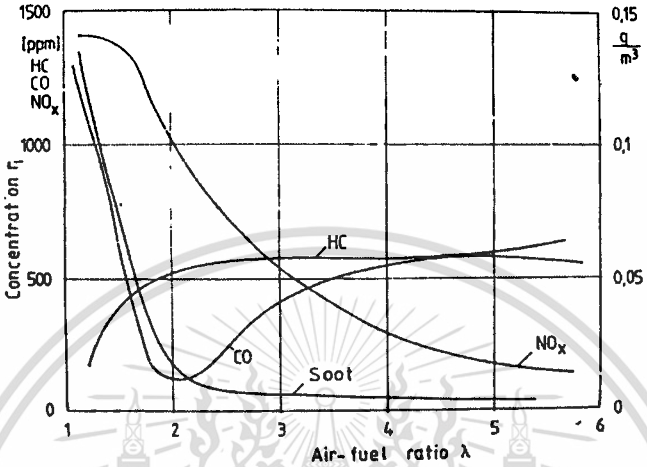


**Figure 2.1** Exhaust concentration as a function of lambda (Schafer and Basshuyscn, 1995).

### 2.3.2 Exhaust Gas Emission

The composition of exhaust gas varies according to the quality of combustion and even more importantly, as a function of the normalized AFR and lambda. Since the condition within the engine operation cannot correspond to the absolute ideal for perfect combustion, a number of incomplete combustion occur, even if a stoichiometric air/fuel ratio (λ=1) is maintained while diesel engines with ECM maintaining lambda-control range always operate with excess air (λ=1.1 ...7.0). Important characteristics of exhaust gas emission form the diesel engine can be discussed as follow (Challen and Baranescu, 1999).

Carbon dioxide ($CO_2$) occurs naturally in the atmosphere, and is a normal product of combustion. Ideally, combustion of a hydrocarbon fuel should produce only carbon dioxide and water ($H_2O$). The relative proportion of these two depends on the carbon-to-hydrogen ratio in the fuel, about 1:1.75 for ordinary diesel fuel.

Carbon monoxide (CO) is toxic. It is an intermediate product in the combustion of a hydrocarbon fuel, so its emission results from incomplete combustion. Emission of CO is therefore greatly dependent on the AFR relative to the stoichiometric proportions. Fuel-rich combustion invariably produces CO, and emission increases linearly with the deviation from stoichiometric.

Hydrocarbon (HC) emissions consist of fuel that is completely unburned or partially burned. The term HCs means organic compounds in the gaseous state; solid hydrocarbons are part of the particulate matter. The mechanisms leading to HC emissions from diesel engine are completely different from those leading to HC emissions from spark ignition (SI engine). In the diesel engine, with its non-homogeneous combustion, HC emissions result from problems of fuel and air mixing, and are largely unaffected by the overall air fuel ratio. There are two primary mechanisms by which fuel escapes the main combustion in a diesel; over-mixed, over-lean regions formed before ignition, and under-mixed fuel injected at low velocity near the end of combustion.

Nitrogen oxides ($NO_x$) are comprised of nitric oxide (NO) and nitrogen dioxide ($NO_2$), with the former making up 70-90% of the total $NO_x$ from diesel engines. $NO_x$ is a side effect of combustion, not an incomplete step. It is accept that nitric oxide (NO) is formed by the extended Zeldovich mechanism ($O+N_2 \text{-->} NO+N$, $N+O_2 \text{-->} NO+O$ and $N+OH \text{-->} NO + H$). Nitrogen oxide ($NO_2$) forms from NO; quenching by excess air in the cylinder can freeze $NO_2$ levels at well above equilibrium concentrations. The formation of NO depends on plentiful oxygen and high temperatures. Gas that burns before the time of peak cylinder pressure is particularly important. After it has burned, it is compressed to a higher pressure and temperature, so the highest temperature of any portion of the cylinder charge is reached.

Diesel exhaust odor results from a combination of aromatic hydrocarbons and oxygenate organic molecules such as aldehydes. The latter tend to be found at the edges of the fuel sprays and during starting. Although aldehydes do contribute to the odor, there appears to be no single group of compounds, which account for a diesel engine's odor.

### 2.3.3 AFR by Spindt Methods

Combustion-based air/fuel determination method at stoichiometric conditions uses the combustion equation for a generalized hydrocarbon with no excess oxygen or hydrocarbons (Heywood, 1988). One mole of hydrocarbon fuel reacting with air at stoichiometric conditions is chosen as the basis for a hydrocarbon represented as $C_aH_b$, the chemical reaction is

$$C_aH_b + n_{air}(O_2 + 3.76N_2) \rightarrow n_{CO_2}CO_2 + n_{H_2O}H_2O + n_{N_2}3.76N_2 \quad (2.7)$$

Where: $n_{air}$ = moles of air ($n_{air} = n_{O_2}$),

$n_{CO_2}$ = moles of carbon dioxide,

$n_{H_2O}$ = moles of water, and

$n_{N_2}$ = moles of nitrogen.

By using the elemental balance equations, the combustion equation may be balanced.

Carbon balance: $n_{CO_2} = a$ (2.8)

Hydrogen balance: $n_{H_2O} = b/2$ (2.9)

Nitrogen balance: $n_{N_2} = 3.773n_{air}$ (2.10)

Oxygen balance: $2n_{CO_2} + n_{H_2O} = 2n_{air}$ ; $n_{air} = a+(b/4)$ (2.11)

The balanced combustion equation is then,

$$C_aH_b + \left(a + \frac{b}{4}\right)(O_2 + 3.76N_2) \rightarrow aCO_2 + \frac{b}{2}H_2O + 3.76\left(a + \frac{b}{4}\right)N_2 \quad (2.12)$$

Since only the ratios of moles of each chemical species are defined, the fuel composition may be written as $CH_y$ where $y=b/a=H:C$ or the carbon/hydrogen ratio of the fuel, and after converting to a mass basis we can develop the stoichiometric air/fuel ratio relationship in terms of "y".

$$\left(\frac{A}{F}\right)_{stoichiometric} = \frac{\left(a + \frac{b}{4}\right)(32 + 3.76(28.16))}{12.011a + 1.008b} \times \left(\frac{\frac{1}{a}}{\frac{1}{a}}\right) = \frac{34.56(4 + y)}{12.011 + 1.008y} \quad (2.13)$$

Although Heywood (1988) does not investigate the stoichiometric air/fuel ratio for an oxygenated fuel, in this case, one mole of an oxygenated hydrocarbon represented as $C_aH_bO_c$ reacts with air at stoichiometric conditions. The chemical reaction for a generalized oxygenated hydrocarbon at stoichiometric conditions is

$$C_aH_bO_c + n_{air}(O_2 + 3.76N_2) \rightarrow n_{CO_2}CO_2 + n_{H_2O}H_2O + n_{N_2}3.76N_2 \qquad (2.14)$$

Again, the elemental balance equations provide a direct solution to the combustion equation. The addition of oxygen to the fuel alters the elemental oxygen balance as follows

$$\textit{Oxygen balance: } n_{air} = a+(b/4)-(c\text{-}2) \qquad (2.15)$$

yielding the following balanced stoichiometric equation.

$$C_aH_bO_c + \left(a + \frac{b}{4} - \frac{c}{2}\right)(O_2 + 3.76N_2) \rightarrow$$
$$aCO_2 + \frac{b}{2}H_2O + 3.76\left(a + \frac{b}{4} - \frac{c}{2}\right)N_2 \qquad (2.16)$$

The effect of oxygen addition to the fuel is a reallocation of oxygen in the air to the fuel, which serves to enrich the oxygenated air/fuel ratio in relation to the nonoxygenated fuel air/fuel ratio. We can notify that $CO_2$ and $H_2O$ are not affected, and nitrogen ($N_2$) experiences the same molar decrease as air.

Similar to the hydrocarbon fuel case, the oxygenated fuel may be normalized to a C1 basis and written as $CH_yO_z$ where $z=c/a=O{:}C$ or the oxygen/carbon ratio is introduced. We can solve the stoichiometric air/fuel ratio in terms of y and z as before.

$$\left(\frac{A}{F}\right)_{stoichiometric} = \frac{\left(a + \frac{b}{4} - \frac{c}{2}\right)(32 + 3.76(28.16))}{12.011a + 1.008b + 16c} \times \left(\frac{\frac{1}{a}}{\frac{1}{a}}\right) = \frac{34.56(4 + y - 2z)}{12.011 + 1.008y + 16z} \qquad (2.17)$$

Spindt (1965) developed the method during an era when oxygenated fuels were infrequently used. Spindt was aware that other elements may be added to the fuel. Two generalizations to accommodate oxygenated fuels were proposed. Firstly, the Spindt method may need to be generalized to recognize the presence of oxygenate in a fuel blend, and secondly, nitrogen oxides ($NO_x$) in the exhaust products may become significant as oxygenates are added to hydrocarbon fuels.

Spindt proposed the following equation to combust one mole of a non-oxygenated hydrocarbon $C_nH_m$ with 100 moles of air as a basis with nitrogen excluded from the analysis.

$$20.99(O_2)+X(C)+Y(H_2)\rightarrow$$
$$A(CO_2)+B(CO)+C(H_2O)+D(H_2)+E(O_2) \tag{2.18}$$

Where *A, B, C, D* represent moles of product and *E* represent moles excess oxygen. After allowing assumptions such as $K$=3.5 for the water-gas shift reaction, Spindt derived the following air/fuel ratio expression.

$$\left(\frac{A}{F}\right)_{actual}^{Spindt\,\#1}=F_b\left[11.492F_c\left(\frac{1+\frac{R}{2}+Q}{1+R}\right)+\left(\frac{120\times F_h}{3.5+R}\right)\right] \tag{2.19}$$

Where:

$$F_c=\frac{12.01X}{12.01X+2.016Y} \tag{2.20}$$

$$F_h=\frac{2.016Y}{12.01X+2.016Y} \tag{2.21}$$

$$F_o=\frac{32.0Z}{12.01X+2.016Y} \tag{2.22}$$

$$F_b=\frac{P_{CO}+P_{CO_2}}{P_{CO}+P_{CO_2}+P_{CH}} \tag{2.23}$$

$$R=\frac{P_{CO}}{P_{CO_2}} \tag{2.24}$$

$$Q=\frac{P_{O_2}}{P_{CO_2}} \tag{2.25}$$

Spindt defined the variables $F_c$ as the fraction of carbon in the fuel, $F_h$ as the fraction of hydrogen in the fuel, $F_b$ as the burn fraction in the products, and $P_i$ as the percentage of the i$^{th}$ species in the exhaust. The fraction of carbon and hydrogen in non-oxygenated fuel sum to one ($F_c$+$F_h$=1), and the burned fraction and unburned fraction, $F_u$, in the exhaust sum to one ($F_b$+$F_u$=1).

Although stated but not explicitly written in Spindt's paper, the following is the more thorough combustion equation implied, reflecting the burned and unburned partitioning of the products:

$$X(C) + Y(H_2) + 20.99(O_2) \rightarrow \left(X(C) + Y(H_2) + 20.99(O_2)\right)F_u + \left(A(CO_2) + B(CO) + C(H_2O) + D(H_2) + E(O_2)\right)F_b \qquad (2.26)$$

In this equation, the significance of the burned fraction and unburned fraction is evident. The burned fraction partitions the products which arise from complete combustion at the flame front and the unburned fraction partitions the products which escape the flame front. This form of the combustion equation illustrates the significance of Spindt's support of the hypothesis that combustion is complete at the flame, and incomplete combustion arises from incomplete passage of the flame through the combustion chamber geometry.

To expand for oxygenate fuels is to accommodate oxygenate addition to the fuel, where the combustion equation must be altered to reflect oxygen in the fuel. Parallel to the convention Spindt used to represent the hydrocarbon $C_nH_m$ as $X(C)$ and $Y(H_2)$, $Z$ moles of oxygen, $Z(O_2)$ and equation 2.26 to represent the oxygenated hydrocarbon $C_nH_mO_r$.

$$20.99(O_2) + X(C) + Y(H_2) + Z(O_2) \rightarrow A(CO_2) + B(CO) + C(H_2O) + D(H_2) + E(O_2) \qquad (2.27)$$

The elemental fractional fuel components, $F_c$ and $F_h$, are altered as $F_o$, the fraction of oxygen in the fuel, is incorporated into the generalized derivation and now $F_c+F_h+F_o=1$. The additional oxygen in the reactants affects the elemental oxygen balance. The additional fuel-bound oxygen is carried through the Spindt Method derivation with the resulting expression which translates the air/fuel ratio by a quantity directly to the fraction of oxygen in the fuel:

$$\left(\frac{A}{F}\right)^{Spindt\#2}_{actual} = F_b\left[11.492F_c\left(\frac{1+\frac{R}{2}+Q}{1+R}\right) + \left(\frac{120\times F_h}{3.5+R}\right)\right] - 4.313F_o \qquad (2.28)$$

Where:

$$F_c = \frac{12.01X}{12.01X + 2.016Y + 32.0Z} \qquad (2.29)$$

$$F_h = \frac{2.016Y}{12.01X + 2.016Y + 32.0Z} \qquad (2.30)$$

$$F_o = \frac{32.0Z}{12.01X + 2.016Y + 32.0Z} \qquad (2.31)$$

The value of the first term in equation 2.28 will differ from the non-oxygenated fuel case since the changes in the exhaust product concentrations of CO, $CO_2$ and $O_2$ will be reflected in the ratios $F_b$, $R$, and $Q$, and fuel composition changes will be reflected in $F_c$ and $F_h$. Therefore, the $(A/F)_{actual}$ would be expected to relate, but not directly, to the oxygen fraction. The development of this expansion to the Spindt Method is presented by Bresenham (1998a).

Spindt's method was constructed to use four inputs: exhaust concentrations of CO, $CO_2$, HC and $O_2$. Heywood (1988) reported that the fifth compound, $NO_x$, was typically excluded from air/fuel ratio determination analysis since for non-oxygenated fuels, the effect of $NO_x$ was sufficiently low (<0.5%) for its effect on equivalence ratio thus to negligible. For high concentrations of oxygenated fuels, the effect of $NO_x$ may become significant since oxygenated fuels increased $NO_x$ formation through leaner engine operation. The oxygenated Spindt Method, equation 2.28 may be further generalized to accommodate $NO_x$ exhaust products. In this case, nitrogen has not been cancelled and must be included in the derivation. The combustion equation then is generalized as following with nitrogen oxide (NO) representing $NO_x$.

$$\begin{aligned} &X(C)+Y(H_2)+Z(O_2)+20.99(O_2)+79.01(N_2)\rightarrow \\ &\quad A(CO_2)+B(CO)+C(H_2O)+D(H_2)+E(O_2)+F(N_2)+G(NO) \end{aligned} \tag{2.32}$$

Where: $F$ and $G$ are added to represent moles nitrogen and nitrogen oxide.

The inclusion of the effect of NO alters the elemental oxygen balance and requires an elemental nitrogen balance equation. The expansion of the Spindt Method for oxygenated fuels to accommodate $NO_x$ emissions is shown by Bresenham *et al.* (1998a). The resulting expression is.

$$\left(\frac{A}{F}\right)_{actual}^{Spindt\#3}=F_b\left[11.492F_c\left(\frac{1+\frac{R}{2}+Q+\frac{S}{2}}{1+R}\right)+\left(\frac{120\times F_h}{3.5+R}\right)\right]-4.313F_o \tag{2.33}$$

Where: the ratio $S=\dfrac{P_{NO}}{P_{CO_2}}$, is percentage NO to $CO_2$ in the first term.

## 2.4 Literature review

In this section, the author has carefully reviewed literatures from many researchers who are interested in alcohol fuel, especially butanol, in order to use it as an alternative fuel in a vehicle and the importance of their works can be summarized as follow;

Lenz and Morelra (1980) have studied economic evaluation of the acetone-butanol fermentation in U.S. that the economics of producing acetone and 1-butanol via fermentation have been examined for a 45x10$^6$ kg of solvents/year plant. It can be concluded that waste based acetone-butanol production via fermentation deserved further attention in view of the attractive whey-based economics and the excellent potential of butanol as a fuel extension, especially for diesohol blending.

Bresenham *et al.* (1998b) suggested a use of generalized Spindt method to accommodate high oxygenated fuel blends because it was more accurate to estimate the equivalence ratio. Figure 2.2 showed results from the seven test engines compared with original Spindt and Spindt oxygenate method. The oxygenated fuel version of the Spindt method improved the original Spindt method by as much as 10% for selected J1088 test modes and over 8% for the aggregate J1088 test modes at the highest oxygenate blend, a 50% ethanol and reformulated blendstock for oxygenated blending or RBOB (French and Malone, 2005). Figure 2.3 showed results from the seven test engines compared by Spindt oxygenate and $NO_x$ method. For high oxygenated fuel blends, the generalized Spindt method accommodating oxygenated fuels with $NO_x$ emission data did not yield a significantly more accurate estimate of the equivalence ratio than the Spindt Method generalized to accommodate oxygenated fuels. Improvements were 0.5% or less for individual J1088 test modes and aggregate J1088 test modes at the highest oxygenate blend investigated, a 50% ethanol and RBOB fuel blend.

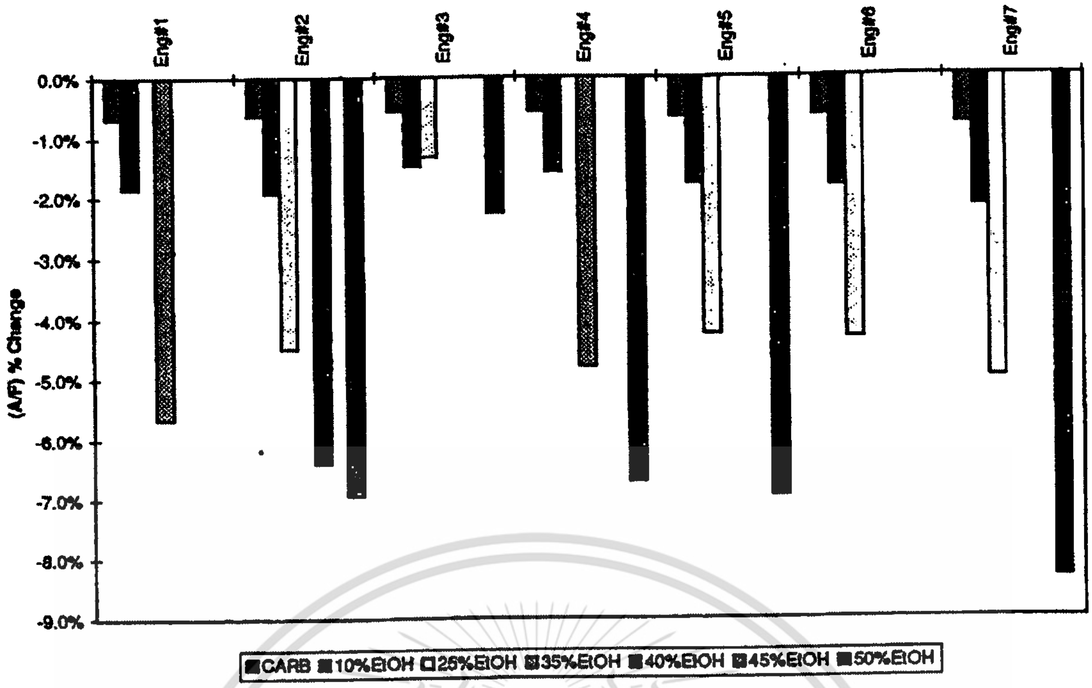


**Figure 2.2** %Change of Air/fuel ratio with Spindt method comparison (oxygenated versus non-oxygenated fuel).

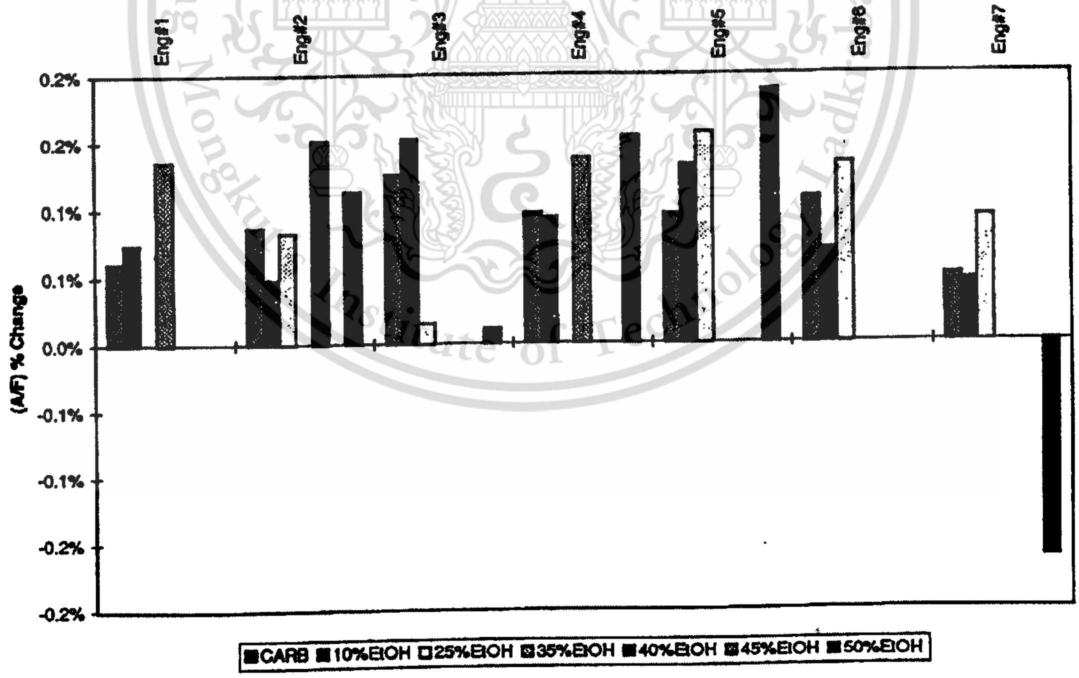


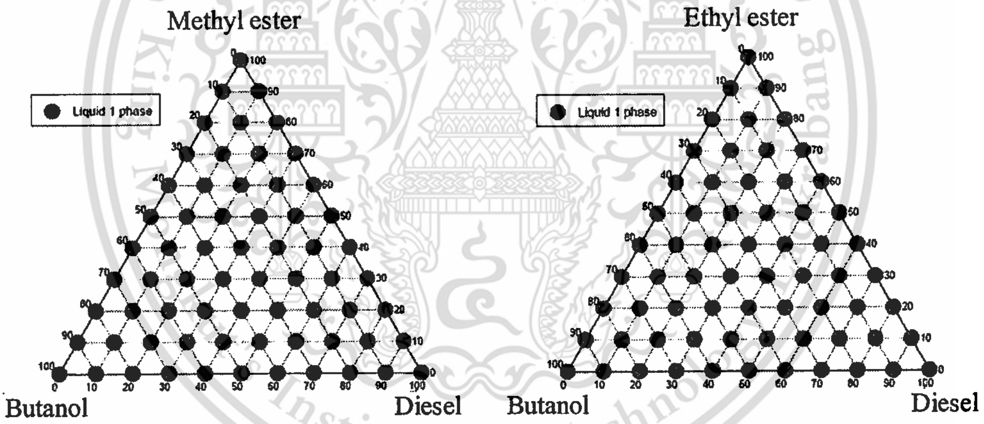
**Figure 2.3** %Change of Air/fuel ratio with Spindt method comparison (oxygenated with $NO_x$ versus oxygenated fuel).

Tanabudipat (2003) has studied a use of diesohol on IDI diesel engine with Ford Ranger WL81 2.499 liter. The results showed that full load power and torque of diesohol in an IDI engine were lower than diesel due to its lower heating value. The differences were progressively worse at the lower speed. The engine brake specific fuel consumption of diesohol was higher than diesel. In-cylinder pressure, fuel line pressure and crank angle were recorded. Fuel injection rate, heat release rate, net heat release and mass fraction burned were estimated. The results showed the maximum in-cylinder pressure of diesohol combustion was slightly lower than diesel. More delay in injection timing and starting of combustion of diesohol was found. However, burn duration of diesohol was similar to the diesel. Heat release rate and net heat release of diesohol combustion were close to diesel because of higher fuel injection per cycle, except at full load that diesel was higher. Mass fraction burned of diesohol combustion was a little less than diesel combustion. It may be concluded that diesohol can replace diesel fuel in an IDI engine as long as some diesohol compatible parts have been replaced.

Smith and Workman (2004) have studied the use of alcohols which are methyl, ethyl and butyl alcohol blend in gasoline and diesel fuel. For the results of the butyl alcohol, it was blended with diesel fuel in virtually every concentration. It does not separate as water was added or as the temperature was decreased. In blends with diesel fuel, butyl alcohol tends to reduce the solidification temperature of the fuel at a low temperature.

Wattanavichien (2004) investigated the characteristics of an OEM high-speed Light Duty IDI Diesel engine operating with diesohol with 10% ethanol. The results showed that diesohol could be used in an IDI engine with some power drop. Power and torque of diesohol at full load were lower and the difference shown progressively worse at a lower speed. The Brake specific fuel consumption of diesohol fuel was higher than diesel fuel. Results of the injection timing of diesohol were approximately 1 degree delay compared with the injection timing of reference diesel. The in-cylinder combustion pressure of diesohol fuel was lower than diesel combustion. For heat release rate diagram, it was found that the starting point of diesohol combustion tended to have some slightly delayed from the point of diesel combustion. The net heat release of both fuels tended to increase with increasing load and diesohol combustion duration tended to have a slightly longer period than diesel. Nevertheless, as engine speed was increased diesohol combustion had a similar ignition delay to diesel.

Chotwichien *et al.* (2007) has studied the use palm oil alkyl esters as an additive in diesel-ethanol and diesel-butanol blends, and found that the use of butanol in diesohol could solve the problem of fuel instability at a low temperature because of its higher solubility in diesel fuel. In addition, the fuel properties results indicated that blends containing butanol had properties closer to diesel than those of blends containing ethanol. Figure 2.4 showed combinations of diesel fuel results blending with ethanol, butanol and biodiesel at 30°C. There was not a problem of segregation and turbidity at all ratios. The results implied that the use of butanol instead of ethanol in diesel with biodiesel could solve the problem of segregation, which had been the main problem of diesohol fuel.



(a) (b)

**Figure 2.4** Three phase diagram of Solubility at 30°C (a) Diesel, butanol and methyl ester, and (b) Diesel, butanol and ethyl ester.

Leelanoi (2007) has studied the use of butanol up to 42% mixing with diesel in direct injection diesel engine to compare engine performance, fuel combustion and engine wearing of the diesel engine between mixed fuels and pure diesel fuel. It was found that 42% of butanol in mixed fuel was the maximum ratio that the diesel engine could be operated as the same conditions with pure diesel fuel without any modification. The break thermal efficiency was averaged at

12.92% higher than pure diesel fuel. For the break specific energy consumption was averaged at 11.73%, which was insignificantly different from pure diesel fuel. The air/fuel ratio was averaged at 3.52% lower than pure diesel fuel. The $O_2$ from exhausted gas emission was also not significantly different from pure diesel fuel. However, the CO and HC from exhausted gas emission were higher than pure diesel fuel. The $CO_2$, $NO_x$ and smoke were lower than pure diesel fuel. The wearing of engine parts was also not significantly found; however, the black slag was found at the piston heads in the case of mixed fuels. In addition, the cetane number of butanol blended diesel from this study showed in Figure 2.5.

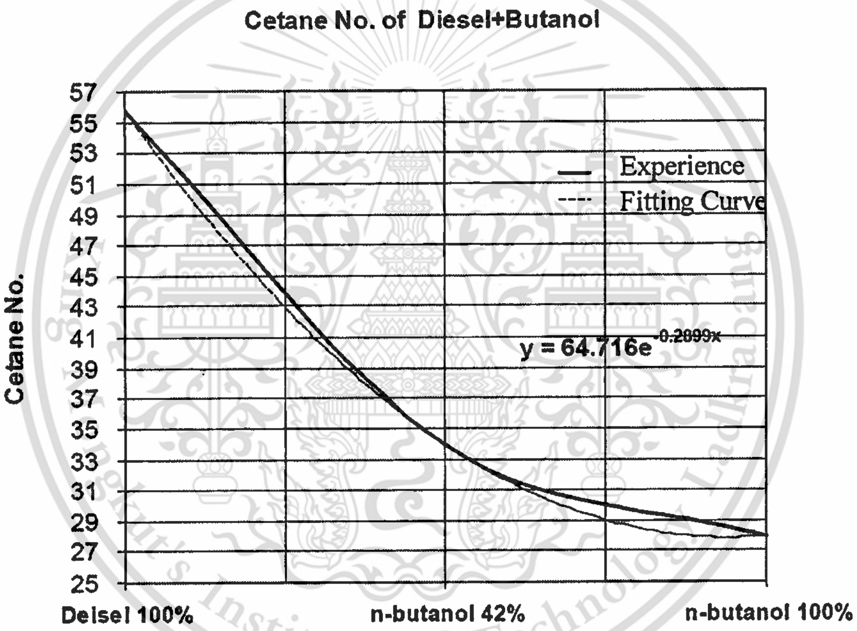


**Figure 2.5** Cetane number of butanol/diesel blend.

Al-Hasan and Al-Momany (2008) investigated the effect of iso-butanol addition to diesel fuel on engine performance parameters by using a single cylinder four stroke CI engine Type Lister 1-8. The tests were performed at engine speed running from 375 to 625 rpm with an increment of 42 rpm at different loads, and with 10, 20, 30 and 40% (v/v) iso-butanol-diesel fuel blends. The overall engine performance parameter measurement was including air/fuel ratio (AFR), exhaust gas temperature, brake power, brake specific fuel consumption and brake thermal efficiency. The experimental results showed that AFR, exhaust gas temperature, brake power and brake thermal efficiency decreased and brake specific fuel consumption increased with iso-butanol addition compared with neat diesel fuel. Also, the obtained results indicated that the engine performance parameters, when using up to 30% iso-butanol in fuel blends, were better than these of 40%.

# CHAPTER 3

# EXPERIMENTAL PROCEDURES

## 3.1 Tested Fuels

This experiment focused on an alcohol fuel, butanol ($C_4H_9HO$), for blending with commercial diesel fuel to become diesohol. The commercial butanol, 99.9% purity, was bought form Thai Agency Company and its properties are exhibited in Table 3.1 with original certification. The commercial diesel fuel was bought form Petroleum Authority of Thailand (PTT) Plc. (Thailand) to ascertain their properties meeting the regulation of Department of Energy Business, Ministry of Energy, Thailand as displayed in Appendix E.

**Table 3.1** Properties of neat butanol

| Item | | Result |
|---|---|---|
| Chemical formula | | $C_4H_9OH$ |
| Appearance | | Substantially Free |
| Odor | | Characteristic & Non residual |
| Color | (Pt-Co) | Less than 5 |
| Distillation, °C | (I.B.P.-D.P.) | 117.2-117.8 |
| Acidity as Acetic Acid | (%wt.) | 0.00125 |
| Water content | (%wt.) | 0.0174 |
| Purity | (%wt.) | 99.90 |
| S.G. @ 15°C | (%wt.) | 0.8131 |

The butanol/diesel-blended samples were prepared by blending butanol with the commercial diesel together at a room temperature without adding any emulsifiers or additives to maintain the homogeneous-fueled condition. The concentrations of butanol/diesel blends were increased by adding butanol at 0, 5, 10, 15, 20, 25, 30, 35 and 40% by volume. These were represented namely BD0 (Diesel), BD5, BD10, BD15, BD20, BD25, BD30, BD35 and BD40, respectively. Then, BDs were used for analyzing chemical and physical properties following

ASTM and CEC standards, and tested in the common rail engine in order to assess performance and emission. Figure 3.1 shows the butanol and diesel samples.

**Figure 3.1** Butanol (left hand) and diesel (right hand) samples.

## 3.2 Tested Engine

The common rail direct-injection diesel engine, ISUZU model 4JJ1/TC, was selected for this experiment because this engine type was very famous in the pickup-trucked market sector, with a large number in Thailand. For the transmission power, if the engine was attached to a transitioned model 4JJ1-TC (A/T), it would have the maximum power of 107 kW at 3,600 rpm, and the maximum torque of 294 N/m at 1,400-3,400 rpm. Meanwhile, if the engine was attached to another model 4JJ1-TC (M/T), it would have the maximum power of 103 kW at 3,600 rpm, and the maximum torque of 280 N/m at 1,400-3,400 rpm. In addition, this engine also achieved the pollution control standard level 3 (Euro 3) by using many technology devices.

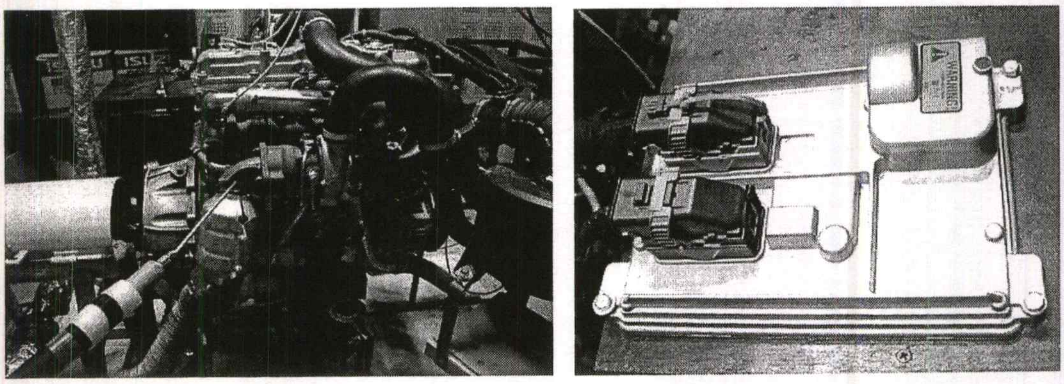
The tested engine was consisted of many mechanical and electrical devices such as intercooler, turbocharger, common rail fuel system, exhaust gas recirculation (EGR) and Electronic Control Module (ECM). The detailed specifications are shown in Table 3.2. Generally, ECM was located in an engine room with supporting bar behind the air filter but in this experiment, ECM was installed close to the test engine by a stand.

The function of ECM was able to calculate within 32 bites and verify data information from other sensors. The main functions of ECM generally controlled amount of fuel, the injection timing system, the EGR system, the warming system, the air flow system, the fuel system, the immobilizer system, and the warning system.

However, it was very necessary that ECM and the other components had not been modified in order to access the ability of this tested engine with BDs. Figure 3.2 shows the tested engine and unmodified ECM

**Table 3.2** Tested engine specification

| Description | Specification |
|---|---|
| Brand | ISUZU |
| Model | 4JJ1-TC |
| Type | Diesel engine, 16 valves, four stroke, |
| Cylinder design, | Inline |
| Number of cylinders | 4 cylinder |
| Injection order | 1-3-4-2 |
| Cylinder bore & stroke | 95.4x104.9 mm |
| Capacity | 2.999 liter |
| Compression ratio | 17.5:1 |
| Pressure in cylinder | 3 MPa |
| Chamber | Open or direct injection |
| Idle speed | 700±25 rpm |
| Idle speed (turn off A/C) | 750±25 rpm |
| Maximum idle speed | 4,400 rpm |
| Fuel system | Common rail system |
| Fuel pump | Denso pump (HP3), Supply fuel pump |
| Nozzle | Electronic control |
| Nozzle holes | 6 |
| Diameter of nozzle hole | 0.14 mm |
| Opening pressure of nozzle | Electronic control |
| Fuel filter | Paper type with water filter |
| Electronic control module | 4J Diesel ECM-IHVP56 (Delphi) |
| Other systems | overhead camshaft, intercooler, turbocharger |



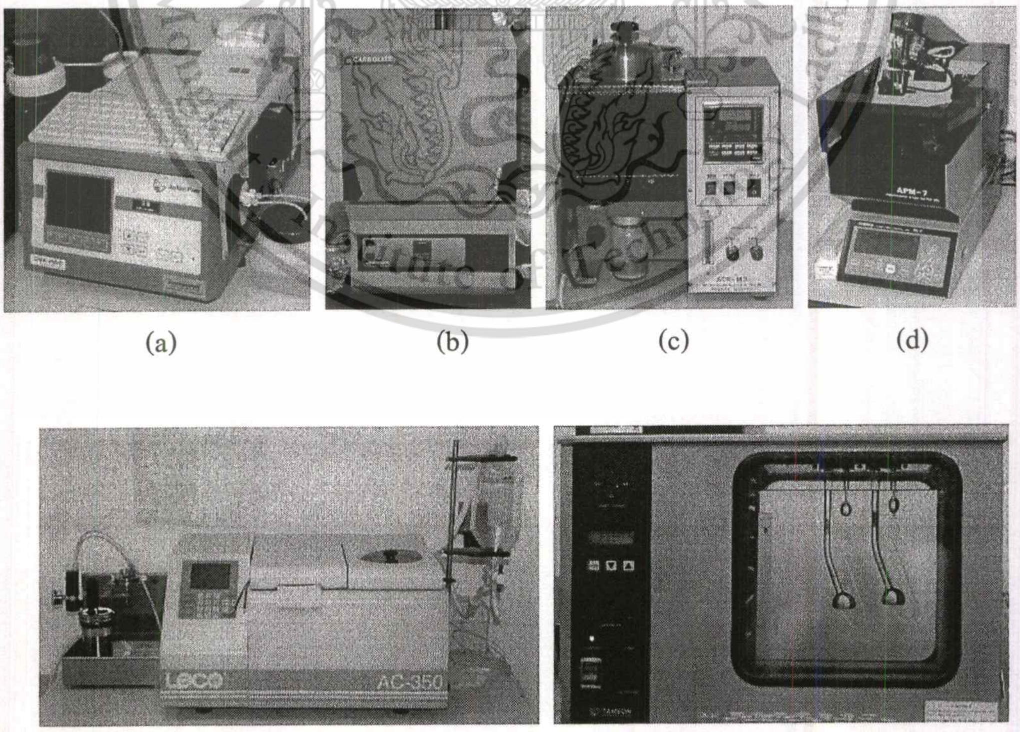
(a) (b)

**Figure 3.2** (a) The tested engine ISUZU model 4JJ1-TC with the other components and (b) unmodified ECM.

## 3.3 Apparatus

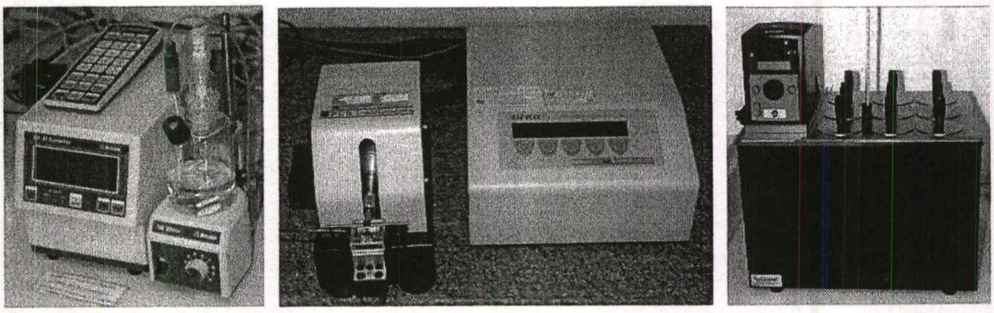
### 3.3.1 Measuring Instruments for Physical and Chemical Property Tests

The physical and chemical properties of BDs were analyzed by using many equipments such as a digital density meter, a furnace, a mircrocabon residue tester, a Pensky-Martens closed cup tester, a bomb calorimeter, a viscometer, a Karl Fisher coulometer, a copper strip corrosion bath and a High Frequency Reciprocating Test Rig (HFRR), as shown in Figure 3.3.



(a) (b) (c) (d)

(e) (f)



(g) (h) (i)

**Figure 3.3** Instruments for physical and chemical property tests (a) digital density meter, (b) furnace, (c) mircrocabon residue tester, (d) Pensky-Martens closed cup tester, (e) bomb calorimeter, (f) viscometer, (g) Karl Fisher coulometer, (h) high frequency reciprocating test rig (HFRR) and (i) copper strip.

### 3.3.2 Equipment for Engine Test

The performance and emission testing system were composed of (1) the common rail direct injection diesel engine, (2) an 150 kW eddy current dynamometer model ED-150 of Tokyo Plant with (3) a mass fuel consumption meter and (4) a computer controller with a "P.Drive" software version 1.57, (5) an exhausted gas analyzer of Horiba model MEXA-1600D with a "MEXA-1600D" software version 1.0.9.0, and (6) various resistance temperature difference (RTD) sensors included a transited box. Then, the schematic diagram of experimental set up was shown in Figure 3.4 with the components of equipments and the print screen samples of software shown in Figure 3.5 -3.6, respectively.

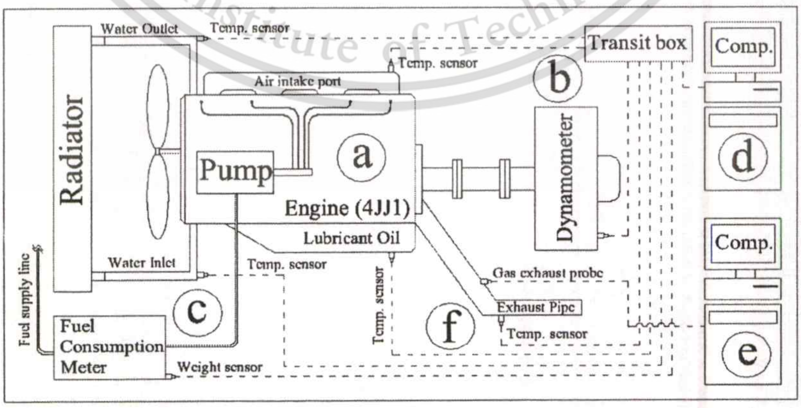


**Figure 3.4** The schematic diagram of engine test system.

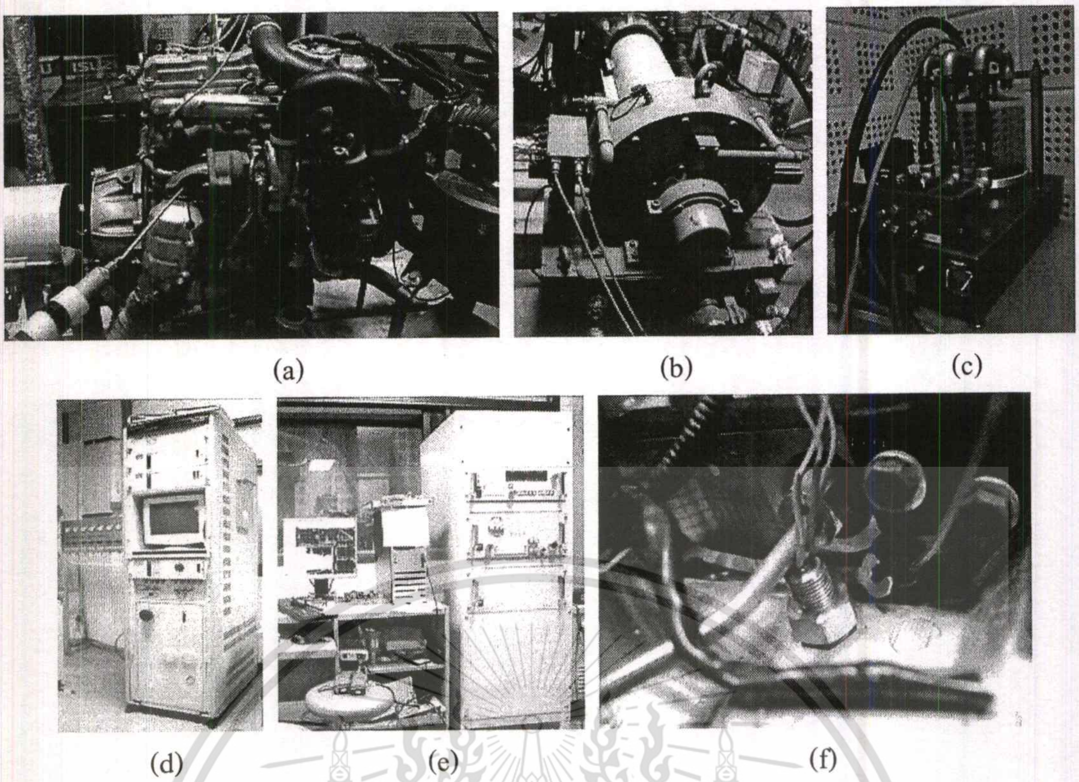
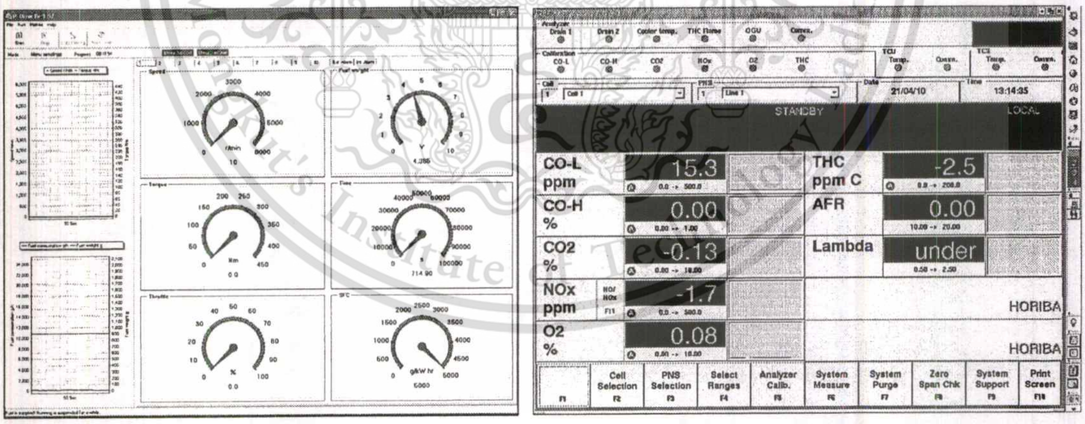


**Figure 3.5** (a) common rail direct injection diesel engine, (b) eddy current dynamometer, (c) mass fuel consumption meter (d) exhausted gas analyzer, (e) computer controller, and (f) RTD temperature sensor.



Cell 1 Cell 1
PNS 1 Line 1
Date 21/04/10
Time 13:14:35
CO-L ppm 15.3 0.0 -> 500.0
THC ppm C -2.5 0.0 -> 200.0
CO-H % 0.00 0.00 -> 1.00
AFR 0.00 10.00 -> 20.00
CO2 % -0.13 0.00 -> 18.00
Lambda under 0.50 -> 2.50
NOx ppm NO/NOx F11 -1.7 0.0 -> 500.0
O2 % 0.08 0.00 -> 10.00

(a) (b)

**Figure 3.6** Print screen of (a) P.Drive and (b) MEXA-1600D software.

## 3.4 Methodology

The overview of methodology is explained by the flow chart of procedure for this experiment in Figure 3.7. First of all, commercial butanol and commercial diesel fuel are blended together by increasing amount of percentage of butanol from minimum (0%) to maximum (40%) by volume. After that, BD0, BD10, BD20, BD30 and BD40 are sampled for physical and chemical property test. Then, BD0, BD5, BD10, BD15, BD20, BD25, BD30, BD35 and BD40 are used for the performance and emission test. Each of the methods will be explained in the next topics.

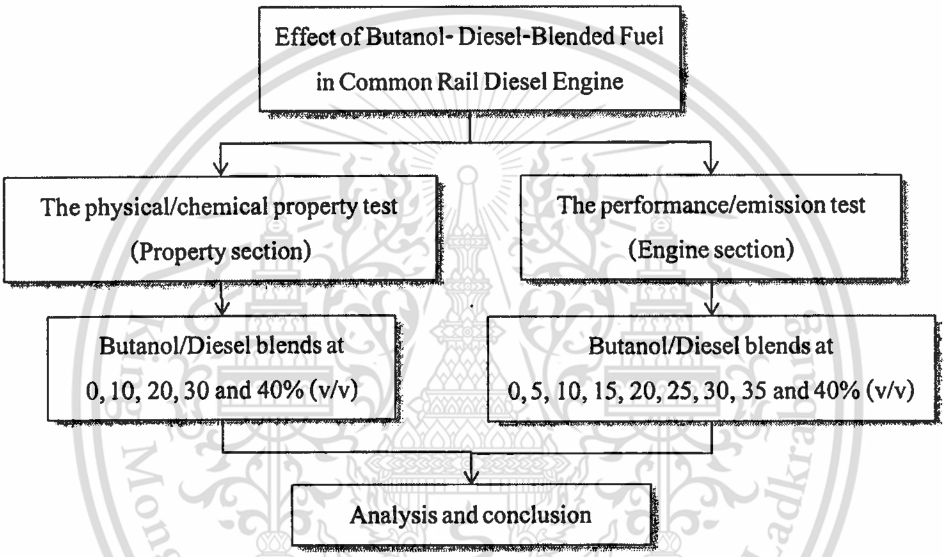


**Figure 3.7** Flow chart of experiment procedures.

### 3.4.1 Physical/Chemical Property Tests

Many standards are used to compare physical/chemical properties with diesel fuel. There are ASTM D93, D130, D524, D240, D445, D482, D4052, D6304, and CEC F-06-A-96. All of the physical and chemical property tests are repeated performed twice or triple times in order to obtain the average results. The summary of the property tests with standard methods are presented in Figure 3.8, and each of the tested standards is described as below.

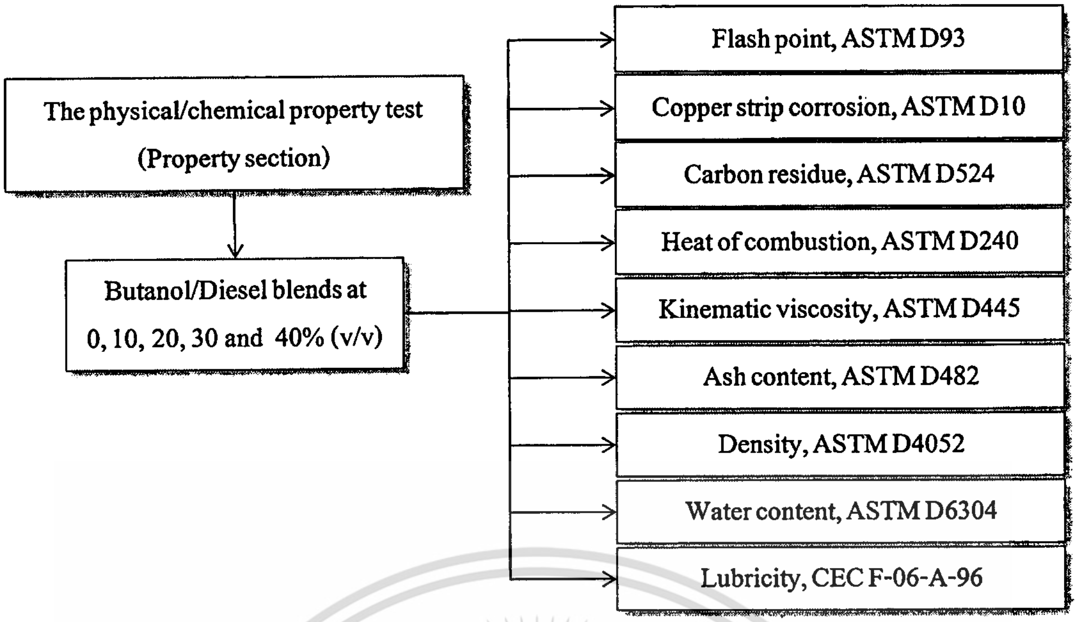


**Figure 3.8** Flow chart of physical and chemical property tests.

**Flash Point (ASTM D93)**, this method used a brass test cup of specified dimension and filled to the inside mark with the sample of BDs and fitted with a cover of specified dimensions. Then, the test cup was heated and the sample stirred at specified rates, by either of two defined procedures. An ignition source was directed into the test cup at regular intervals with simultaneous interruption of the stirring, until a flash was detected.

**Copper Strip Corrosion (ASTM D130)**, this standard used a polished copper strip, which was immersed in a specific volume of BDs under condition of temperature and time. At the end of the heating period, the copper strip was removed, washed and the color and tarnish level assessed against the ASTM Copper Strip Corrosion Standard.

**Carbon Residue (ASTM D524)**, the BDs sample was weighed into a special glass bulb having a capillary operating which was placed in a metal furnace maintained at approximately 550°C. The BDs sample was thus quickly heated to the point at which all volatile matter was evaporated out with or without decomposition; while the heavier residue remaining in the blub undergoes cracking and coking reactions. In the latter portion of the heating period, the coke or carbon residue was subjected to further slow decomposition or slight oxidation due to possibility of breathing air into the bulb. After a specified heating period, the bulb was removed from the bath, cooled in desiccators and again weighed. The residue remaining was calculated as a percentage of the original amount.

**Heat of Combustion (ASTM D240),** this standard was determined by bringing the BDs sample in an oxygen bomb calorimeter under controlled conditions. The heat of combustion was computed from temperature observation before, during and after combustion, with proper allowance for thermochemical and heat transfer corrections. Either isothermal or adiabatic calorimeter jackets could be used.

**Kinematic Viscosity (ASTM D445),** this method used the time to measure a fixed volume of liquid to flow under gravity through the capillary of a calibrated viscometer under a reproducible driving head and at a closely controlled temperature. The kinematic viscosity was calculated for the measured flow time and the calibration constant of the viscometer. Two such determinations were needed to calculate a kinematic viscosity result that was the average of two acceptable determined values.

**Ash Content (ASTM D482),** the BDs sample containing in a suitable vessel was ignited and allowed to burn until only ash and carbon remained. The carbonaceous residue was reduced to an ash heating in a muffle furnace at 775°C. After that, the sample was cooled and weighed to calculate the mass of the ash as a percentage of the original amount.

**Density (ASTM D4052),** A small volume (approximately 0.7 ml) of the sample of BDs was introduced into an oscillating sample tube. The change in oscillating frequency caused by the changes in the mass of the tube was used in conjunction with calibration data to determine the density of the sample.

**Water content (ASTM D6304),** the BDs sample was injected into the titration vessel of a coulometric Karl Fischer apparatus, in which iodine for the Karl Fisher reaction was generated coulometrically at the anode. When all of the water was titrated, excessive iodine was detected by an electrometric end point detector, and the titration was terminated. Based on the stoichiometry of the reaction, 1 mol of iodine reacts with 1 mol of water; thus, the quantity of water was proportional to the total integrated according to Faraday's Law.

**Lubricity (CEC F-06-A-96),** this standard was carried out using a high frequency reciprocating rig (HFRR). The instrument used an electromagnetic drive to oscillate an upper 6 mm diameter steel ball bearing against a stationary lower steel test plate. The contacts were flooded by the BDs sample. The reciprocation frequency and stroke length were controlled to 50 Hz and 1 mm, respectively, throughout the 75 minute test. The contact was fully immersed in the test fuel, which was maintained at 60°C. The ball was loaded against the plate by means of a suspended 200 gm weight. All test parameters were controlled automatically through a PC via a custom electronic interface. The friction coefficient, electrical contact resistance and temperature were displayed in graphical format as the test proceeded and the test data was saved to file. The performance of the fuel lubricity was assessed by measuring the diameter of the wear scar product formed on the ball bearing using a 1 micron resolution microscope. In addition, the test result of BDs was sensitive to the moisture content of the atmosphere, consequently an adjustment was made depending on the ambient conditions and the atmosphere was controlled by using a covered bath.

### 3.4.2 Engine Performance and Emission

The tested engine was set up on the 150 kW eddy current dynamometer by connecting the propeller shaft between flywheel and dynamometer plate flange in the testing room, and connected to the other systems such as a cooling water system, the exhaust gas analysis system, engine speed controller, temperature sensor, etc.

The engine operation was also divided into two sections which were full load and partial load performance test. The full-load test was a method to assess the engine maximum torque and power. During testing, its throttle was fixed at the widest position. Then, loads were applied to the tested engine causing the speed to drop. The tested engine was assessed for performance curve, as well as fuel consumption. The temperatures of air inlet, exhaust gas and lubricant oil were monitored at each of the engine speeds, and exhaust emission such as THC, CO, $CO_2$, $NO/NO_x$ and $O_2$ were measured and analyzed by gas analyzer. All of the test results were collected by data logging P.Drive and MEXA-1600D software.

For the partial load performance test, the constant loads were determined under the same load and speed condition in three loads to test the engine, and the engine throttle was varied to keep the normal range speed. The engine was investigated the performance and exhaust emission to compare each of the parameters, and all of the test results were collected as same as full load condition.

The BDs sample (BD0, BD5, BD10, BD15, BD20, BD25, BD30, BD35 and BD40) were blended enough to test, approximately 25 liters per test. The test condition for full load was set up by changing the engine speed between 800 to 4,400 rpm by 200 rpm increment and allowing various torque values applied to the tested engine. For the partial load, they were described by considering the result of pure diesel at full load condition. Subsequently, the test results of pure diesel fuel were separated into three portions of load, which were 50, 100 and 150 N•m. The test speeds of partial load were measured between 1,000 to 3,500 rpm with 500 rpm increment.

Before observing each of the tests, all of the tested systems had to be checked. The tested engine was initially warmed up in the tested condition, as checked by cooling water at 85°C. Then, the required engine speed was obtained by adjusting the accelerator electrical pedal slowly and breaking torque was corrected and adjusted by the 150 Kw eddy current dynamometer. Both operations were remotely conducted from computer controller in the control room.

Between the testing of different butanol blends, careful switching was followed to ensure that the engine, fuel system (fuel line, fuel filter, high pump and rail) and fuel consumption meter were running with the new blend sufficiently. When the operating conditions were reached and reliably stabilized, the variables were continuously measured and recorded for three times to obtain an average value of the experimental data, e.g. torque load, fuel consumption, air inlet/exhaust gas/lubricant oil temperatures and gas emission. The detail of the flow chart was shown in Figure 3.9.

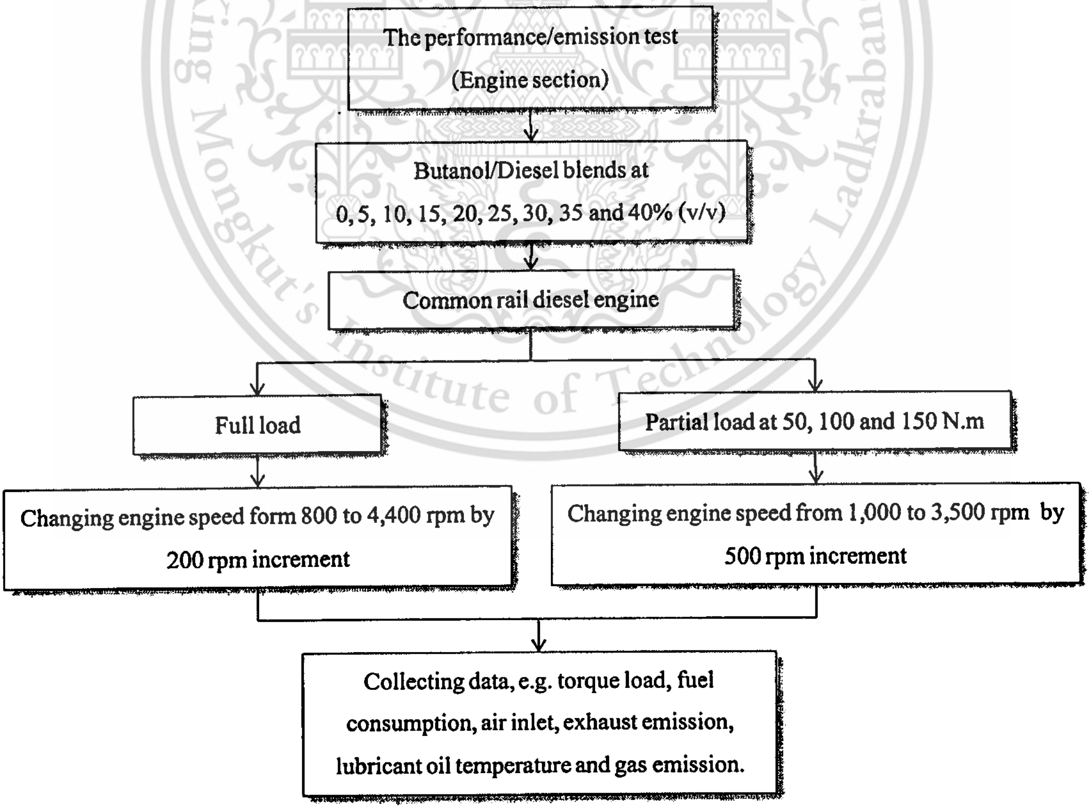


**Figure 3.9** Flow chart of performance and emission tests.

# CHAPTER 4

# EFFECT ON PHYSICAL AND CHEMICAL PROPERTIES

According to the experimental procedure from the previous chapter, the test results are separated into two chapters, chapter 4 and 5. This chapter is about the test property of BDs, meanwhile chapter 5 is about the test results of engine performance and emission. Both chemical and engine tests were conducted with various concentrations of butanol in diesel fuel. Generally, some characteristics of physical and chemical properties of both butanol and diesel are different. If we blended butanol with diesel fuel together, the properties of BDs were changed as well. Therefore, it is necessary that the BDs are analyzed in order to investigate how its properties changed. Consequently, the samples of BDs were tested by the following various standards compared with diesel standard result.

## 4.1 Density

Density was a fundamental physical property that could be used in conjunction with other properties to characterize both the light and heavy fractions of BDs. Determination of the density or relative density of petroleum and its products was necessary for the conversion of measured volumes to volumes at the standard temperature of 15°C (ASTM D4052). The test results of density in Figure 4.1 showed density values of diesel, BD10, BD20, BD30, BD40 and butanol, superimposed with the range of diesel standard.

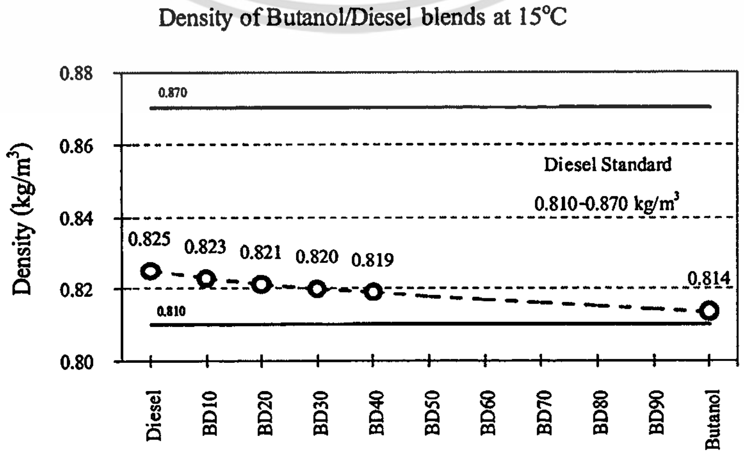


**Figure 4.1** Density of BDs at 15°C.

Since the density of butanol (0.814 $kg/m^3$) was not so much different from that of diesel fuel (0.825 $kg/m^3$), its blends of up to 40% butanol in diesel were less than 1% variation from diesel density. Furthermore, at a constant heating value, lower density was meaning of reduced maximum power output, higher density increased output and increased particle formation (Nylund, *et al*, 2005).

### 4.2 Carbon Residue

The carbon residue value is the amount of carbonaceous which can deposit within the combustion chamber of an engine; therefore, the amount of carbon residue at the end of the combustion process has an effect on the engine life and the quantity of exhaust emission. It is important value to consider because the presence of additives in fuel, such as an ash-forming detergent additive, can increase the carbon residue value of fuel after burning (ASTM D524). The carbon residue value can indicate the tendency of the burner BDs to form deposits in a glass tube which correlates with combustion chamber.

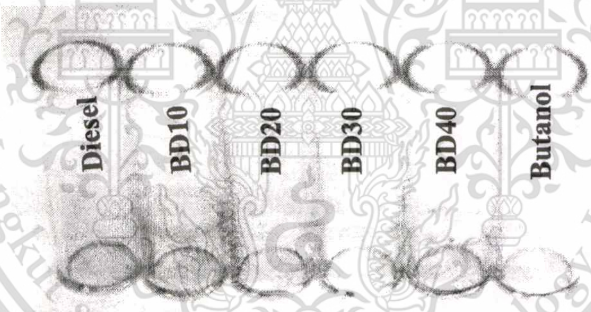


**Figure 4.2** Samples of carbons deposited in the glass tubes.

For the entire test results of carbon residue of BD0-BD40 and butanol, they showed value of %wt less than 0.05 %wt within the specific standard. When comparing the test results, the test values were close to 0 %wt and significantly different, as shown in Table 4.1. All of the test results showed that BDs blended from butanol and diesel were a pure substance without any impurity formation, as shown in Figure 4.2.

**Table 4.1** Carbon residue of BDs after heat at 550°C

| Type of Fuels | Carbon Residue (%wt) |
|---|---|
| Diesel | 0.0067 |
| BD10 | 0.0166 |
| BD20 | ~0.0000* |
| BD30 | ~0.0000* |
| BD40 | ~0.0000* |
| Butanol | 0.0066 |
| Diesel Standard | <0.0500 |

* Negligible within measuring error

## 4.3 Ash Content

Ash content can be derivable from oil or from extraneous solids such as dirt, rust, abrasive solids and soluble metallic soaps (ASTM D482) that the solids cause the wear of injection unit, pistons, ring, and liners and also increase engine deposits. Figure 4.3, the test results implied that diesel and butanol blends were free of noticeable impurities because negligible ash contents were found in crucibles, less the diesel standard limit of 0.01 %wt. Similar to carbon residue result, butanol and diesel can be blended without any formation of water-soluble metallic compounds.

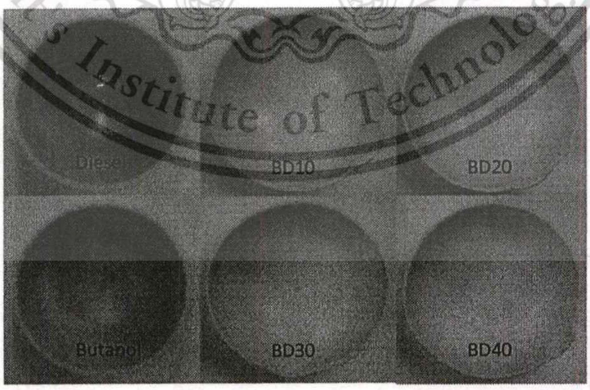


**Figure 4.3** Negligible ash content in the crucibles after heating at 775°C.

## 4.4 Heat of Combustion

The gross heat of combustion, the quantity of energy per unit mass of fuel, is a critical property of fuels for use in an internal combustion engine. As a characteristic of the substance, the heat of combustion is a measurement of the energy available from a fuel. The knowledge of this value is essential when considering the thermal efficiency of engine for power or heat generation. Heat of combustion is used as a basis for comparing various fuels since the fuel with higher heat of combustion is more economic at a given cost (ASTM D240). Figure 4.4 shows the heating values of BDs tended to be decreasing in a linear fashion with increasing blend fraction of butanol. For diesel fuel, heating value per mass was 45.6 MJ/kg. The corresponding value for butanol was 34.9 MJ/kg different form diesel fuel 23.4%. For a given power output, the mass fuel consumption with butanol would be 1.3 times higher compared with diesel. For engines running on neat alcohol, the fuelling rate has to be modified. Modifications may also be needed when running on BDs. Increased fuelling rates lengthen the injection period, and may thus affect engine and emission performance.

In addition, butanol has higher heating value than ethanol because butanol with chemical structure as $C_4H_9OH$ has longer chain, with four atoms of carbons and eleven atoms of hydrogen, and releases more energy up to 15% (Chotwichien, 2007).

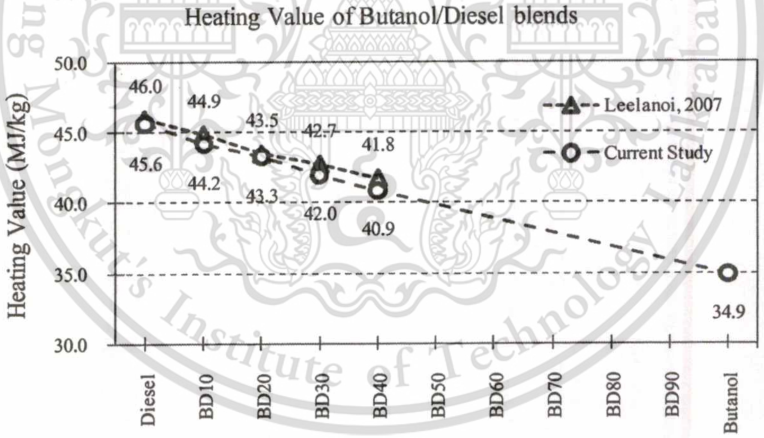


**Figure 4.4** Gross heat of combustion of BDs.

## 4.5 Kinematic Viscosity

The viscosity of many petroleum fuels is important for the estimation of optimum storage, handling, and operational conditions. Thus, the accurate determination of viscosity is essential to many products. In addition, many petroleum products and some non-petroleum materials are used as lubricants, and the optional operation of the equipment depended upon the appropriate viscosity of the liquid being used (ASTM D445). Viscosity and fuel density are the two important parameters when designing fuel systems. Low viscosity will increase a leakage and a delay start of injection in fully mechanical injection systems. High viscosity will impose additional loads on the injection system. In the common rail fuel system, a timing injection and a high pressure pump may be affected by the kinematic viscosity of BDs. Figure 4.5, the kinematic viscosities of BDs show non-linear reduction of viscosity with increasing %butanol blend, especially for a relatively large drop with small amount of butanol because kinematic viscosity are changed by increasing %butanol blend, which affect to dynamic viscosity and inertial force in BDs. Nevertheless, all of the test results are within the diesel standard between 1.8 and 4.1 cSt.

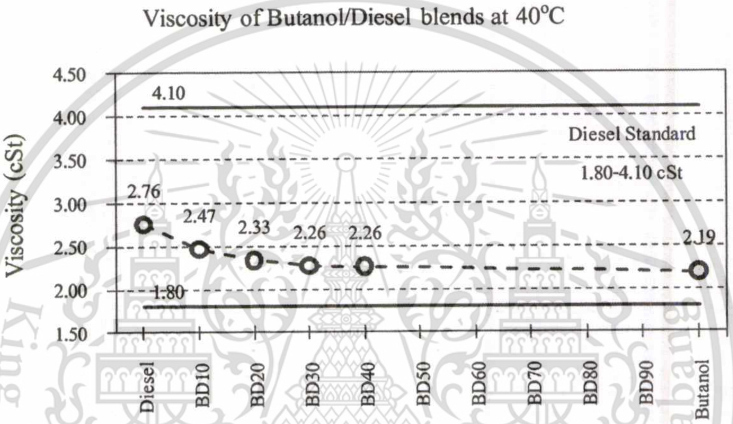


**Figure 4.5** Kinematic Viscosity of BDs.

## 4.6 Water Content

A knowledge of the water content in fuel oils, lubricating oils, additives, and related products is important in the manufacturing, purchasing, sale or transferring of such petroleum products in order to help assess their quality and performance characteristics. For fuel oils, the presence of moisture could lead to premature corrosion, and to wear such load resulting debris in degradable fuel oils may prematurely plug the filters and undesirably support deleterious bacterial growth (ASTM D6304). The solubility of water into diesel fuel and butanol are very limited. Any free water may cause problems which are damages and corrosion in the high-pressure injection system in common rail fuel system. The results of water content exhibited in Figure 4.6 show a steep increasing until 40% butanol blends with gradually increasing for high butanol blends. Diesel fuel generally has very little water content, about 105 ppm, because water could not dissolve into diesel fuel. On the other hand, since the purity of tested butanol was 99.9%, a little water of 1,871 ppm was acceptable. When butanol was blended with diesel fuel, water content would increase with concentration of butanol.

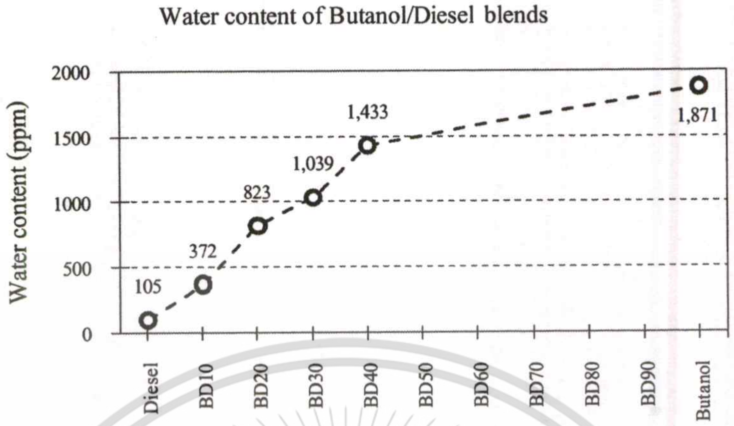


**Figure 4.6** Water content of BDs.

## 4.7 Copper Strip Corrosion

It is known that crude petroleum contains sulfur compounds, most of which are removed during refining. However, some sulfur compounds remaining in the petroleum product can cause a corroding action on various metals, and this corrosion is not necessarily related directly to the total sulfur content. The effect can vary according to the chemical types of sulfur compounds present (ASTM D130). Corrosion is the tendency of the fuel oil to reach with copper, brass, or bronze part of the fuel system. This specification does not indicate the corrosion of steel part of the engine. In this experiment, all of the test results by copper strip corrosion for BDs were exhibited in "1a" level as shown in Figure 4.7 being also within the standard range (Number 1a-1c). Hence, no corrosion was expected when BD10-BD40 were used in the diesel engine.

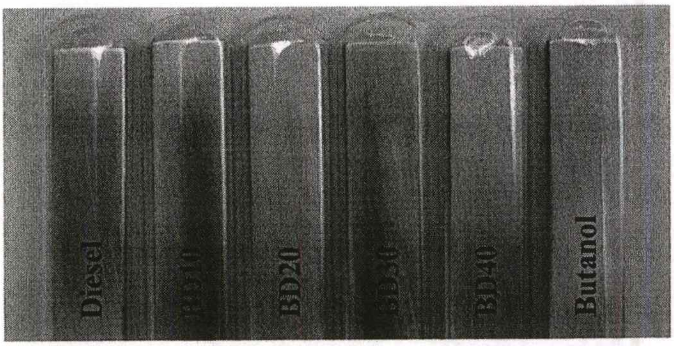


**Figure 4.7** Copper strip corrosion of BDs.

## 4.8 Flash Point

The flash point is one important parameter to measure the tendency of the tested sample to form a flammable mixture with air under controlled conditions. It is only one of a number of properties, which must be considered in assessing the overall flammability hazard of a material. Flash points are used in shipping and safety regulations to define flammable and combustible materials. Furthermore, results of these tests may be used as elements of a fire risk assessment, which takes into account all of the factors related to an assessment of the fire hazard of a particular end use (ASTM D93). Since flash point is a well-known problem for diesohol with ethanol. The test results of flash point property of BDs were shown in Figure 4.8 with after the rapid reduction in the first 5% blend (from 64 to 39°C). Above 4% butanol blend, the flash point values remained around 37-39°C. This phenomenon was appeared for all blends (4-40%) and pure butanol (100%). This could be implied that the drop of flash point value in the fuels was not depending on the amount of added butanol. Due to a reduction of flash point, butanol in fuel blends was vaporized earlier with increasing fuel temperature, and hence the fire flashing was observed during flash point testing.

Furthermore, another problem of BDs is safety issue because BDs have low flash point temperature close to environment temperature. Therefore, BDs need to handle the same category as gasoline for storage and transportation.

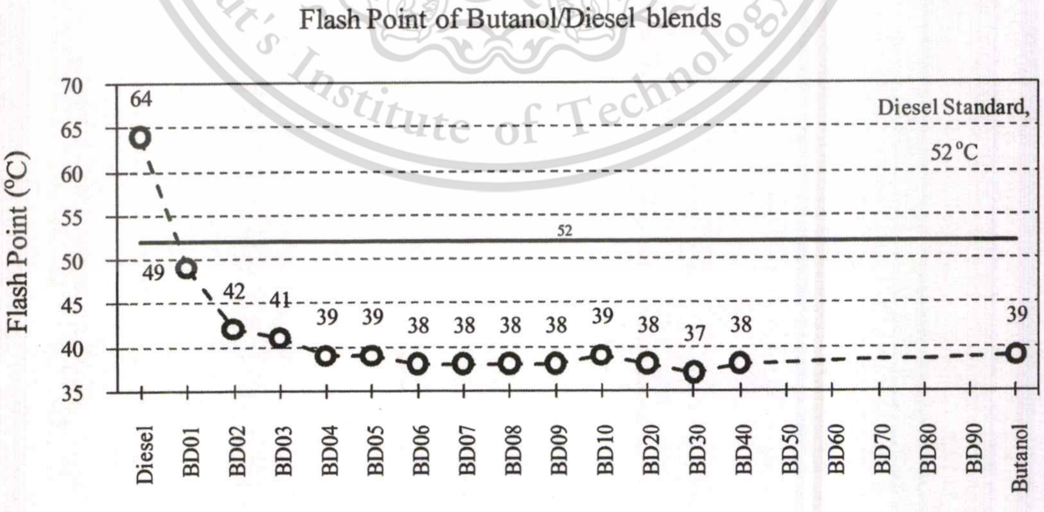
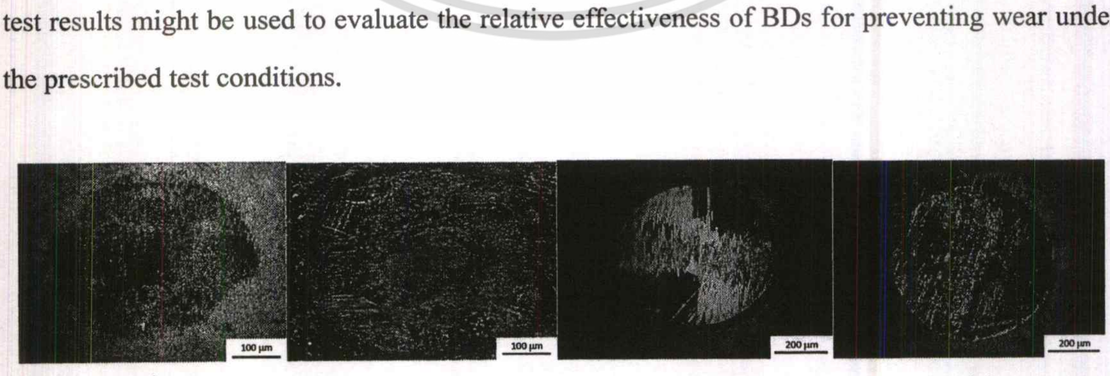


**Figure 4.8** Flash point of BDs.

## 4.9 Lubricity

Diesel fuel injection equipments have some reliance on lubricating properties of the diesel fuel, especially in common rail fuel system. Shortened life of engine components, such as diesel fuel injection pumps and injectors, has sometimes been ascribed to lack of lubricity in a diesel fuel (CEC F-06-A-96). Lubricity is also a problem of BDs. As well known, the high-pressure injection system is prone to wear and corrosion. Most diesel fuels are treated with multi-functional additive packages to improve lubricity and suppress corrosion, but on the other hand the lubricity of butanol is poor. All of the test results of lubricity show the immediate increase with BD40, outside the diesel standard level of 460 μm. The pure butanol shows the highest value on a wear scar (WS1.4) because butanol is an eminent solvent deteriorating the lubricity that it could be observed from the upper ball bearing. In Figure 4.9 (a) the ball bearing tested with BD10 reveals a little wear scare with horizontal diameter of 440 μm and vertical diameter of 350 μm on the surface, which yields WS1.4 of 370 μm. Figure 4.9 (b) shows the result of BD20 with a small wear scare, horizontal diameter of 490 μm and vertical diameter of 404 μm on the surface, and WS1.4 is calculated to be 427 μm. Figure 4.9 (c) shows the result of BD40 with a medium wear scare, horizontal diameter of 610 μm and vertical diameter of 560 μm on the surface, and WS1.4 is calculated to be 583 μm. Figure 4.9 (d) shows the result of pure butanol with a plainly large wear scare, horizontal diameter of 630 μm and vertical diameter of 640 μm in the surface, and WS1.4 is calculated to be 641 μm. Therefore, it could be implied that the higher butanol fraction was blended into diesel fuel, the less lubricity of BDs become. However, the results show that only BD10 and BD20 are acceptable because the wear scar value is not over the diesel standard value; while the BD40 and butanol are not acceptable, as shown in Figure 4.10. Furthermore, the test results might be used to evaluate the relative effectiveness of BDs for preventing wear under the prescribed test conditions.



(a) (b) (c) (d)

**Figure 4.9** Wear scar on upper ball bearing with (a) BD10, (b) BD20, (c) BD 40 and (d) butanol.

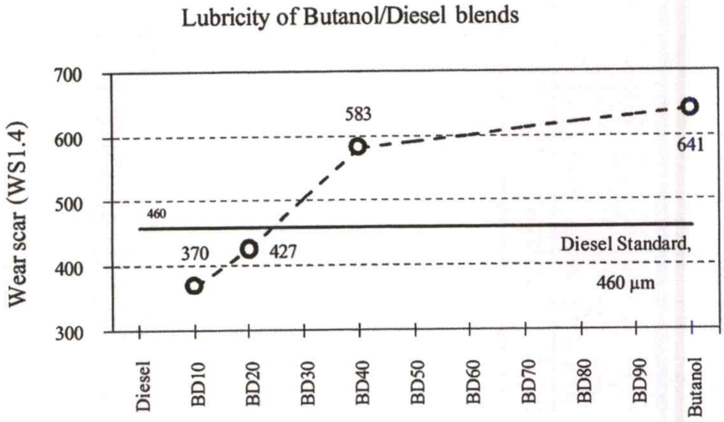


**Figure 4.10** Lubricity of BDs with wear scar 1.4 value.

## 4.10 Phase Stability

The purpose of this pre-test is to verify that butanol could be blended efficiently at a higher concentration in diesel fuel. This experiment is also prepared by blending various concentration of butanol into diesel fuel at room temperature (25°C) for storage up to six months. When butanol and diesel fuel are blended at the following specific ratio (5, 10, 15 …50%), butanol is quite able to dissolve into diesel fuel in a few second. The blending results of BDs demonstrate that blending high concentrations of butanol up to 50% in diesel result in homogenous mix with good stability without any emulsifier and additive, even after six months of storage in an indoor area, as shown in Figure 4.11.

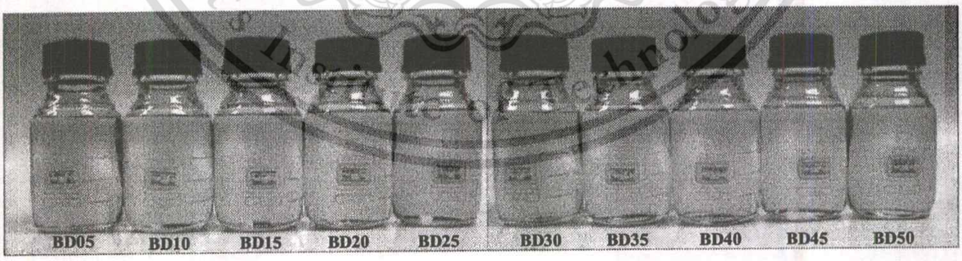


**Figure 4.11** Samples of BDs after six month.

# CHAPTER 5

# EFFECT ON ENGINE PERFORMANCE

This chapter is presented with the report on the results of testing BDs in common rail diesel engine in order to investigate the performance and emission. Similar to the chemical properties test, BDs are also prepared by blending various concentration of butanol into diesel fuel at a room temperature condition (25°C). The test results shown here aim to assess the limitation of using BDs in common rail diesel engine with no modification, especially for the adaptation capability of ECM. The test result of diesel fuel is referenced for comparison at the full and partial loads in terms of the following parameters.

- Toque and power of the engine
- Break specific fuel consumption
- A/F ratio and Lambda
- Emission such as $CO_2$, CO, $O_2$, $NO_x$ and THC
- Temperature of lubricant oil, manifold air (air inlet) and exhaust gas (air outlet).

The engine pre-test was conducted by using BD0 to BD50. The engine speeds were slowly changed by adjusting a paddle from idle speed to maximum speed (800-4,400 rpm.) without applied loads. At each testing speeds, the engine was held for a few second to check for any abnormal vibration and knocking. The test results at a low concentration of butanol did not show any abnormal behavior. On the other hand, the tested engine with a high concentration of butanol (more than BD40) indistinctly started to show a small amount of noises and vibrations. Please refer to the raw data of this experiment in the Appendix B and C.

## 5.1 Test Results at Full Load

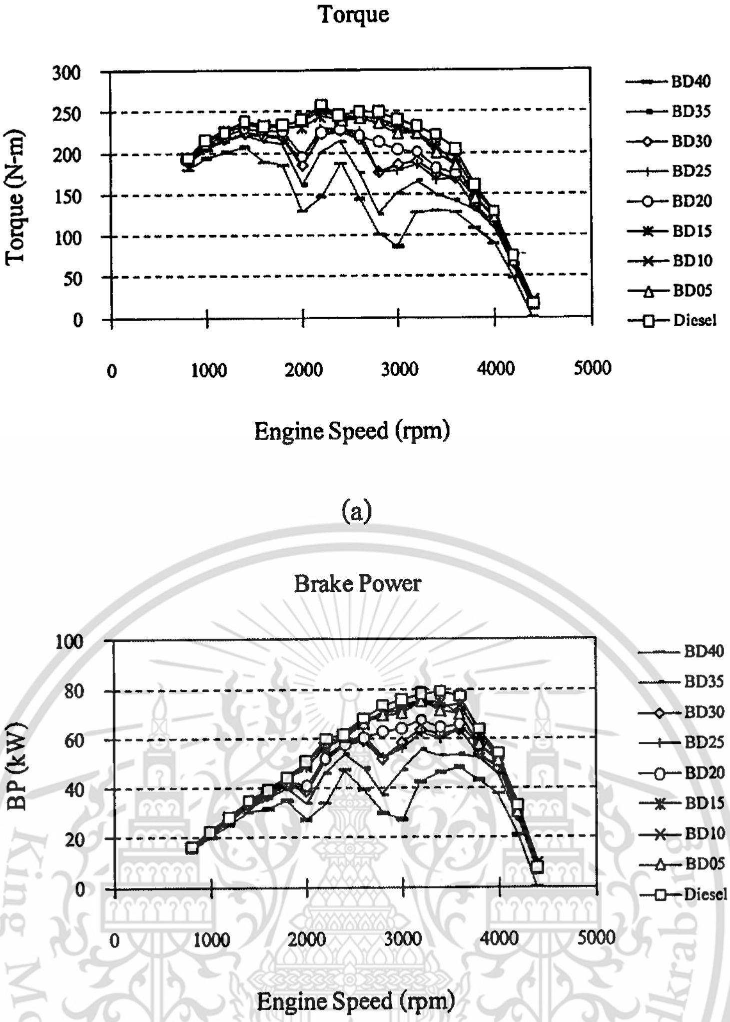
The test results at full load were conducted with BD0 to BD40 in order to determine how the tested engine operated. The turbo diesel engine with common rail system was tested and evaluated in term of engine performance and fuel consumption, temperature, and exhaust gas emission.

### 5.1.1 Engine Performance and Fuel Consumption

According to chemical test in chapter 4, both density and viscosity properties are affected by butanol blend, which will directly affect the atomization characteristic of the fuel droplet once injected into the cylinder (Tanabudipat, 2003). Also, injection timing of the butanol/diesel blend may be different from that of pure diesel due to the ECM algorithm and feedback control, especially at the high load condition. However, the current study is only focused on the adaptive capability of the unmodified ECM with the following results.

Figure 5.1 (a) and (b) shows the engine performance in terms of torque and break power for various blends of butanol/diesel. The torque and power of the engine are the highest when they are powered by diesel fuel as it contains the highest heating value comparing to other tested fuels as shown in Figure 4.4. It is clear that pure diesel curve yields the highest torque and power. It also shows that BD15 give the results close to commercial diesel fuel, due to the engine compatibility by OEM ECM. It is interesting to note that the engine performance is not much deteriorated for up .to 15% blend of butanol (BD15). This implies the adaptive capability of engine ECM to cope with butanol blend. However, for higher blends of BD20 up, the performance curves show some drop at 2,000 and 2,800 rpm, probably from the fact that ECM tries to adjust the engine operation. The engine performance is much inferior because of the onset breakdown of ECM control when BD25, BD30, BD35 and BD40 are applied. For this reason, those test results of higher blends exhibited abnormal behavior (Thongchai *et al*, 2009a,b).

In addition, butanol has a lower cetane number than diesel, especially in the neat butanol with cetane number 28, as shown in Figure 2.5. Cetane number leads to ignition delay and engine knocking problem. Pertaining to using higher concentration of butanol, ECM may tried to manage parameters to control the engine operation in suitable condition by receiving feedback signals from various sensors to calculate and compare with its information (data map, curve stored). If the input data (such as engine speed, air intake pressure and temperature, cooling water, fuel temperature and pressure, EGR, throttle and air flow rate) is not match with pre-stored memory, ECM may lead to make a mistake to predict the necessary injection timing and the quantity of fuel delivery, which would deteriorate the performance curve. For example, Figure 5.2 (a) shows injection quantity of BDs which is rerated to torque and brake power.



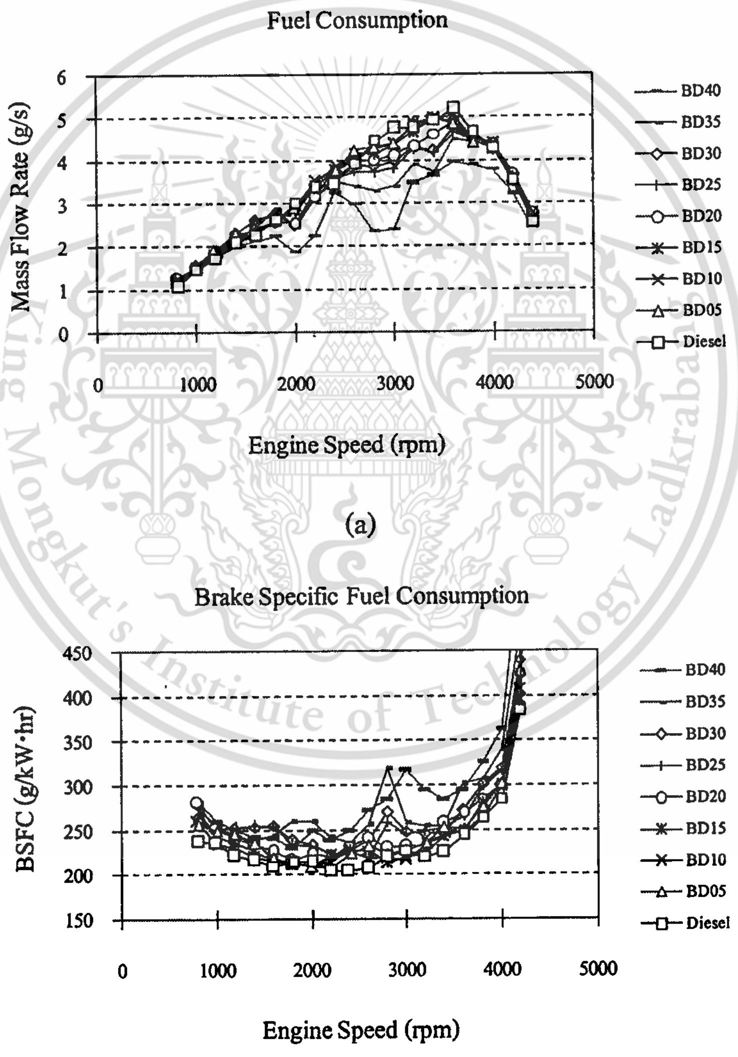
(a)

(b)

**Figure 5.1** Engine performance, (a) torque and (b) power, results at various butanol/diesel blends under full load condition.

The fuel consumption rates of all BDs under full load showed in Figure 5.2 (a). The fuel consumption rates are increased by applying maximum loads and increasing engine speed at the same time. The fuel consumption curves rise from 1,000 to 3,600 rpm and the maximum fuel consumption rate occurs around 3,600 rpm. After that, the fuel consumption curves would drop until 4,200 rpm. The fuel consumption curves of BD5-BD30 are similar to diesel curve but remaining lower value than diesel fuel; even though, the fuel consumption results of BD35 and BD40 shown the irregular curve and peak at 2,000 and 2,800 rpm, due to ECM adjustment.

The brake specific fuel consumption (BSFC) values are known as an indicator for engine fuel efficiency which is the fuel consumption rate per engine power. Figure 5.2 (b) shows the BFSC values under full load of BD05, BD10, BD15 and BD20 being insignificantly different from diesel fuel. Similar to the performance curve, BSFC behavior is not too much different from that of diesel for butanol blend up to 20% (BD20). The brake specific fuel consumption curves of BD25, BD30, BD35 and BD40 show the irregularly peak at 2,800 rpm, probably due to ECM adjustment. Related to the test results, BSFC rate is generally optimized in the range of 1,000 – 3,000 rpm for the appearance of butanol in fuels blend up to 20%.



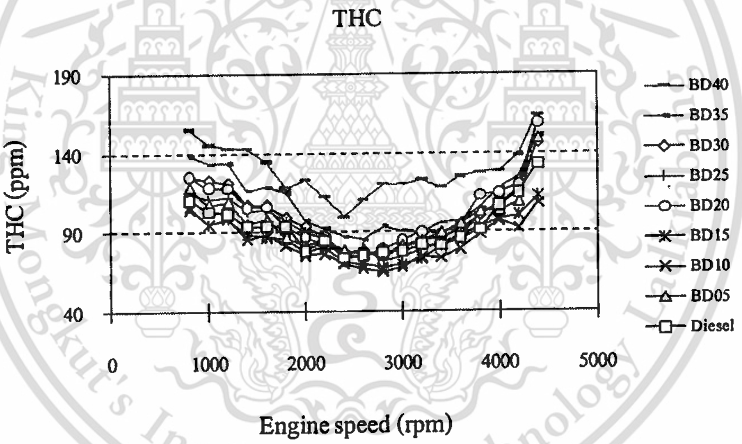
(a)

(b)

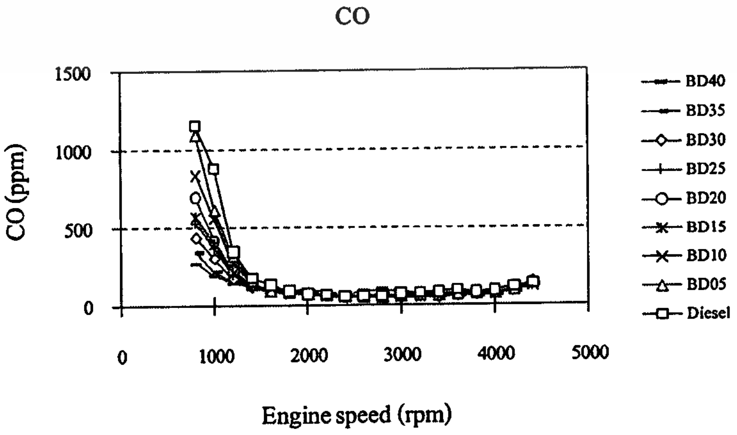
**Figure 5.2** (a) Fuel consumption and (b) brake specific fuel consumption under full load condition.

### 5.1.2 Emission

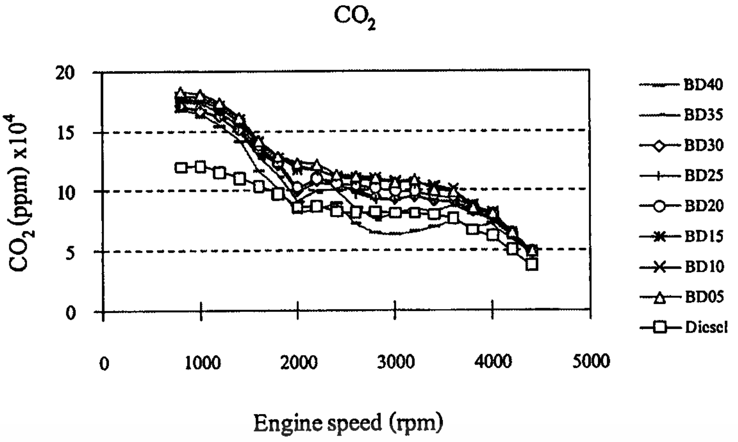
Emission results of THC, CO, $CO_2$, NO/$NO_x$ and $O_2$ at full load condition are shown in Figure 5.3 (a) – (e). For unburned hydrocarbon, Figure 5.3 (a) shows virtually no difference between BDs and diesel cases with the lowest value at the medium engine speed. Figure 5.3 (b) shows quite a complete combustion at engine speed of 1,600 rpm or greater with virtually no difference between BDs and diesel cases. However, at a low engine speed (<1,600 rpm), CO emission is quite high, and the effect of butanol (oxygen containing molecule) helps decrease CO level by promoting more complete combustion. Figure 5.3 (c) showing $CO_2$ further supports this explanation that butanol helps promote more complete combustion. For NO/$NO_x$ emission results shown in Figure 5.3 (d), ECM has shown good capability to control EGR valve such that NO/$NO_x$ trends decrease with increasing engine speeds for all butanol blending, despite some data scattering for engine speed lower than 2,200 rpm. Lastly, a low unused $O_2$ amount at a low engine speed, shown in Figure 5.3 (e), is consistent with high CO and $CO_2$ emission results, and vice versa.



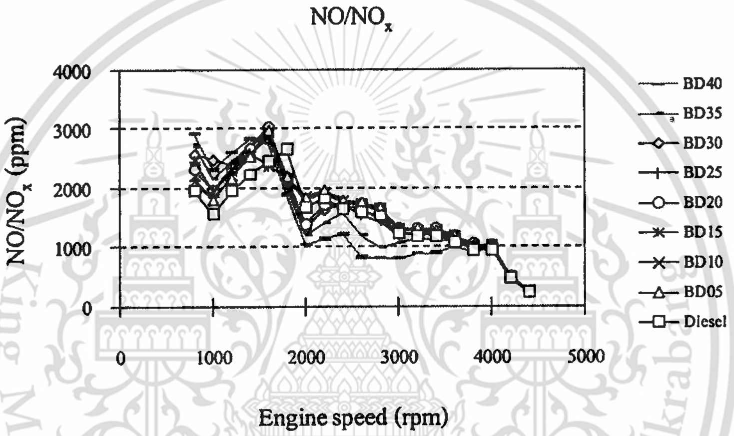
(a)



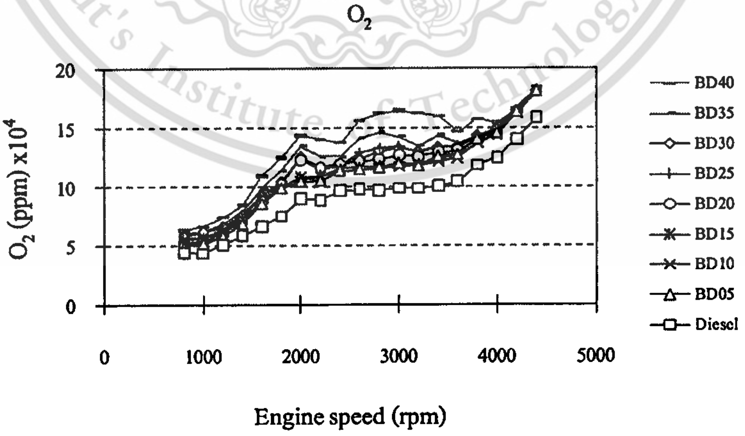
(b)



(c)



(d)

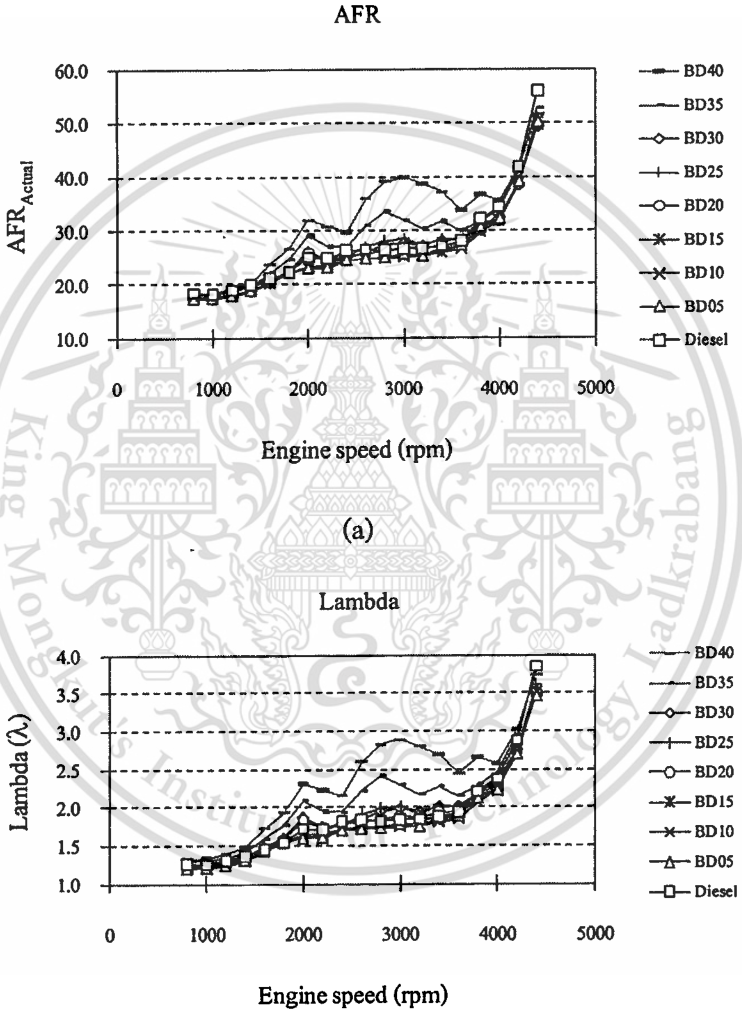


(e)

**Figure 5.3** Exhaust gas emission results of (a) THC, (b) CO, (c) CO$_2$, (d) NO/NO$_x$ and (e) O$_2$ at various butanol/diesel blends under full load condition.

### 5.1.3 Air/Fuel Ratio and Lambda

To explain relation between exhaust gas and air/fuel ratio (AFR), Spindt method is used because it is a method based on the ratios of select exhaust gas components which are carbon monoxide (CO), carbondioxide ($CO_2$), oxygen ($O_2$), and total hydrocarbons (THC), the fuel flow rate, and fuel characteristics (carbon and hydrogen fraction). Spindt observed that the majority of the unburned hydrocarbons are the result of unburned fuel rather than partially combusted, non-fuel hydrocarbons (Bresenham, 1998b).



(b)

**Figure 5.4** (a) Air/fuel ratio ($AFR_{actual}$) and (b) lambda ($\lambda = AFR_{Actual}/AFR_{Stoichiometric}$) of various butanol/diesel blends under full load condition.

The adaptive capability of ECM is further shown in Figure 5.4 (a) for air/fuel ratio and Figure 5.4 (b) for lambda value, which Spindt formula is used to calculate BDs (Bresenham, 1998b and Pulkrabek, 1997). It is clear that AFR and lambda show insignificantly different results between BDs and diesel fuel (for BD05-BD30) except BD35 and BD40 because ECM tries to decrease amount of fuel injection but the access air still remained in order to find suitable operating condition to increase the engine power, as shown in Figure 5.2 (a). The AFR and lambda results indicated that the emission of THC trended to be stable and $NO_x$ also trended to reduce when they are increased values (Schafer and Basshuyscn, 1995), as shown in Figure 5.3 (a) and (d). In addition, Figure 5.4 (a) and (b) shows the calculating results of Spindt method at full load. When the engine speed is increased, AFR and lambda values are slowly increased from 800 to 3,600 rpm, and then rapidly increased between 3,600 and 4,400 rpm.

### 5.1.4 Temperature of Engine Operation

Further investigations into temperatures of lubricant oil, exhaust gas and air inlet (after EGR: exhaust gas recirculation) are shown in Figure 5.5 (a), (b) and (c), respectively.

Figure 5.5 (a) shows a lower lubricant oil temperature for all butanol/diesel curves at all engine speeds because butanol, which can easily vaporize at a lower temperature than diesel, has absorbed some heat in the engine via latent heat of vaporization. In other words, the engine is cooler by the presence of butanol blending. However, Figure 5.5 (b) shows that exhaust gas from butanol/diesel blends is hotter. This can be explained by recourse to pressure data in Wattanavichien's research, which clearly shows the ignition retardation with higher heat released for 10% ethanol-blended diesel. Since butanol has higher density and higher heating value than ethanol (Chotwichien, 2007), the interpretation by Wattanavichien research of BD blends would lead to the shorter ignition retardation and even higher heat released. Altogether, exhaust gas temperature of BD blends is higher than that of diesel, especially at a low engine speed, where enough time is allowed for combustion. However, this explanation is purely based on the mechanic response to butanol blending without knowledge of response from ECM. With regard to air inlet temperature shown in Figure 5.5 (c), the behavior is quite subtle since ECM would expect air inlet of butanol/diesel cases to be cooler by adjustment of the exhaust gas taking from EGR. This rather similar air inlet temperature at low engine speed (up to 2,000 rpm) and hotter air inlet at high engine speed (above 2,000 rpm) for butanol/diesel cases can only be explained by the ECM control of EGR valve to adjust how much exhaust gas is allowed back into inlet manifold. Potentially, ECM could try to adjust lower exhaust gas temperature of diesel by increasing exhaust gas volume. Further investigation into ECM signals is required to support this explanation.

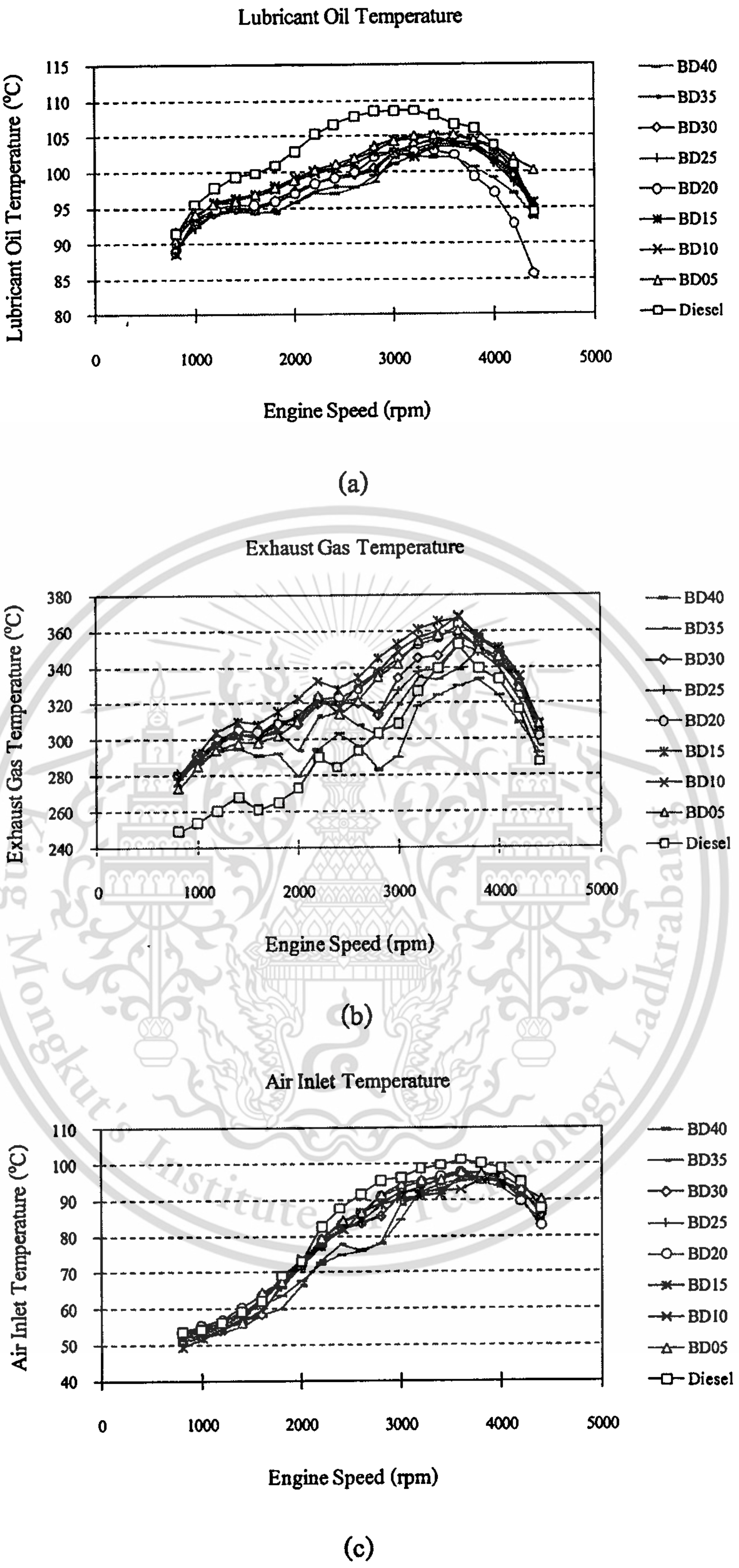


**Figure 5.5** Temperatures of (a) lubricant oil, (b) exhaust gas and (c) air inlet at various butanol/diesel blends under full load condition.

## 5.2 Test Results at Partial Load

The test results of partial load are conducted for BD0 to BD40 to assess normalized engine operation efficiency at 50, 100, and 150 N•m, which is selected from engine performance come with diesel at full load.

### 5.2.1 Fuel Consumption

The fuel consumption results of BDs are compared with diesel fuel in the partial load as shown in Figure 5.6 (a), (b) and (c). The fuel consumption results are found that the BDs results are slightly increased throughout the tested speed (1,000-3,500 rpm) in each of the loads. The fuel consumption rates of BDs are not different from diesel fuel at 50, 100, and 150 N•m that they were average 6, 4 and 10%, respectively. It could be explained that BDs are tested on the same load as diesel fuel and BDs have lower heating value than diesel as shown in the Figure 4.4. The fuel consumption results of diesel and BDs at the partial load trend to increase fuel consumption rate slightly throughout the test speed when it is compared with each of the tested loads (50, 100, and 150 N•m)

Figure 5.7 (a), (b) and (c) show the brake specific fuel consumption results at 50, 100 and 150 N•m torque loads in the unit of g/kW•hr. For each case, diesel case still yields the lowest brake specific fuel consumption. At the lowest load, 50 N•m, brake specific fuel consumption increases with an increasing engine speed while the higher butanol blended curves show cup-like behavior. This cup-like behavior is diminished with increasing load to 100 and 150 N•m. At a given load condition, the effect of BDs on the brake specific fuel consumption is not significantly different from diesel fuel at all speeds. All of the brake specific fuel consumption results of BDs are a little bit higher than diesel fuel. The average brake specific fuel consumptions of all BDs throughout the engine speed at 50, 100 and 150 N•m are 6.1, 4.1 and 10.0%, respectively. It may be implied that the heating value of BDs is not significant different from diesel fuel, as showed in Figure 4.4. Furthermore, at the medium load (100 N•m), the brake specific fuel consumption results are reduced up to 22% and 33% for the high load (150 N•m).

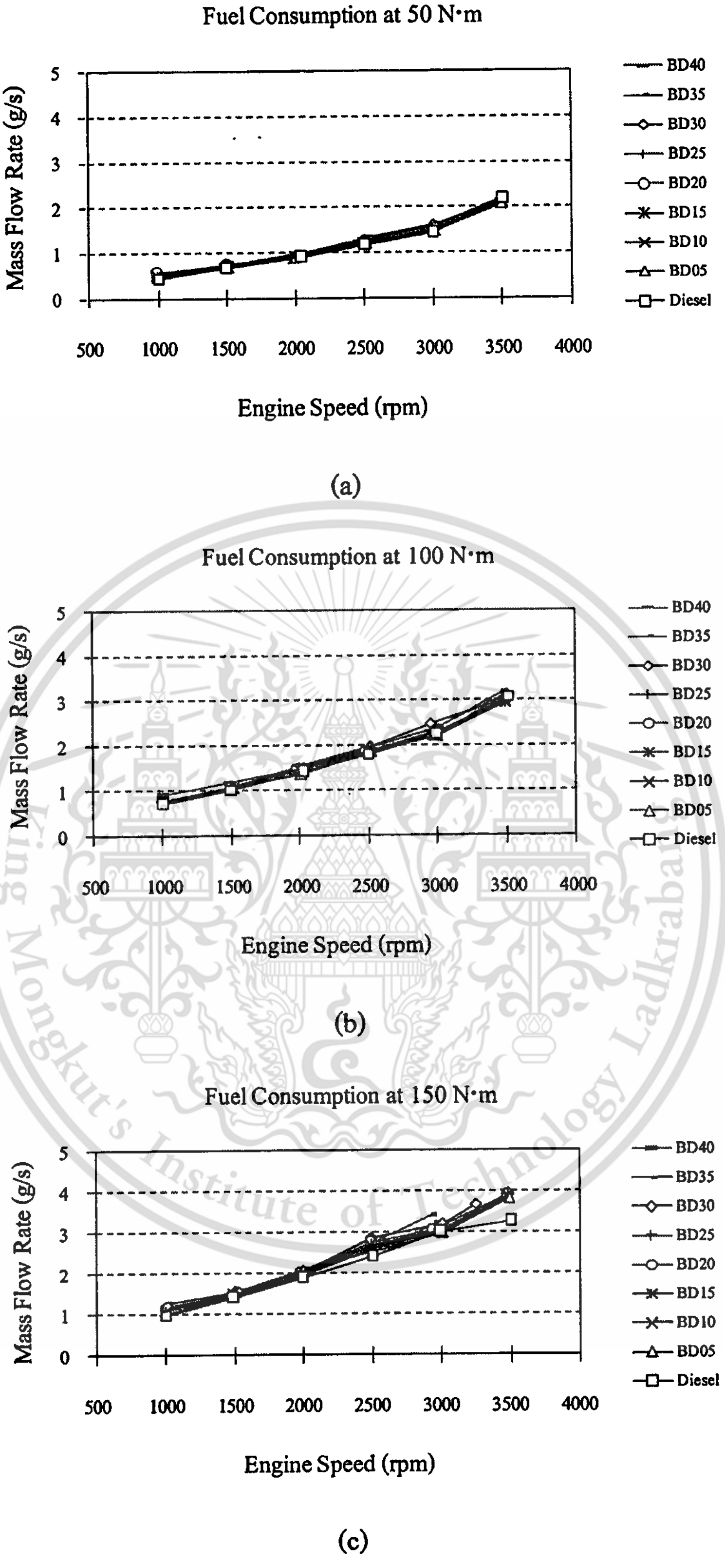
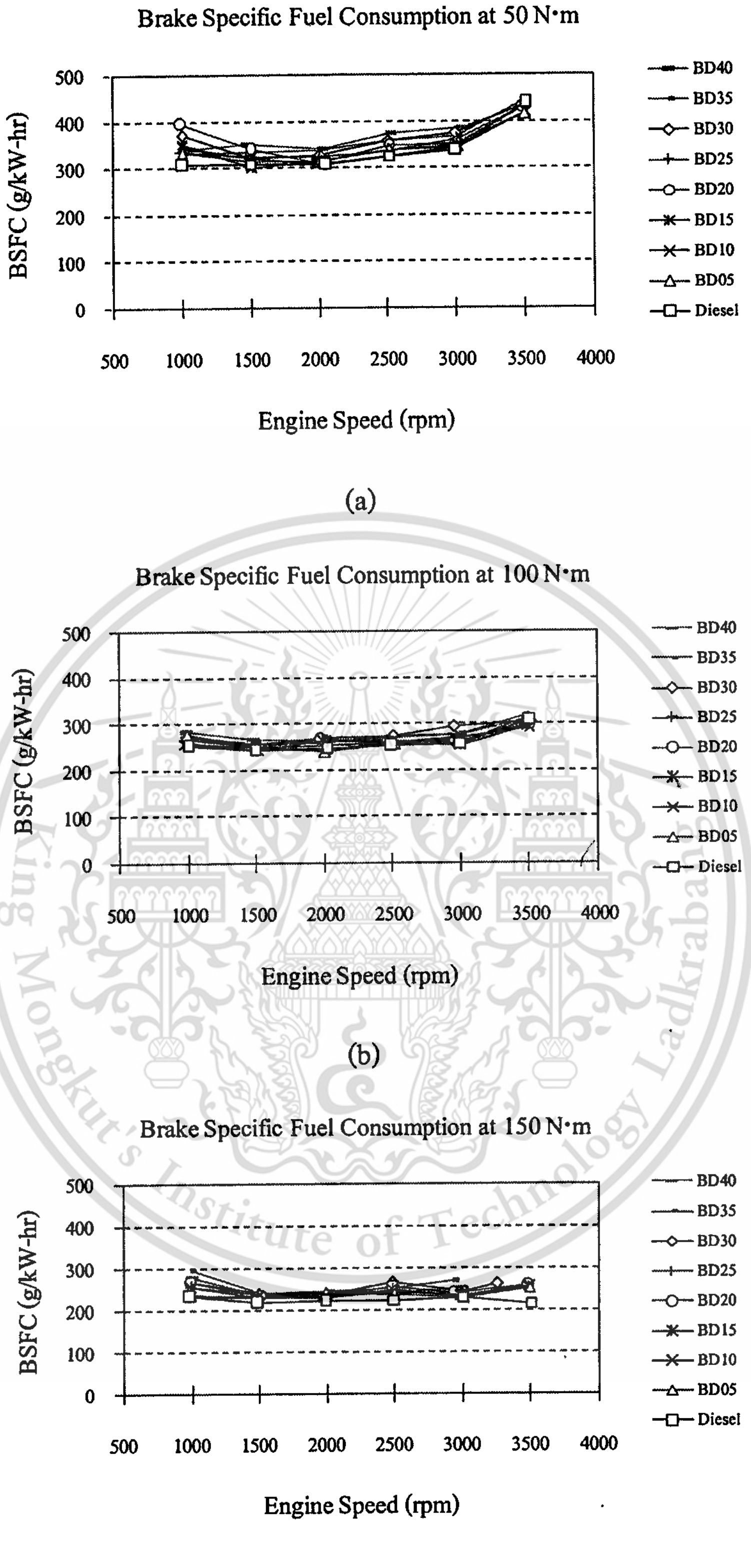


**Figure 5.6** Fuel consumption under partial loads at (a) 50 N•m, (b) 100 N•m and (c) 150 N•m for various butanol/diesel blends.



(a)

(b)

(c)

**Figure 5.7** Brake specific fuel consumption (BSFC) under partial loads at (a) 50 N•m, (b) 100 N•m and (c) 150 N•m for various butanol/diesel blends.

### 5.2.2 Emission

The amount of emissions produced from fuel combustion at the partial loads is compared between BDs and diesel fuel. These emissions are illustrated as the following

The emission results of THC emission at the partial load condition show unburned hydrocarbon in Figure 5.8 (a), (b) and (c). Almost all of test results of BDs produced THC emission are similar to the diesel fuel at the medium – high load conditions. Unlikely, THC emission produced at the low load condition which BD30, BD35 and BD40 are not similar to the diesel fuel at each of the engine speeds.

From Figure 5.8 (a) is compared to the amount of THC emission caused by the burning of BDs and Diesel fuel at 50 N·m is found that when the engine speed increased, the amount of THC emission is increased up until 2,000 -2,500 rpm and then falling down to 3,500 rpm quickly, and the test results of BDs increased higher concentration of butanol produce the amount of THC emission less than diesel fuel (averagely 12.8%) except BD35 and BD40. It could be explained that the amount THC emission could derive from two primary reasons; one is the fuel escaping from the main combustion in a diesel engine which is over-mixed and over-lean regions (λ) formed before ignition as show in the Figure 5.14 (a), and the other one is the under-mixed fuel injected at low velocity near the end of combustion. These emission test result are correspond with fuel consumption, lambda and air inlet temperature, which are according to ECM adjusting the optimum engine operation as shown in Figure 5.6 (a), 5.14 (a) and 5.17 (a) respectively.

Figure 5.8 (b) – (c) were showing of more complete combustions that the test results of the torque load at 100 and 150 N·m bring about a little amount of THC emission value between 1,000 – 3,500 rpm, which is lower than the results diesel fuel at 0.4% averagely. It is explanatory that ECM could optimize the engine operations in these loads. It is agreed with fuel consumption, lambda and air inlet temperature, which is due to ECM adjusting the optimum engine operation as shown in Figure 5.6 (b) and (c), 5.14 (b) and (c), and 5.17 (b) and (c). In addition, the test results show THC emission trending to decrease when comparing with each of the tested loads.

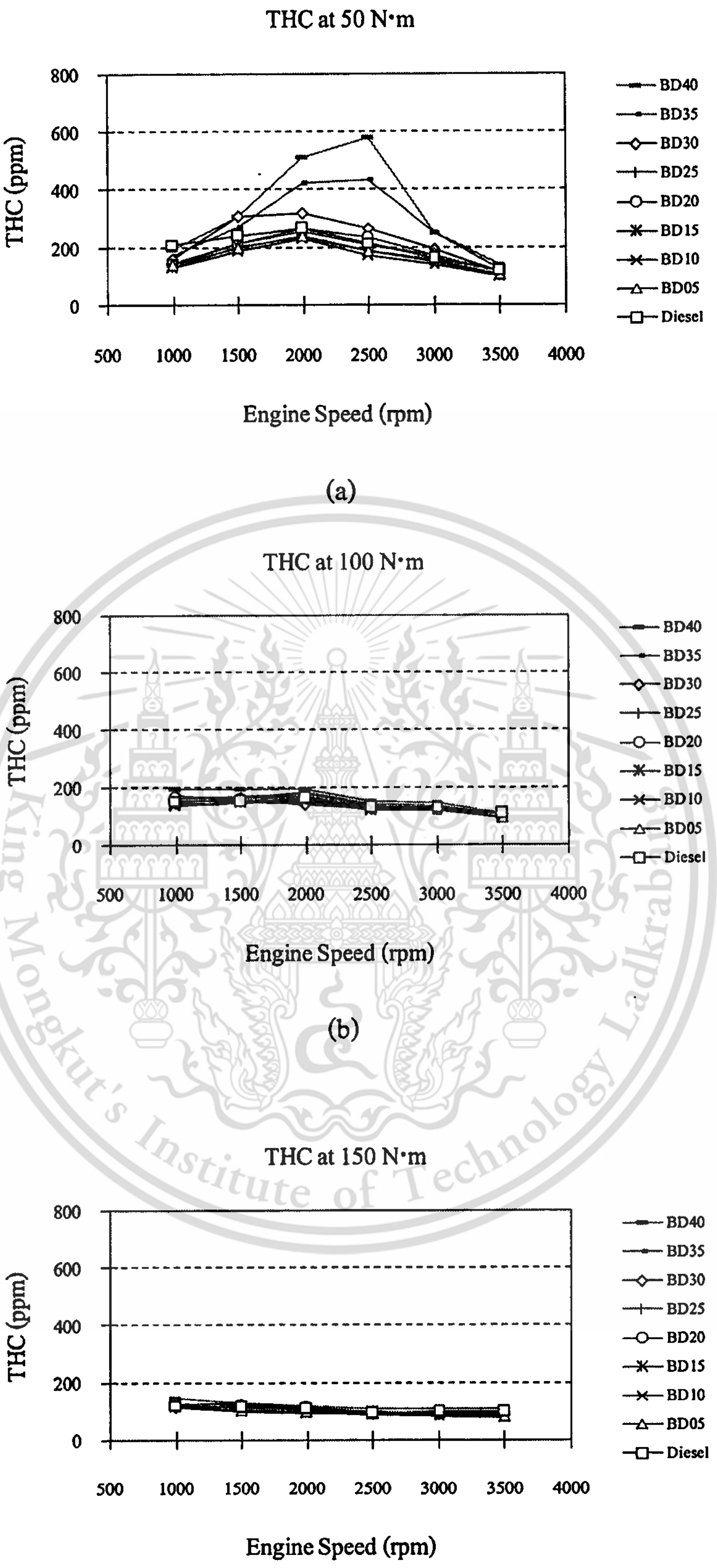


**Figure 5.8** Exhaust gas emission (THC) under partial loads at (a) 50 N•m, (b) 100 N•m and (c) 150 N•m for various butanol/diesel blends.

Figure 5.9 (a), (b) and (c) show the results of CO emission at the partial load condition. Almost of all the test results of BDs produce CO emission which is similar to the diesel fuel at the medium – high load conditions. Improbably, CO emission produced at the low load condition is not similarly to the diesel fuel at each of the engine speeds.

Figure 5.9 (a), The torque load at 50 N•m indicates that when the engine speed is increased, the amount of CO emission is also increased until 2,000 rpm and then decreased down to 3,500 rpm rapidly, and the test results of BDs cause the amount of CO emission which is higher than diesel fuel, especially BD30, BD35 and BD40. It could be explained that carbon elements of butanol and diesel are not interacted with oxygen completely due to ECM adjusting lambda (λ) during combustion on account of to the temperature of combustion of butanol which is lower than diesel fuel, and ECM tried to optimize for the best engine operation in this load. Therefore the carbon is still much remaining in CO emission. It implies that the more incomplete combustion, the more carbon remaining in CO emission. This result is consistent with fuel consumption, lambda, and air inlet temperature, which is due to ECM adjusting the optimum engine operation as shown in Figure 5.6 (a), 5.14 (a) and 5.17 (a) respectively.

Figure 5.9 (b) and (c) show more complete combustions that the test results of the torque load at 100 and 150 N•m cause a little amount of CO emission value between 1,000 – 3,500 rpm and the test results of BDs are similar to the test result of diesel fuel with a bit lower values averagely 5.9% than diesel fuel. It is explanatory that butanol (higher oxygen molecule content) in diesel fuel could improve the combustion by reducing CO emission and ECM could optimize the engine operations in these loads. It is agreeable with fuel consumption, lambda and air inlet temperature, which is due to ECM adjusting the optimum engine operation as shown in Figure 5.6 (b) and (c), 5.14 (b) and (c), and 5.17 (b) and (c). Furthermore, Figure 5.9 (a), (b) and (c) are still future supported the complete combustion behavior when using the BD fuel. In addition, the test results show CO emission trending to decrease when comparing with each of the tested loads.

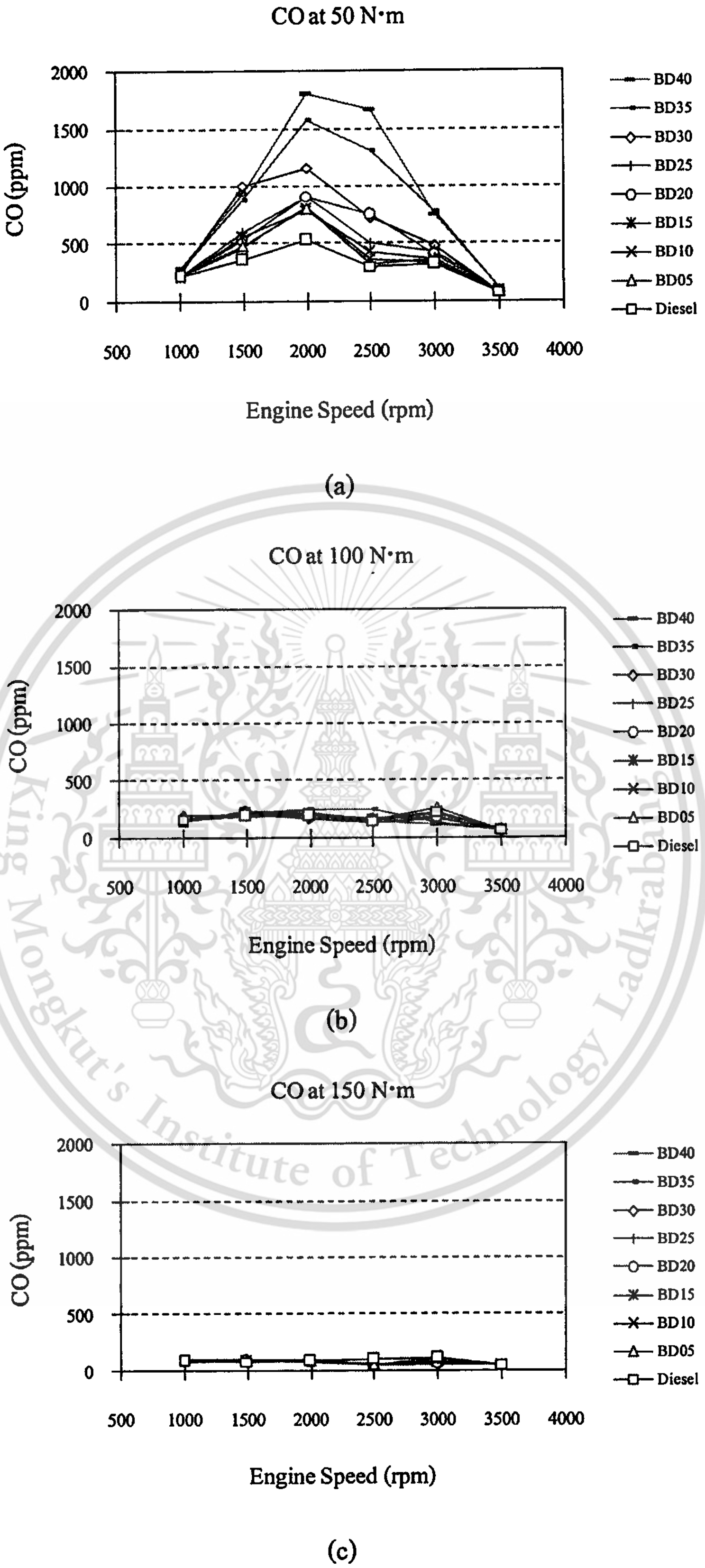
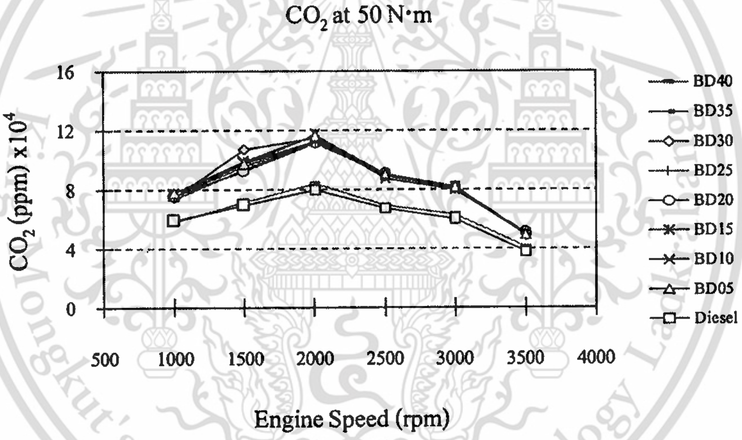


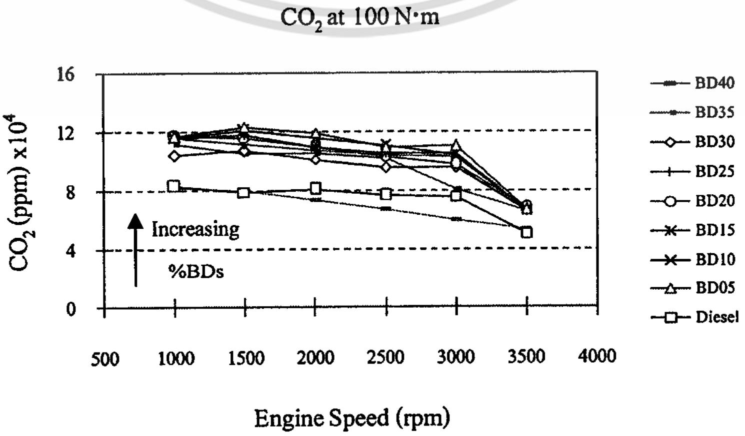
**Figure 5.9** Exhaust gas emission (CO) under partial loads at (a) 50 N·m, (b) 100 N·m and (c) 150 N·m for various butanol/diesel blends.

The emission results of $CO_2$ emission at the partial load condition show the test results in Figure 5.10 (a), (b) and (c). Almost of all the BDs results produced $CO_2$ emission higher than diesel fuel in each of the load conditions.

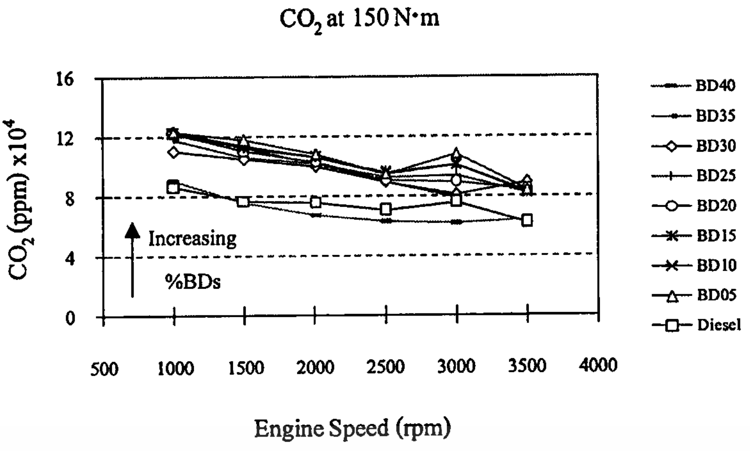
Figure 5.10 (a) show the amount of $CO_2$ emission by the burning of BDs and Diesel fuel at 50 N•m. From these results, it is found that when the engine speed is increased, the amount of $CO_2$ emission is also increased up until 2,000 rpm which is the highest complete combustion and then decrease falls down to 3,500 rpm rapidly. Figure 5.10 (b) and (c) tested at 100 and 150 N•m show the test results of $CO_2$ that slowly decreased between 1,000 to 3,500 rpm. The results of BDs at 50, 100 and 150 N•m produced the amount of $CO_2$ emission more than diesel fuel at the average of 34.8, 36.0 and 34.6%, respectively, except BD40. It could be implied that the more the amount of butanol added, the more oxygen elements increased.



(a)



(b)



(c)

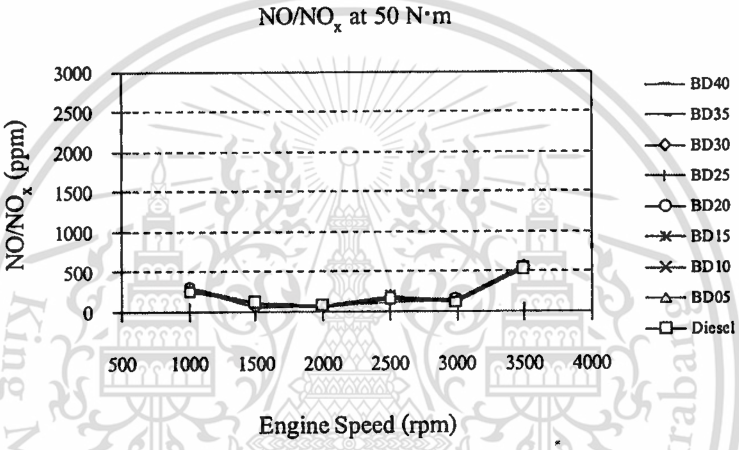
**Figure 5.10** Exhaust gas emission (CO$_2$) under partial loads at (a) 50 N•m, (b) 100 N•m and (c) 150 N•m for various butanol/diesel blends.

For this reason, the carbon and oxygen had more opportunity to achieve the complete reaction in the combustion chamber to become CO$_2$ emission which the value is higher than diesel fuel. Furthermore, CO$_2$ has an effect on CO by reducing the amount of CO in the same time as mentioned in chemical balance, as supporting by the test results of CO in Figure 5.9 (b) and (c). In addition, the test results show CO$_2$ emission trending to slightly decrease when comparing with each of the tested loads.

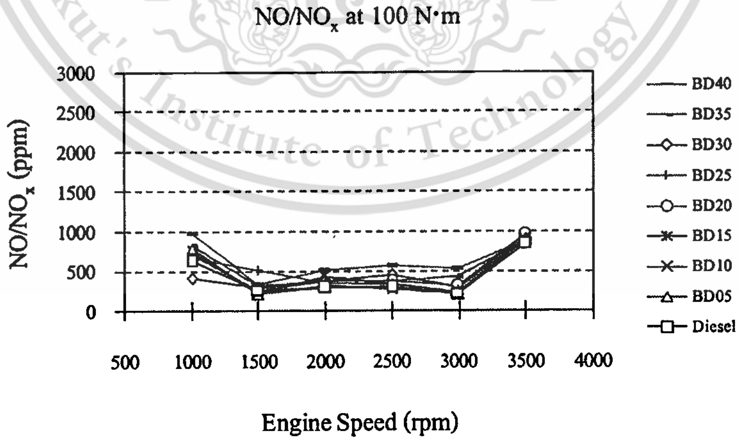
Figure 5.11 (a), (b) and (c) show the emission results of NO/NO$_x$ emission at the partial load condition. Almost of all the BDs results produced higher NO/NO$_x$ emission than diesel fuel in each of the load conditions.

From Figure 5.11 (a) shows the amount of NO/NO$_x$ emission by the burning of BDs and Diesel fuel at 50 N•m. These test results indicate that when the engine speed is increased, the amount of NO/NO$_x$ emission is decreased from 1,000 to 2,000 rpm and then increased from 2,000 to 3,500 rpm slowly. Figure 5.11 (b) shows the test results at 100 N•m. When the engine speed is increased, the amount of NO/NO$_x$ emission is decreased until 1,500 rpm and then kept stable values from 2,500 to 3,000 rpm. After that, it is increased until 3,500 rpm. For Figure 5.11 (c), it shows the results at high load (150 N•m) which lead to a high combustion temperature. It is continuously decreased from 1,000 to 3,000 rpm and slightly increased a little bit after 3,000 rpm.

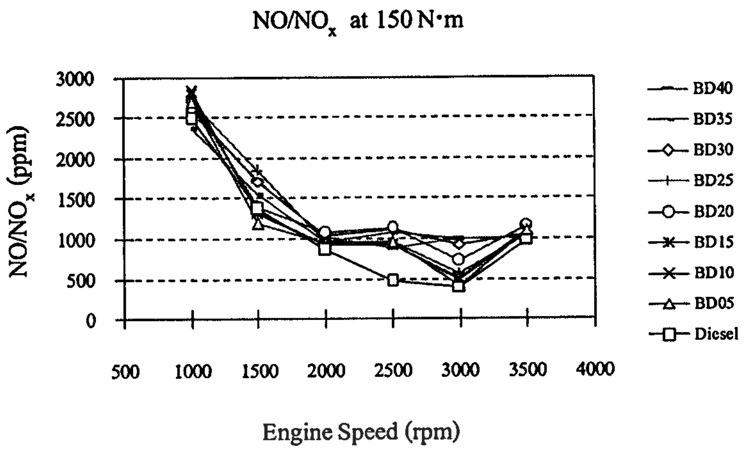
All of the results of BDs at 50, 100 and150 N•m are similar to the result of diesel fuel with a bit higher values than diesel fuel by averagely of 1.7, 22.7 and 39.2%, respectively. It could be implied that the more amounts of butanol added, the more oxygen elements increased. Therefore, in the combustion chamber, if the oxygen highly exists, it will lead to the extremely complete combustion and get a higher temperature. For this reason, nitrogen and oxygen have more opportunity to form NO/NO$_x$ emission, because temperature of combustion affect on amount of NO/NO$_x$, as supporting by the test results of exhaust gas temperature, as shown in Figure 5.16 (a), (b) and (c). In addition, the test results show NO/NO$_x$ emission trending to slightly increase in the low-medium loads but NO/NO$_x$ emission the high loads is quickly increased more than in the low-medium load, especially in the low engine speed at 1,000-2,000 rpm.



(a)



(b)



(c)

**Figure 5.11** Exhaust gas emission (NO/NO$_x$) under partial loads at (a) 50 N•m, (b) 100 N•m and (c) 150 N•m for various butanol/diesel blends.

The test results of $O_2$ emission at the partial load condition show in Figure 5.12 (a), (b) and (c). Almost of all the BDs results produce $O_2$ emission higher than diesel fuel in each of the partial load conditions.

From Figure 5.12 (a) shows the amount of $O_2$ emission by the burning of BDs and Diesel fuel at 50 N•m. These test results are found when the engine speed is increased, the amount of $O_2$ emission are slightly decreased from 1,000 to 2,000 rpm after that steeply increased until 3,500 rpm. Figure 5.12 (b) and (c) show the test results of $O_2$ at 100 and 150 N•m, which are slowly increased from 1,000 to 3,500 rpm. The results of BDs at 50, 100 and 150 N•m produce the amount of $O_2$ emission higher than diesel fuel averagely by 12.0, 15.4 and 16.2%, respectively. It can be explained that increasing amount of $O_2$ emission with the result of BDs due to butanol has the oxygen component, as shown in the chemical formula in chapter 2. Therefore, oxygen of butanol is incorporated with oxygen from the air environment in order to be used in combustion. Thus, the more percentage butanol increased, the more oxygen molecule occurred. For this reason, the amount of $O_2$ from the exhaust gas emission of BDs is higher than diesel fuel. In addition, the results of $O_2$ emission trend to slowly increase when comparing with each of the test loads.

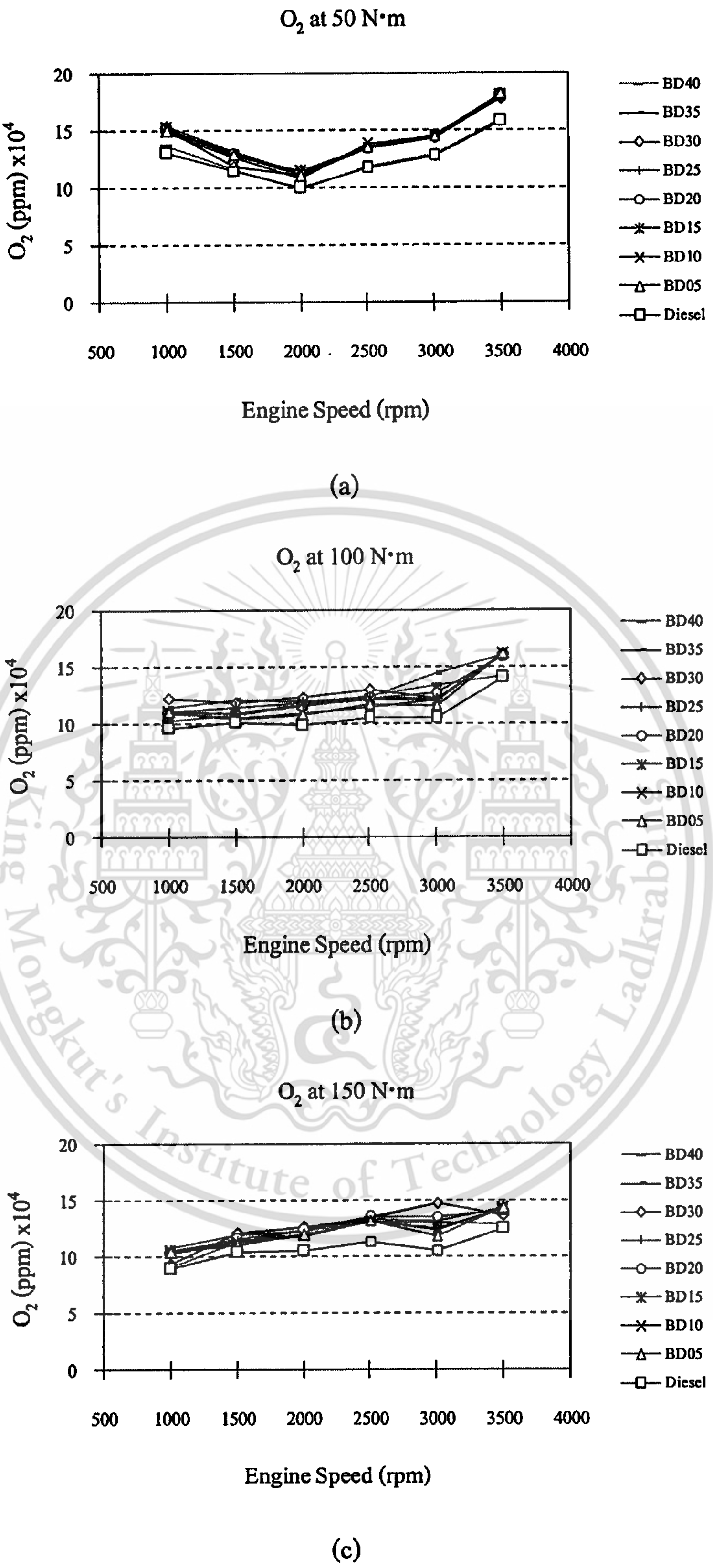
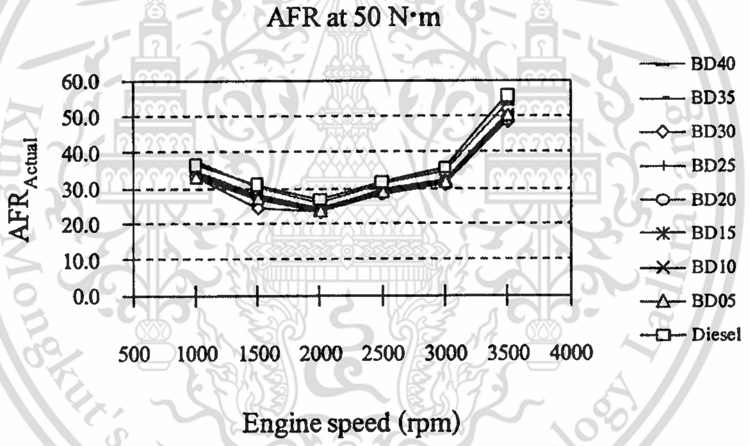


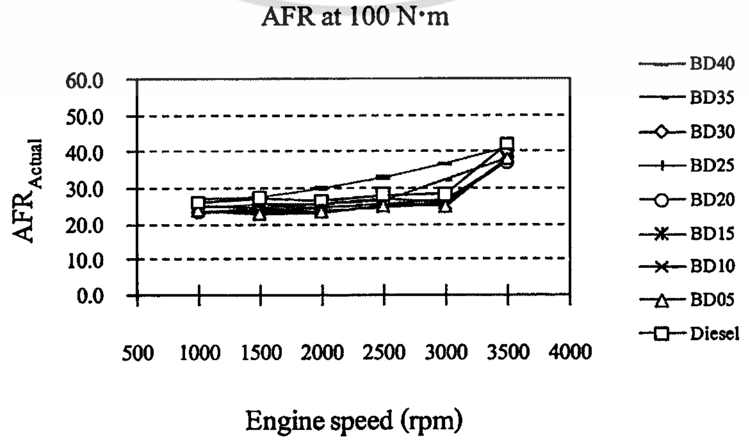
**Figure 5.12** Exhaust gas emission ($O_2$) under partial loads at (a) 50 N·m, (b) 100 N·m and (c) 150 N·m for various butanol/diesel blends.

### 5.2.3 Air/Fuel Ratio and Lambda

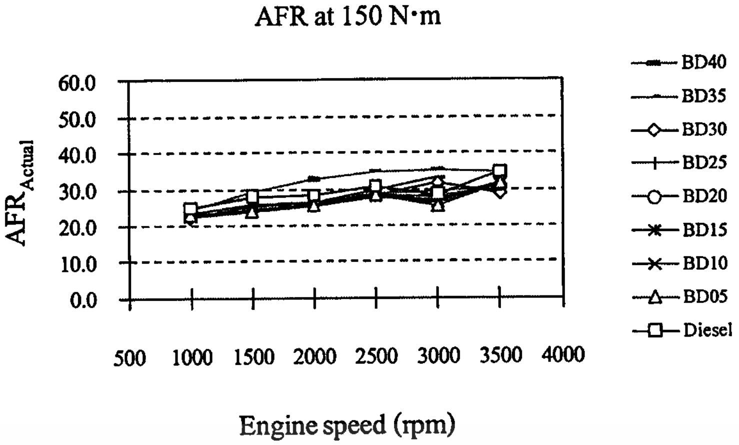
The Spindt formula is also used for calculating AFR and lambda values for BDs at the partial loads. Figure 5.13 (a) and 5.14 (a), AFR and lambda results with the test load at 50 N•m show that if the engine speed is increased, AFR and lambda is also tended to increase the value at each of the speeds. Almost of all the AFRs of BDs are lower than the AFR of diesel fuel because BDs contain oxygen and need a less amount of air to burn. It is consistent with AFR from the theoretical calculations that show more butanol having the lower oxygen. At higher partial load of 100 and 150 N•m, as shown in Figure 5.13 (b) and (c) and 5.14 (b) and (c), the test results are similar to AFR and lambda at 50 N•m which speed up the engine then AFR and lambda increase at each speed. It is found that AFR and lambda of DBs are lower than AFR of diesel fuel averagely.



(a)



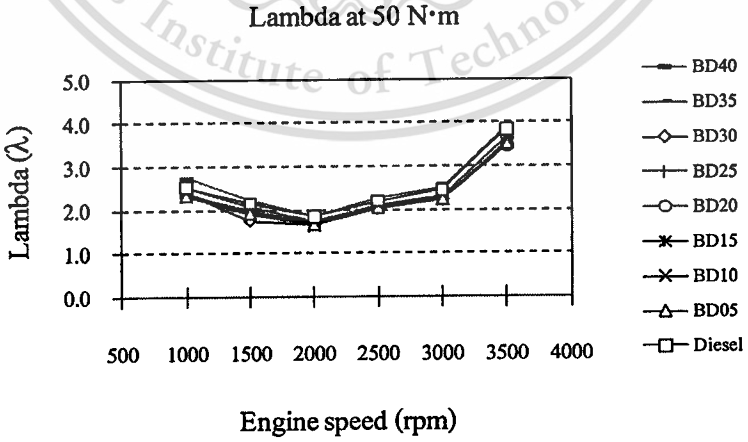
(b)



(c)

**Figure 5.13** Air/fuel ratio ($AFR_{actual}$) under partial loads at (a) 50 N•m, (b) 100 N•m and (c) 150 N•m for various butanol/diesel blends.

In addition, AFR and lambda results of BDs show a little bit different from the diesel fuel results. Although, BD30 and BD40 show irregular AFR and lambda values because ECM tried to adjust the amount of access air into a combustion chamber to optimize the engine operation. Furthermore, AFR and lambda values are slightly reduced in each of the torque loads (50, 100 and 150 N•m). However, ECM is able to maintain all of the AFR and lambda values which are higher than stoichiometric values (13.8-14.5 $kg_a/kg_f$).



(a)

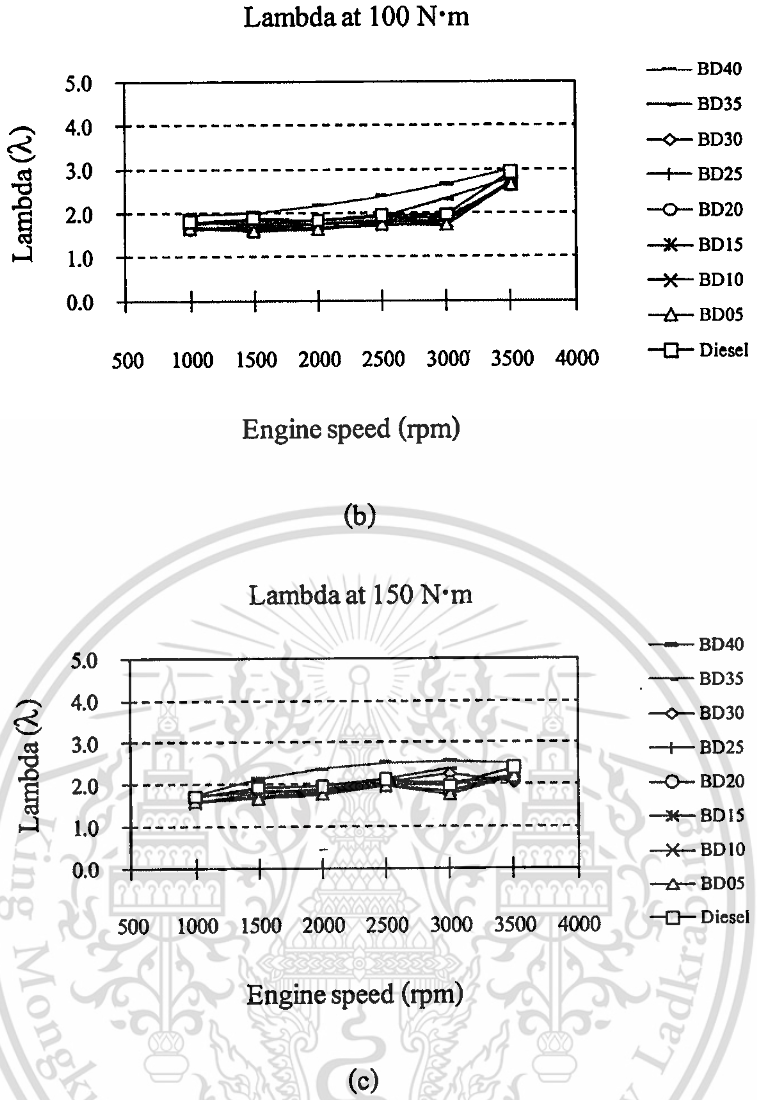


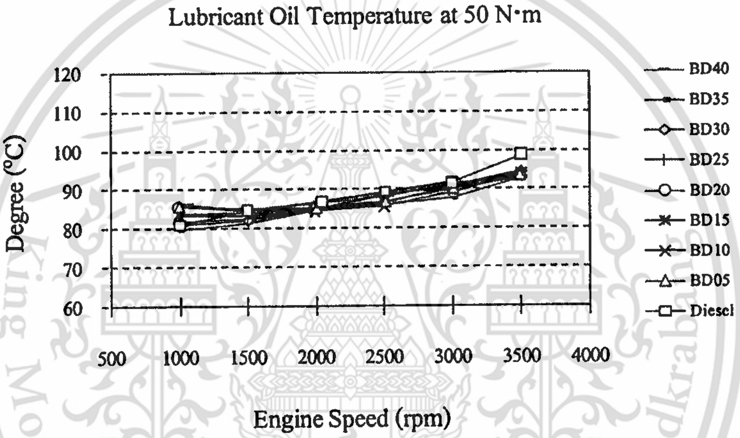
**Figure 5.14** Lambda ($\lambda = AFR_{Actual}/AFR_{Stoichiometric}$) under partial loads at (a) 50 N•m, (b) 100 N•m and (c) 150 N•m for various butanol/diesel blends.

### 5.2.4 Temperature of Engine Operation

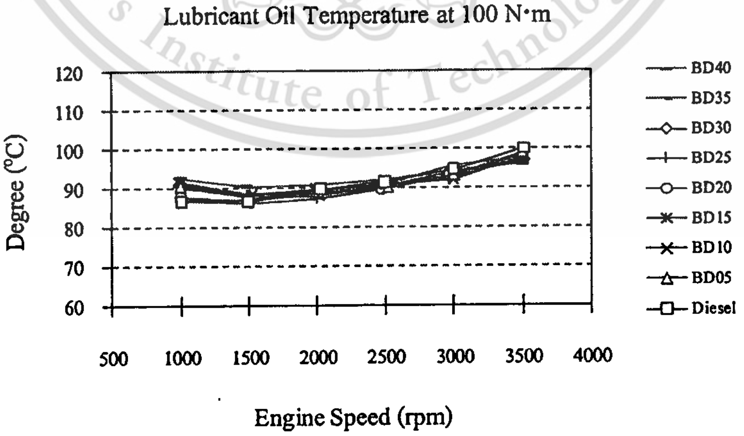
The temperatures of lubricant oil, exhaust gas and air inlet (after EGR: exhaust gas recirculation) show the partial load conditions in Figure 5.15, 5.16 and 5.17 respectively. These temperatures are illustrated as follow.

Form Figure 5.15 (a), (b) and (c), the lubricant oil temperature results of BDs are compared with diesel fuel in the partial load at 50, 100, and 150 N•m. The results show that the lubricant oil temperature is slightly increased throughout the test speed. The results of BDs are close to the results of diesel fuel. It can be explained that those results are similar to the results of lubricant oil temperature at full load. Butanol, which can be easily vaporized at lower temperature than diesel, has absorbed some heat in the engine via latent heat of vaporization. In other words, the engine is cooler by the presence of butanol blending. Another reason, the heating value and the heat release rate of diesel fuel are higher than BDs. Therefore, the heat energy of diesel fuel is conducted to lubricant oil more than BDs (Wattanavichien, 2004). However, the lubricant oil temperature results are insignificantly different between diesel and butanol, averagely by 2%.

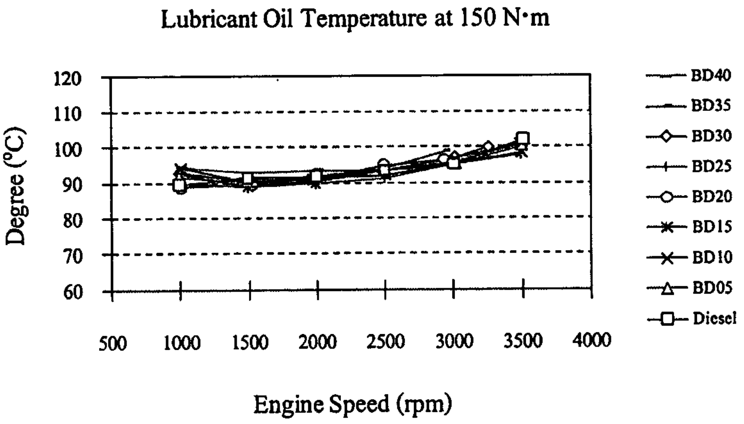
In additional, Form Figure 5.15 (a), (b) and (c), the lubricant oil temperature results at the partial load trend to slightly increase temperature throughout the test speed. When it is compared with each of the test loads at 50, 100 and 150 N·m and almost of the BDs results are a little bit lower than the diesel fuel result.



(a)



(b)

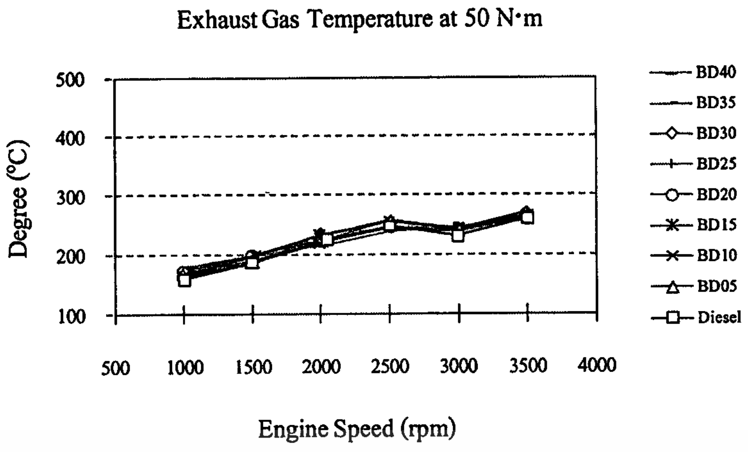


(c)

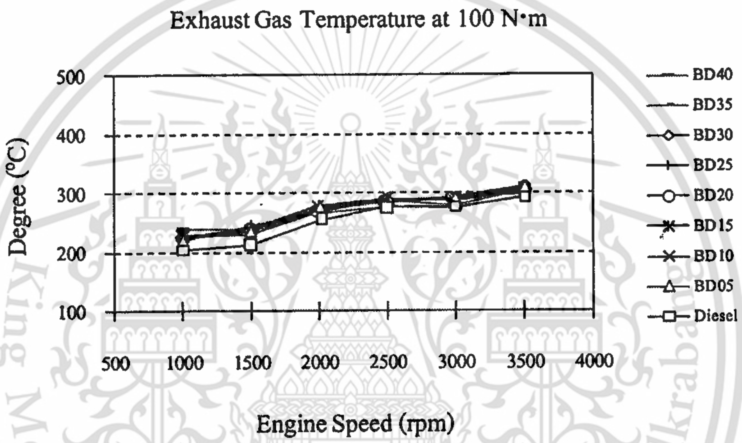
**Figure 5.15** Lubricant oil temperature results under partial loads at (a) 50 N•m, (b) 100 N•m and (c) 150 N•m for various butanol/diesel blends.

The test results of exhaust gas temperature at the partial load condition show in Figure 5.16 (a), (b) and (c). Almost of all the test results of exhaust gas temperatures are lower than diesel fuel in each of the partial load conditions.

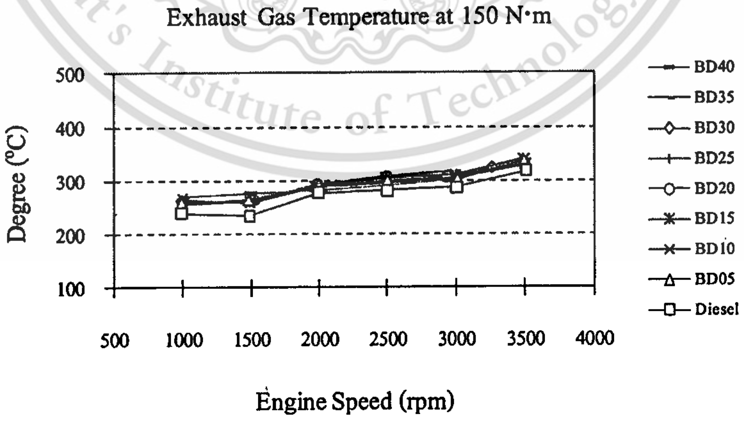
Figure 5.16 (a), (b) and (c) were showed the BDs results of exhaust gas temperature comparing with diesel fuel at 50, 100, and 150 N•m. The lubricant oil temperature results show that when the engine speed increased, the exhaust gas temperature is slightly increased throughout the test speed. All of the BDs results are similar to the test result of diesel fuel. The exhaust gas temperature values of BDs at 50, 100 and 150 N•m is a bit higher than diesel fuel averagely at 3.2, 6.7 and 7.6, respectively. It can be explained that BDs have lower cetane number than diesel fuel, which have affected on a long ignition delay and even higher heat energy. Therefore, the combustion of BDs is longer than diesel and increases the exhaust gas temperature. In addition, the exhaust gas temperature results show trend to slightly increase when comparing with each of the tested loads.



(a)



(b)

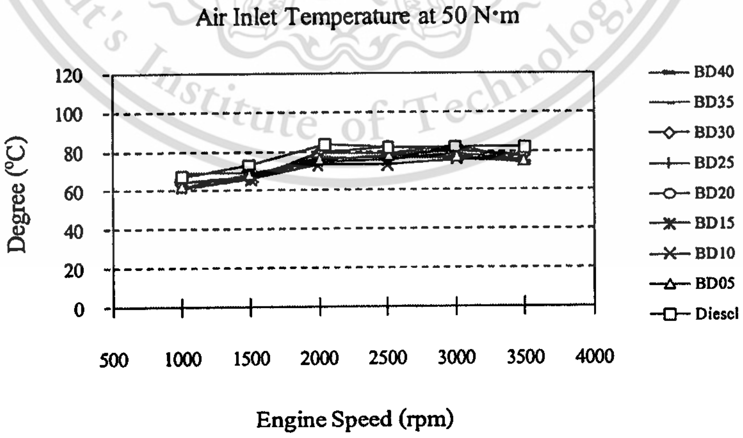


(c)

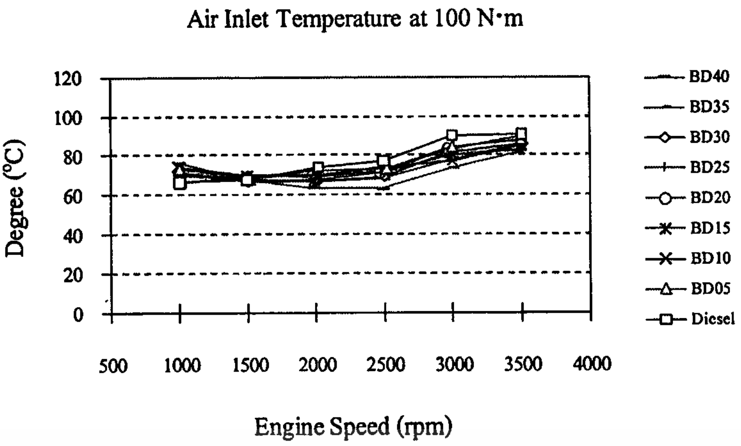
**Figure 5.16** Exhaust gas temperature results under partial loads at (a) 50 N•m, (b) 100 N•m and (c) 150 N•m for various butanol/diesel blends.

The test results of air inlet temperature at the partial load condition are shown Figure 5.17 (a), (b) and (c). Almost of all the test results of air inlet temperatures are lower than diesel fuel in each of the load conditions.

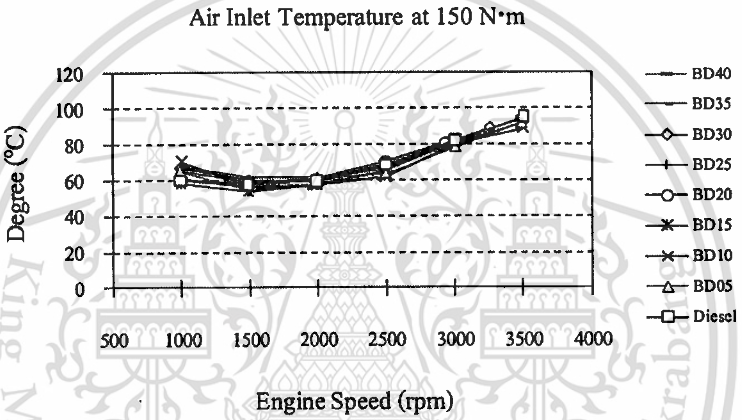
From Figure 5.17 (a), it shows the air inlet temperature results between BDs and Diesel fuel at 50 N•m. These test results are found when the engine speed is increased, air inlet temperature is slightly increased from 1,000 to 2,000 rpm and then its value is steady from 2,000 and 3,500 rpm. Figure 5.17 (b) and (c) show the test results at 100 and 150 N•m. When the engine speed is increased, air inlet temperature is slowly increased from 1,000 to 2,000 rpm, and then slightly increased between 2,300 and 3,500 rpm. Almost of all the BDs results at 50, 100 and 150 N•m are similar to the diesel fuel result with a little lower value than diesel fuel averagely by 6.2, 3.8 and 0.8%, respectively. It could be explained that the test results of air inlet temperature at full load test that ECM control of EGR valve to adjust how much exhaust gas is allowed back into inlet manifold. Potentially, ECM could try to adjust lower exhaust gas temperature of diesel by increasing EGR rate. Another reason, due to the lubricant oil temperature results using BDs are lower engine temperature than diesel as shown in Figure 5.15. Therefore, it could make air surrounding temperature lower temperature than diesel before drawing into air manifold. In addition, the test results show air inlet temperature trending to increase slightly when comparing each of the partial loads.



(a)



(b)



(c)

**Figure 5.17** Air inlet temperature results under partial loads at (a) 50 N•m, (b) 100 N•m and (c) 150 N•m for various butanol/diesel blends.

# CHAPTER 6

# CONCLUSIONS AND SUGGESTIONS

The present study has focused on testing of BDs for using in common rail diesel engine to access the limitations of this engine type. The following conclusions and suggestions have drawn.

## 6.1 Conclusions

1) From the results of BDs physical/chemical properties, there are many interesting points as follow.

- Form the BDs properties of density, carbon residue, ash content and copper strip corrosion, those test results are very similar to and insignificantly different from the test results of diesel fuel when BDs have more concentrations of butanol into diesel fuel.
- The heating values of BDs are less slightly than the heating values of diesel fuel by approximately 3-10%. Moreover, the heating values of BDs at the higher percentage of butanol are better than the heating values of ethanol/diesel blends with emulsifier (Cheenkachorn *et al.*, 2008).
- The viscosity of the BDs significantly drops with addition of 10% butanol or BD10, which could affect on the fuel spray pattern and the atomization capability.
- The flash points of BDs are close to neat butanol. Therefore, it can easily ignite when temperature is higher than 37-39 °C.
- Higher blend of butanol than 20% may jeopardize lubricity property beyond the standard limit.

2) The effects of BDs tested under the full and the partial loads in common rail diesel engine. There are rigorously evaluated and engine compatibilities in terms of engine performance, fuel consumption and emission gas, in comparison to those of diesel results. Important findings are as follow.

(a) At full load condition:

- Effect of butanol blending decreases engine operating temperature via latent heat of vaporization. However, butanol/diesel blends increases the exhaust gas temperature, especially at low-medium engine speeds.

- The Common rail Diesel engine with unmodified ECM can maintain the desired lambda value on butanol blending up to 30%

- Unmodified common rail diesel engine can be fueled with BDs of between 5-20% without any significant drops in engine performance and fuel consumption.

- The oxygen content in butanol molecule can enhance the complete combustion, resulting in lower CO and higher $CO_2$.

- Effect of butanol blending can decrease THC, CO and $NO_x$ emission by using the concentration of butanol up to 20% without dropping engine performance.

(b) At partial load condition:

- Effect of butanol blending on the fuel consumption is slightly different between diesel and BDs, which is not greater than 10%.

- Effect of butanol blending on the operation temperature of common rail diesel engine is quite adjacent to using diesel fuel with each parameter.

- Air/fuel ratio and lambda of BDs are also slightly different between diesel and BDs, which is not more than 10% for air/fuel ratio and 7.5% for lambda value.

- Exhaust emission results of BDs are quite good, which are exhibited complete combustion when it is compared with diesel fuel. Even though, it is found irregularly curves due to the low efficiency of engine at 50 N•m.

For the physical/chemical reasons, BDs could be blended to use up to 10% because all of the BD10 results are ranged in the diesel standard (may include cetane number, Leelanoi 2007) except flash point that is out of diesel standard range. Therefore, it needs to carefully handle and store DBs like gasoline because it has lower flash point when add a few butanol (37-39°C). However, this property does not affect on the engine performance as shown in the engine section. Using BDs higher than 10%, it is necessary to improve some chemical properties such as flash point, lubricity and cetane number.

For the engine performance/emission test, it can be concluded that BDs up to 20% is able to use instead of the diesel fuel in a common rail diesel engine without any additives and emulsifiers because these test results show the engine performance which the quality is close to the neat diesel fuel. For exhaust gas emission, BD05-BD20 results show that the common rail diesel engine have more complete combustions with better results of THC, CO, $CO_2$ and $O_2$, whereas NO/$NO_x$ results are a little bit higher than diesel result. However, using BDs higher than 20%, it may lead to deteriorate the engine performance.

## 6.2 Suggestions

Although this work is finished, it is only the first step towards to use butanol/diesel blended in common rail diesel engine. In order to promote the use of butanol/diesel blended fuel in diesel engines, there are some suggestions that the following opinions have been provided the further work to study as follow:

- According to chemical/physical property test in chapter 4, the results of butanol/diesels blend, which are flash point, heating value and lubricity, show inferior quality. These properties should be improved by developing new formula with additives such as biodiesel for using at high concentration of butanol.

- Liquid n-butanol is common with most organic solvents alcohol having effect like ethanol that fuel blended butanol should be studied corrosion effect on non-metal and metal parts within fuel systems in long term (Naeqeli *et al*, 1997).

- The engine durability test should be studied for long a running operation on the actual load cycle in order to investigate wear and tear in moving parts, especially in the combustion chamber.

# REFERENCES

[1] Al-Hasan, I.M.,and Al-Momany, M., **"The Effect of Iso-butanol-Diesel Blends on Engine Performance,"** Dept of Mechanical Engineering, Al-Balqa' Applied University, TRANSPORT, October 2008.

[2] **Annual Book of ASTM Standard**, section five, petroleum product, lubricant, and fossil fuels, volume 05.01, 05.02, 50.03, ASTM International, West Conshohocken, PA 19428-2959., 2005.

[3] Annual Book of CFC Standard, **CEC F-06-96 issue 3.2**, Measurement of Diesel Fuel Lubricity (HFRR fuel lubricity tester), Coordinating European Council, UK, September 2007 (www.cectests.org).

[4] Braess, H-H., and Seiffent, U., **Handbook of Automotive Engineering**, Warrendale, Pa., SAE International, 2005.

[5] Bresenham, D., **"Assessment of proposed Spindt method expansions for use with highly oxygenated fuels in small utility engine emissions testing applications,"** M.S. Thesis, College of Engineering and Applied Science, University of Wisconsin-Milwaukee, 1998a.

[6] Bresenham, D., Reisel, J., and Neusen, K., **"Spindt Air-Fuel Ratio Method Generalization for Oxygenated Fuels,"** The University of Wisconsin-Milwaukee, Center for Alternative Fuels, SAE TECHNICAL PAPER SERIES, 982054, 1998b.

[7] Bosch, R., **Diesel-engine management**, Stuttgart, Germany; Warrendale, PA : SAE Society of Automotive Engineers, 1999.

[8] Cengel, A., Y. and Boles A., M., **Thermo dynamics**, Second Edition (International Edition), McGraw-Hill, Inc., 1994.

[9] Challen, B. and Baranescu, r., **Diesel engine reference book**, 2nd ed., Oxford, Butterworth-Heinemann, 1999.

## REFERENCES (CONT.)

[10] Chollacoop, N. *et al.*, **"Research and Development Project on Bio-Ethanol Fuels for Diesel Vehicles in Thailand,"** 2nd Biomass Asia Workshop, Bangkok, December 13-15, 2005.

[11] Chotwichien, A., Luengnaruemitchai, A., Jai-In, S., **"Utilization of Palm Oil Alkyl Esters as an Additive in Diesel-Ethanol and Diesel-Butanol Blends,"** 3rd Energy Technology Network of Thailand (ENETT 2550), Bangkok, Thailand, May 23-25, 2007.

[12] Department of Alternative Energy Development and Efficiency (DEDE), **Gasohol National Policy**, 2 September 2003 (www.dede.go.th).

[13] Department of Energy Business (DOEB), **Diesel Specification** (http://elaw.doeb.go.th), 2008.

[14] French, R., Malone, P., **Phase equilibrium of ethanol fuel blends**, Fluid Phase Equilibria 228–229, 2005.

[15] Fuels and Lubricants Test Equipment, **HFRR Installation and Preparation Manual,** PCS Instruments, London, UK.

[16] Heisler, H.,**Vehicle and Engine Technology**, Edward Arnold, London, 1999.

[17] Heywood, J. B., **Internal Combustion Engine Fundamentals**, McGraw-Hill, Inc., 1988.

[18] Jurgen, K., R., **Automotive Electronics Handbook**, Second Edition, ISBN 0-07-034453-1, McGraw-Hill, Inc., 1999.

[19] Leelanoi, P., **"The Performance Study of a Diesel Engine Using Buthanol Base Diesohol Fuel,"** Master thesis, M.Eng. (Mechanical En-gineering), Graduate School, Srinakharinwirot University, Thailand, May, 2007.

[20] Lenz, T.0. and Morelra, A.R., **"Economic Evaluation of the Acetone-Butanol Fermentation,"** Ind. Eng. Chem. Prod. Res. Dev. 1980, 19, 478-483.

[21] Merck, **Handbook of Environmental Fate and Exposure Data for Organic Chemicals,** Volume II. Lewis Publishers. Chelsea, Michigan, 1990.

# REFERENCES (CONT.)

[22] Ministry of Energy, **Statistic Data**, available online, Thailand, 2009. (www.energy.go.th)

[23] Nylund, N., *et al*, **“Alcohols/Ethers as Oxygenates in Diesel Fuel: Properties of Blended Fuel of and Evaluation of Practical Experiences IEA Advanced motor Fuel,”** Annex XXVI, Final Report, TEC TransEnergy Consulting Ltd, Finland, 2005.

[24] Pulkrabek, W.W., **Engineering Fundamen-tals of the Internal Combustion**, International Edition, Prentice-Hall International, INC, 1997.

[25] Schafer, F. and Basshuyscn, R., V., **Reduced Emission and Fuel Consumption in Automobile** Engine, Wien , Springer-Verlag, New York, 1995.

[26] **SIDS Initial Assessment Report for SIAM 13**, UNEP PUBLICATIONS, Bern, Switzerland, November, 2001.

[27] Smith, J., L. and Workman J., P., **Alcohol for Motor Fuels**, FARM & RANCH SERIES, Colorado State University, Cooperative Extension, Reviewed 12/2004.

[28] Spindt, R. S., **“Air-Fuel Ratios from Exhaust Gas Analysis,”** SAE Paper No. 650507, 1965.

[29] Stone, R., and ball, J., K., **“Automotive Engineering Fundamentals,”** Warrendale, Pa., SAE International, 2004.

[30] Tanabudipa, P., **“Comparative studies of diesohol on CI engine's combustion and performance,”** Master Thesis, ISBN 9741735413, Chulalongkorn University, Bangkok, Thailand, 2003.

[31] Thongchai, S., Chollacoop, N., Topaiboul, S., Charoenphonphanich,c., and Kamimoto, T., **“Effect of Butanol-Diesel Blends on Performance and Emission of Commonrail Engine,”** The 2nd Thammasat University International Conference on Chemical, Environmental and Energy Engineering (TU-ChEEE 2009), Bangkok, Thailand, March 3-4, 2009a.

# REFERENCES (CONT.)

[32] Thongchai, S., Chollacoop, N., Topaiboul, S., Suwannakij, K., Charoenphonphanich, c., and Hanamura, K., **"Feasibility Study of Using High Butanol-Diesel Blends in Commonrail Engine,"** The 23rd Conference of the Mechanical Engineering Network of Thailand, Chiang Mai, November 4-7, 2009b.

[33] Union Carbide Corporation, **Material Safety Data Sheet**, Solvents and Coatings Materials Division, Union Carbide Corporation, February 8, 1999.

[34] USEPA. U.S. Environmental Protection Agency. **Exposure Factor Handbook**. Office of Health and Environmental Assessment, Washington, D.C., 1996.

[35] Wattanavichien, K., **"A Comparative Analysis of Engine's Combustion and Performance of an OEM I.D.I. Diesel engine fuelled with diesohol and diesel fuel,"** The 18th Conference of the Mechanical Engineering Network of Thailand (ME-NETT 18), Khon Kaen, Thailand, October 18-20, 2004.

[36] Weast, R.C. and Astle, M.J. **CRC Handbook of Data on Organic Compounds**. Volumes I and II. CRC Press Inc. Boca Raton, FL, 1985.

[37] Wu, M., Wang, M., Liu, J., and Huo, H., **Life-Cycle Assessment of Corn-Based Butanol as a Potential Transportation Fuel**, Center for Transportation Research, Energy Systems Division, Argonne National Laboratory, November 2007.

# APPENDIX A

## Proceeding

**Appendix A-1:** The 2nd Thammasat University International Conference on Chemical, Environmental and Energy Engineering (TU-ChEEE 2009), Bangkok, Thailand, March 3-4, 2009.

**Appendix A-2:** The 23rd Conference of the Mechanical Engineering Network of Thailand, Chiang Mai, November 4-7, 2009.

# Effect of Butanol-Diesel Blends on Performance and Emission of Commonrail Engine

**Sakda Thongchai**
Department of Mechanical Engineering, Faculty of Engineering,
King Mongkut's Institute of Technology Ladkrabang, Bangkok 10520, Thailand
E-mail: sakda_thongchay@hotmail.com

**Nuwong Chollacoop** and **Subongkoj Topaiboul**
Bioenergy Research Laboratory, National Metal and Materials Technology Center (MTEC), Thailand

**Chinda Charoenphonphanich**
Department of Mechanical Engineering, Faculty of Engineering,
King Mongkut's Institute of Technology Ladkrabang, Bangkok 10520, Thailand

**Takeyuki Kamimoto**
Department of Mechanical Engineering, Tokyo Institute of Technology, Japan

## Abstract

This research explores possibility of using a new mixture of diesohol, diesel/butanol instead of diesel/ethanol, in commonrail compression-ignition engine, as an attempt to solve the miscibility problem in diesel/ethanol and the water absorption in ethanol. Butanol and diesel were blended at butanol concentrations of 5, 10, 15, 20, 25 and 30 by volume without any emulsifier. The butanol-diesel blends were then tested with Isuzu engine (model 4JJ1) without any modification for engine performance, fuel consumption and emissions, with comparison to commercially available diesel in the market. The results reveal that butanol/diesel blends up to 15 – 20% (without emulsifier additive) can be used in commonrail engine without any modification to the engine since ECM (electronic control module) of the engine can maintain set lambda value despite the butanol blending. Higher than 15 – 20% butanol blending in diesel deteriorates engine performance and fuel consumption. Furthermore, oxygen content in butanol helps achieve more complete combustion.

**Keywords:** Diesohol, Butanol, Common-rail engine

## 1. Introduction

Since the global crude oil prices have been soaring continually, the concerns for a renewable source have been explored in an effort to reduce the reliance on petroleum fuels for energy generation especially in transportation sectors. Among many other net oil importing countries, Thailand has been trying to find alternative fuel source especially for diesel since Thailand consumption of diesel is approximately twice that of gasoline. Both biodiesel and diesohol (diesel/ethanol blend) have been considered and subjected to many years of research and development in Thailand. For diesel/ethanol blend, even though they seem to have conflicting properties like cetane in diesel and octane in ethanol, the rationale behind diesel/ethanol blend is that Thailand has surplus of domestic ethanol production, and ethanol-blended gasoline has already been adopted in national strategic plan since 2003 [1]. If ethanol can be blended with diesel at small fraction, the amount of crude oil import would decrease due to higher domestic demand of diesel.

At the present, only biodiesel is adopted nationwide as 2% mandatory blend to diesel fuel

[2] while diesohol (diesel/ethanol blend) still faces some technical issues such as a need for emulsifier additive, a water-absorption nature of ethanol and a rather low flash point [3]. The flash point issue cannot be solved for diesel/alcohol blend due to the chemical property of alcohol but the need for additive and the water-absorption nature of ethanol can be avoided by the use of butanol.

The major drawback in diesohol with ethanol is that ethanol changes the fuel characteristics of the blend, especially by causing instability and reducing the cetane number [4]. To use of butanol in diesohol could solve the problem of fuel instability at low temperatures because of its higher solubility in diesel fuel. Since butanol has both lower vapor pressure and lower water solubility, there is no need for emulsifier additive, unlike diesohol with ethanol or methanol [5]. In addition, the fuel properties of diesohol with butanol indicate closer properties to diesel than those with ethanol.

## 2. Experimental Procedure

### 2.1 Tested engine and fuels

The tested engine is ISUZU model 4JJ1 with commonrail technology, as detailed in Table 1.

Table 1: Tested engine specification

| Description | Specification |
|---|---|
| Brand | ISUZU |
| Model | 4JJ1-TC |
| Type | Diesel engine, 4 cylinders, 16 valves, four stroke, overhead camshaft (DOHC), intercooler, turbo |
| Fuel system | Common-rail, direct injection |
| Capacity | 2.999 liter |
| Cylinder bore & stroke | 95.4x104.9 mm |
| Compression ratio | 17.5 |
| Electronic control module | 4J Diesel ECM-IHVP56 (Delphi) |

Table 2: Properties of butanol [5]

| Item | | Result |
|---|---|---|
| Chemical formula | | $C_4H_9OH$ |
| Appearance | | Subsantially Free |
| Odor | | Characteristic & Non residual |
| Colour | (Pt-Co) | Less than 5 |
| Distillation, °C | (I.B.P.-D.P.) | 117.2-117.8 |
| Acidity as Acetic Acid | (Wt.%) | 0.00125 |
| Water content | (Wt.%) | 0.0174 |
| Purity | (Wt.%) | 99.90 |
| S.G. @ 15/4 °C | (Wt.%) | 0.8131 |
| Flash point | (°C) | 35 |
| Heating value | (MJ/kg) | 36.5 |

The tested diesohol fuel is prepared by blending 99.9% purity butanol to commercially available diesel in Thai market at a concentration of 5, 10, 15, 20, 25 and 30% (v/v), which are named BD5, BD10, BD15, BD20, BD25 and BD30, respectively. The properties of butanol are shown in Table 2.

### 2.2 Apparatus

The schematic diagram of experimental set up is shown in Fig. 1, which is composed of 150kW eddy current dynamometer with mass fuel consumption meter (Tokyo Plant model ED-150), exhausted gas analyzer (Horiba model MEXA-1600D) and various temperature sensors.

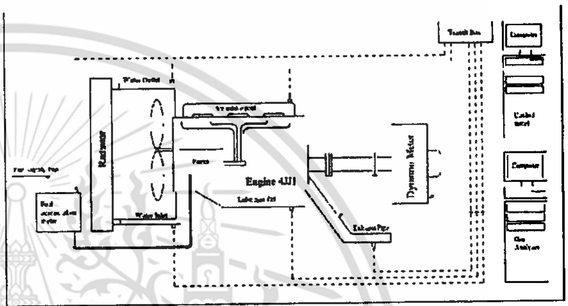


Figure 1: Schematic diagram of experimental set up

### 2.3 Methodology

The tested engine was set up on dynamometer with original ECM (electronic control unit) from the manufacturer without any modification to assess performance curve, as well as fuel consumption, at full load for engine speed of 800 – 4,400 rpm. Brake specific fuel consumption (BSFC) at partial load was obtained at 50, 100 and 150 N.m torque. The temperatures of air inlet, exhausted gas and lubricant oil were monitored at all engine speeds as well. Emission at full load was obtained for THC, CO, $CO_2$, NO/NOx and $O_2$.

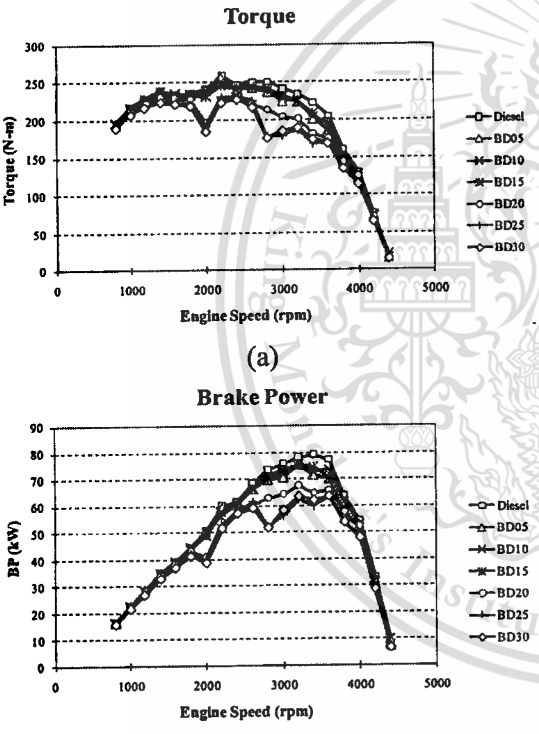
For each test, the engine was initially warmed up, and the required engine speed was obtained by adjusting the accelerator electrical pedal. Between the testing of different butanol blends, careful switching was followed to ensure that the engine, fuel system (fuel line, fuel filter) and fuel consumption meter were running with new blend for a sufficient. When the operating conditions were reached and reliably stabilized, the variables were continuously measured and recorded for three times to obtain an average value of the experimental data, e.g. torque load, fuel consumption, air inlet/exhaust gas/lubricant oil temperatures and gas emission.

## 3. Results and Discussions

The results shown here aim to test the limit of using butanol/diesel blends in commonrail engine with no modification, especially on the adaptation capability of ECM with this fuel blend. Engine performance, fuel consumption and emission are discussed as follows.

### 3.1 Engine performance and fuel consumption

The effects of butanol blends in commercially available diesel on commonrail engine were analyzed in terms of engine performance, fuel consumption with reference to exhaust gas temperature, air inlet temperature, lubricant oil temperature and lambda.



(a)

(b)

Figure 2. Engine performance, (a) torque and (b) power, results at various butanol/diesel blends under full load condition

Fig 2 shows the engine performance in terms of torque and power for various blends of butanol/diesel. It is clear that pure diesel curve yield the highest torque and power due to a higher heating value of diesel than butanol. It is interesting to note that the engine performance is not much deteriorated for up to 15% blend of butanol (BD15). This implies the adaptive capability of engine ECM to cope with butanol blend. For higher blends of BD20 up, performance curves show some drop at 2,000 and 2,800 rpm, probably from the fact that ECM was trying to adjust engine operation. Note that higher butanol blends of 35 – 60% were also tested but the results show abnormal behaviour, and thus not included for discussion. The BD25 and BD30 data are included here to signify the onset breakdown of ECM control.

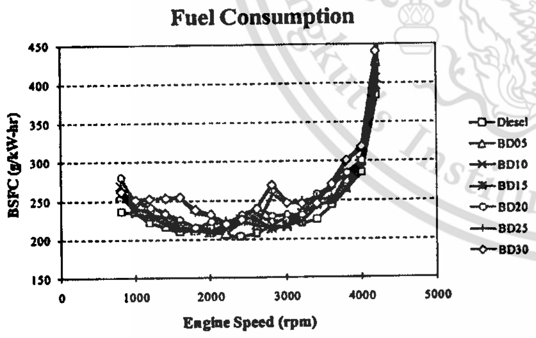
For brake specific fuel consumption (BSFC), Fig. 3(a) shows fuel consumption result at full load. Similar to the performance curve, fuel consumption behaviour is not too much different from that of diesel for butanol blend up to 20% (BD20). The BD25 and BD30 curves show irregular peak at 2,800 rpm, probably due to ECM adjustment. Overall, this commonrail engine is optimized for fuel consumption in the range of 1,000 – 3,000 rpm for up to 20% blend with butanol. For fuel consumption at partial loads, Figs 3(b), 3(c) and 3(d) show those of 50, 100 and 150 N.m torque loads. For each case, diesel still yields the lowest fuel consumption. At low load of 50 N.m, fuel consumption increases with increasing engine speed while higher butanol blends affect the curves to show cup-like behavior. This cup-like behavior is diminished with increasing load to 100 and 150 N.m. Furthermore, at medium to high loads of 100 – 150 N.m, BSFC results of up to 30% butanol blend (BD30) are not significantly different from neat diesel.

Further investigations were looking at temperatures of lubricant oil, exhaust gas and air inlet (after EGR: exhaust gas recirculation), as shown in Figs 4(a) – 4(c), respectively. Fig. 4(a) shows lower lubricant oil temperature for all butanol/diesel curves at all engine speeds because butanol, which can easily vaporize at lower temperature than diesel, has absorbed some heat in the engine via latent heat of vaporization. In other words, the engine is cooler by the presence of butanol blending.

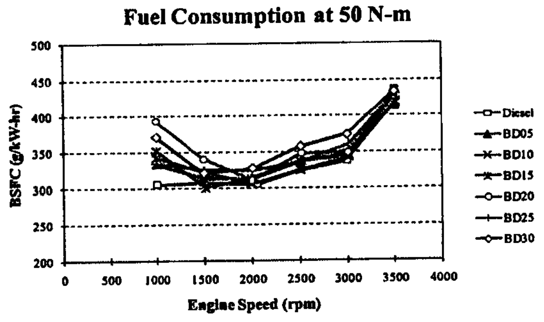
However, Fig 4(b) shows that exhaust gas from butanol/diesel blends is hotter. This can be explained by recourse to pressure data in [6], which clearly shows ignition retardation with higher heat released for 10% ethanol-blended diesel. Since butanol has higher density and higher heating value than ethanol [5], the interpretation of [6] to BD blend would lead to shorter ignition retardation and even higher heat released. Altogether, exhaust gas temperature of BD blends is higher than that of diesel, especially at low engine speed where enough time is allowed for combustion. However, this explanation is purely based on the mechanic response to butanol blending without knowledge of response from ECM.

With regard to air inlet temperature shown in Fig 4(c), the behavior is quite subtle since one would expect air inlet of butanol/diesel cases to be hotter due to hotter exhaust gas. This rather similar air inlet temperature at low engine speed (up to 2,000 rpm) and hotter air inlet at high engine speed (above 2,000 rpm) for butanol/diesel cases can only be explained by the ECM control of EGR valve to adjust how much exhaust gas is allowed back into inlet manifold. Potentially, ECM could try to adjust lower exhaust gas temperature of diesel by increasing exhaust gas volume. Further investigation into ECM signals is required to support this explanation.

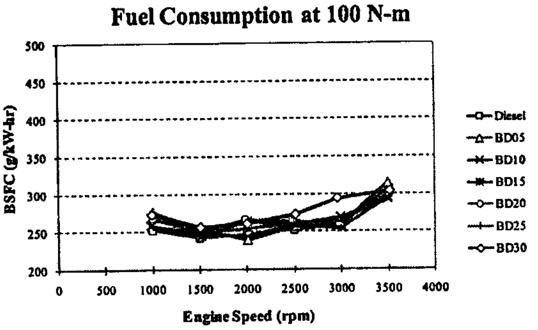
The adaptive capability of ECM is further shown in Fig. 5(a) for air/fuel ratio and Fig. 5(b) for lambda value, where Spindt formula is used to take into accout of butanol blending [7, 8]. It is clear that AFR and lambda show insignificantly different data between BD cases and neat diesel.


Fuel Consumption

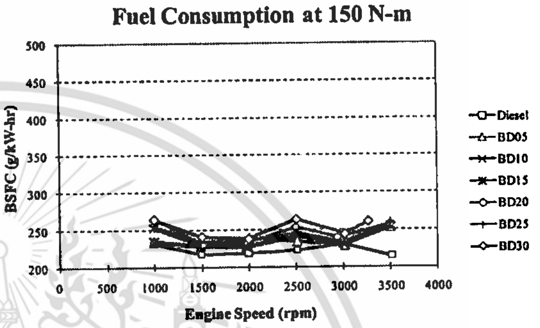
(a)


Fuel Consumption at 50 N-m

(b)

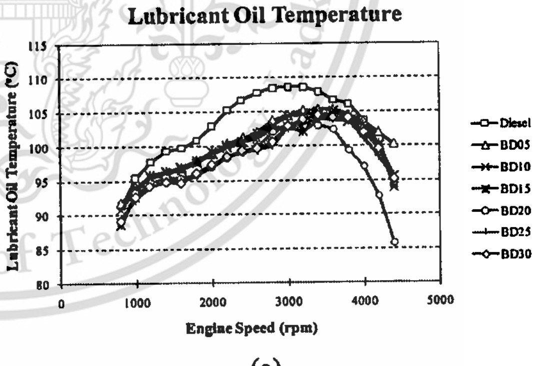

Fuel Consumption at 100 N-m

(c)

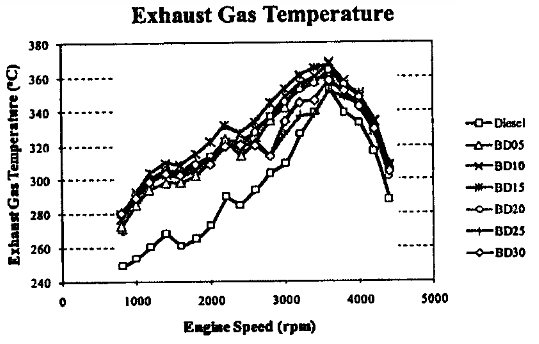

Fuel Consumption at 150 N-m

(d)

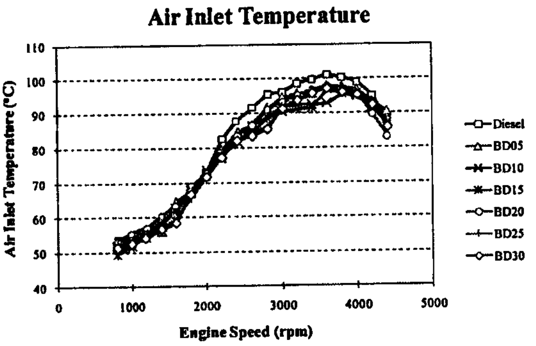
Figure 3. Brake specific fuel consumption (BSFC) results at (a) full load and partial loads at (b) 50 N.m, (c) 100 N.m and (d) 150 N.m for various butanol/diesel blends


Lubricant Oil Temperature

(a)

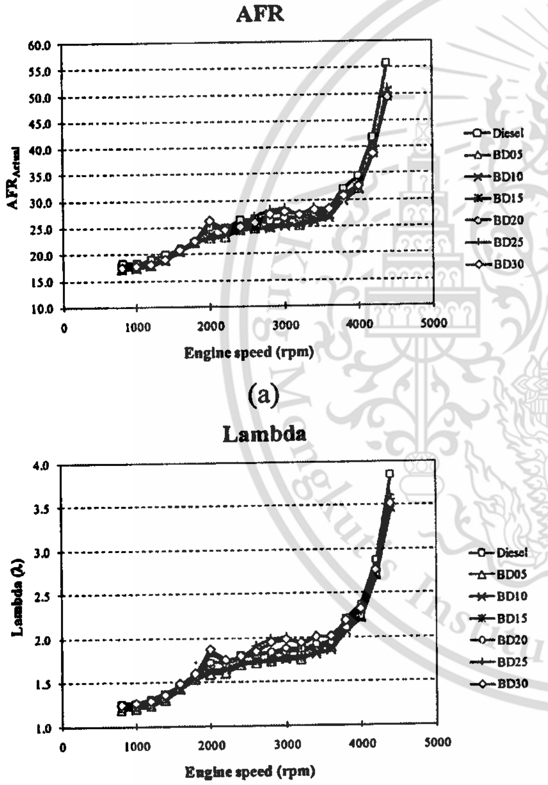

Exhaust Gas Temperature

(b)



(c)

Figure 4. The temperatures of (a) lubricant oil, (b) exhausted gas and (c) air inlet at various butanol/diesel blends under full load condition



(a)

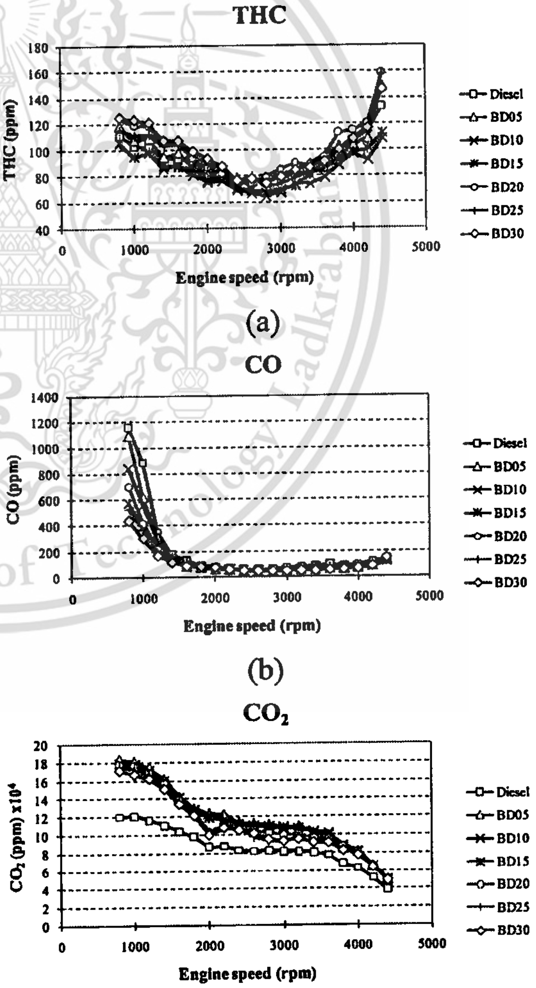
(b)

Figure 5. (a) Air/fuel ratio ($AFR_{actual}$) and (b) lambda ($\lambda = AFR_{Actual}/AFR_{Stoichiometric}$) of various butanol/diesel blends under full load condition

### 3.2 Emission

Emission results of THC, CO, $CO_2$, $NO/NO_x$ and $O_2$ at full load condition are shown in Figs 6(a) – 6(e). For unburned hydrocarbon, Fig. 6(a) shows virtually no difference between BD and diesel cases with the lowest value at the medium engine speed. Fig 6(b) shows quite complete combustion at engine speed of 1,600 rpm or greater with virtually no difference between BD and diesel cases. However, at low engine speed (< 1,600 rpm), CO emission is quite high, and the effect of butanol (oxygen containing molecule) helps decrease CO level by promoting more complete combustion. Fig 6(c) further supports this explanation that butanol helps promote more complete combustion.

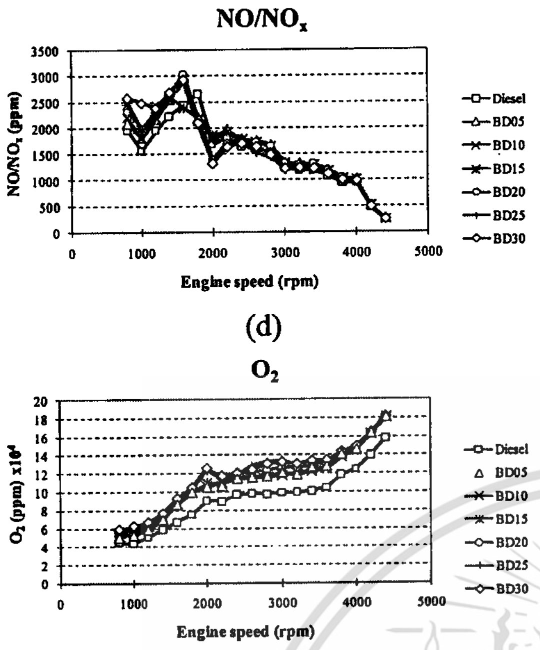
For $NO/NO_x$ emission results shown in Fig 6(d), ECM has shown good capability to control EGR valve such that $NO/NO_x$ trends decrease with increasing engine speeds for all butanol blending, despite some data scattering for engine speed lower than 2,200 rpm. Lastly, low unused $O_2$ amount at low engine speed, shown in Fig 6(e), is consistent with high CO and $CO_2$ emission results, and vice versa.



(a)

(b)

(c)



(d)

(e)

Figure 6. Emission results of (a) THC, (b) CO, (c) $CO_2$, (d) NO/NOx and (e) $O_2$ at various butanol/diesel blends under full load condition

## 4. Conclusion

The effects of butanol/diesel blends of 5, 10, 15, 20, 25 and 30% on commonrail direct injection engine were rigorously evaluated on engine performance, fuel consumption and emission, in comparison to those of diesel results. Important findings are as follows:

1. Unmodified commonrail engine can use butanol/diesel blend up to 15 – 20% without significant drop in engine performance and fuel consumption.
2. Effect of butanol blending decreases engine operating temperature via latent heat of vaporization.
3. Effect of butanol blending increases exhaust gas temperature, especially at low-to-medium engine speeds.
4. Engine ECM can maintain desired lambda value on butanol blending up to 30%
5. Oxygen content in butanol helps achieve more complete combustion (lower CO and higher $CO_2$)

## 5. Acknowledgement

The authors gratefully acknowledge the contribution of Bioenergy Research Laboratory at National Metal and Materials Technology Center (MTEC), Faculty of Engineering at King Mongkut's Institute of Technology Ladkrabang, Faculty of Engineering, Tokyo Institute of Technology (TIT) and Thailand Advanced Institute of Science and Technology (TAIST) and Tokyo Institute of Technology for supports with the test instruments and technical assistance.

## 6. References

[1] Department of Alternative Energy Development and Efficiency (DEDE), Gasohol National Policy, 2 September 2003, http://www.dede.go.th/dede/fileadmin/usr/bers/gasohol_documents/510121_gasohol_policy.pdf

[2] Deparment of Energy Business (DOEB), Diesel Specification, 2008, http://elaw.doeb.go.th/document_doeb/3_0001.pdf

[3] Chollacoop, N. et al. "Research and Development Project on Bio-Ethanol Fuels for Diesel Vehicles in Thailand," 2nd Biomass Asia Workshop, Bangkok, December 13-15, 2005

[4] Leelanoi, P., The Performance Study of a Diesel Engine Using Buthanol Base Diesohol Fuel, Master thesis, M.Eng. (Mechanical Engineering), Graduate School, Srinakharinwirot University, Thailand, May, 2007.

[5] Chotwichien, A., Luengnaruemitchai, A., Jai-In, S., Utilization of Palm Oil Alkyl Esters as an Additive in Diesel-Ethanol and Diesel-Butanol Blends, 3rd Energy Technology Network of Thailand (ENETT 2550), Bangkok, Thailand, May 23-25, 2007.

[6] Wattanavichien, K., A Comparative Analysis of Engine's Combustion and Performance of an OEM I.D.I. Diesel engine fuelled with diesohol and diesel fuel, MENETT 18, Khon Kaen, Thailand, October 18-20, 2004

[7] Bresenham, D., Reisel, J., and Neusen, K., Spindt Air-Fuel Ratio Method Generalization for Oxygenated Fuels, SAE Technical paper series 982054 , September, 1998

[8] Pulkrabek, W.W., Engineering Fundamentals of the Internal Combustion, International Edition, Prentice-Hall International, INC, 1997.

The 23rd Conference of the Mechanical Engineering Network of Thailand
November 4 – 7, 2009, Chiang Mai

# Feasibility Study of Using High Butanol-Diesel Blends in Commonrail Engine

Sakda Thongchai[1], Nuwong Chollacoop[2,*], Subongkoj Topaiboul[2], Kiatkong Suwannakij[2],
Chinda Charoenphonphanich[1] and Katsunori Hanamura[3]

[1] Department of Mechanical Engineering, Faculty of Engineering,
King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand 10520
[2] Bioenergy Research Laboratory, National Metal and Materials Technology Center (MTEC), Thailand 12120
[3] Department of Mechanical Engineering, Tokyo Institute of Technology, Tokyo, Japan 152-8550
* Corresponding Author: E-mail: nuwongc@mtec.or.th

## *Abstract*

With a recent energy crisis, alternative fuel, especially for transportation, has been explored. For particular fuel consumption distribution in Thailand, with twice diesel fuel consumption than gasoline, NGV and biodiesel have been successfully promoted to reduce this uneven diesel-gasoline consumption pattern; whereas, diesohol (10% ethanol blend in diesel) was tested for performance and emission with acceptable results. However, ethanol-diesel blend still faces challenges in finding suitable emulsifier, preventing water absorption from ambient and adapting existing distribution infrastructure to cope with low flash point. Hence, the present study evaluates feasibility in using butanol blending with diesel (BDx) due to no need for emulsifier, less water absorption and less difference of physical/chemical properties in the blends. Butanol and diesel were blended at butanol concentrations of 10, 20, 30 and 40% by volume (BD10, BD20, BD30 and BD40) without any emulsifier additive to observe solubility and stability. Relevant physical and chemical properties were measured and compared to specification of Thai diesel. Then, butanol-diesel blends of 5, 10, 15, 20, 25, 30, 35 and 40 by volume (BD5, BD10, BD15, BD20, BD25, BD30, BD35 and BD40) were tested with unmodified Isuzu commonrail engine (model 4JJ1) for engine performance, fuel consumption and emissions, with comparison to commercially available diesel in the market. The physical/chemical properties of the blends reveal acceptable values; whereas, the engine testing results reveal that BD15/20 can be used in commonrail engine without any modification to the engine since ECM (electronic control module) of the engine can maintain set lambda value despite the butanol blending. Nonetheless, higher than BD15/20 could deteriorate engine performance and fuel consumption.

***Key words:*** Diesohol, Butanol, Commonrail engine

## 1. Introduction

Nowadays, petroleum diesel oil has been used in numerous industries in order to drive economic growth. Especially, transportation sector has consumed petroleum diesel oil, which was approximately 53 million liter per day in the first quarter year 2009 [1]. Therefore, diesohol, a diesel blended with ethanol, was an alternative fuel to reduce dependence on imported oil and quantity of petroleum diesel oil. However, diesohol still faces several problems, such as water-absorption nature of ethanol and a rather low flash point [2]. The major drawback in diesohol with ethanol was that ethanol changes the fuel characteristics of the blend, especially by causing instability and reducing the cetane number [3]. A use of butanol in diesohol could solve the problem of fuel instability at low temperatures because of its higher solubility in diesel fuel. Since butanol has both lower vapor pressure and lower water solubility, there was no need for emulsifier additive, unlike diesohol with ethanol or methanol [4]. In addition, the fuel properties of diesohol with butanol indicate closer properties to diesel than those with ethanol. As a result, this research has demonstrated a new concept by blending butanol (instead of methanol or ethanol) in diesel and testing with commonrail engine.

## 2. Experimental Procedures

The main objectives of this research focus on characteristic of physical/chemical properties of tested fuels and compatibility of the unmodified commonrail diesel engine by using the butanol/diesel blends up to 40%, especially on the adaptation capability of ECM with this fuel blend and comparison to commercially available diesel fuel.

### 2.1 The blended fuels and engine system

The tested fuels were prepared by blending 99.9% purity of butanol with commercial diesel available in Thai markets, without adding any emulsifiers. The volume percentages of butanol blending were varied from 5, 10, 15, 20, 25, 30, 35 and 40. These represent as BD5, BD10, BD15, BD20, BD25, BD30, BD35 and BD40, respectively. The pure butanol properties were obtained from manufacturer, as shown in Table 1.

Table 1: Properties of pure butanol

| Item | | Result |
|---|---|---|
| Chemical formula | | $C_4H_9OH$ |
| Appearance | | Substantially Free |
| Odor | | Characteristic & Non residual |
| Colour | (Pt-Co) | Less than 5 |
| Distillation, °C | (I.B.P.-D.P.) | 117.2-117.8 |
| Acidity as Acetic Acid | (Wt.%) | 0.00125 |
| Water content | (Wt.%) | 0.0174 |
| Purity | (Wt.%) | 99.90 |
| S.G. @ 15/4 °C | (Wt.%) | 0.8131 |

The tested engine was ISUZU model 4JJ1, an intercooled turbo diesel engine with commonrail system including exhaust gas recirculation (EGR) equipment. This engine was set up without any modifications, as detailed in Table 2.

Table 2: Tested engine specification

| Description | Specification |
|---|---|
| Brand | ISUZU |
| Model | 4JJ1-TC |
| Type | Diesel engine, 4 cylinders, 16 valves, four stroke, overhead camshaft (DOHC), intercooler, turbo |
| Fuel system | Common-rail, direct injection |
| Capacity | 2.999 liter |
| Cylinder bore & stroke | 95.4x104.9 mm |
| Compression ratio | 17.5 |
| Electronic control module | 4J Diesel ECM-IHVP56 (Delphi) |

### 2.2 Apparatus

The physical/chemical properties of butanol/diesel blends was analyzed by many types of equipment such as a digital density meter, a furnace, a mircrocabon residue tester, a pensky-martens closed cup tester, a bomb calorimeter, a viscometer, a karl fisher coulometer, a copper strip corrosion bath and a high frequency reciprocating test rig (HFRR).

The schematic diagram of engine test setting is shown in Fig. 1. It was composed of (1) the commonrail direct injection engine, (2) the 150kW eddy current dynamometer model ED-150 of Tokyo Plant with (3) mass fuel consumption meter and (4) computer controller, (5) an exhausted gas analyzer of Horiba model MEXA-1600D, and various RTD temperature sensors.

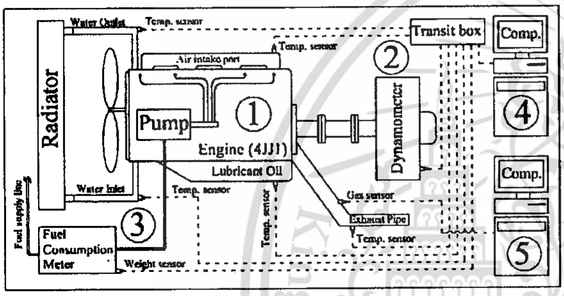


Fig. 1: Schematic diagram of engine test system

## 2.3 Methodology

### 2.3.1 Physical/chemical properties

The tested methods used in this experiment are of ASTM standards [5] and CFC standard [6] as shown in Table 3. All of physical/chemical property tests were repeated for a few times to obtain the average results.

Table 3: Tested Standard

| Description | Standard |
|---|---|
| Flash point | ASTM D93 |
| Copper strip corrosion | ASTM D130 |
| Carbon residue | ASTM D524 |
| Heat of combustion | ASTM D240 |
| Kinematic viscosity | ASTM D445 |
| Ash content | ASTM D482 |
| Density | ASTM D4052 |
| Water content | ASTM D6304 |
| Lubricity (WS. 1.4) | CFC F-06-A-96 |

### 2.3.2 Engine performance and gas emission

The engine was installed on dynamometer test bench to evaluate engine performances, fuel consumption rate and emission. The original electronic control unit (ECM) was connected to the engine without any modification. In the full load condition, the engine speeds were varied from 800 – 4,400 rpm and emission results of THC, CO, $CO_2$, NO/$NO_x$ and $O_2$ were collected.

For each condition, the engine was firstly warmed up, and the engine speed was adjusted via the electrical accelerator tuner. At the end of each test and each butanol blend, it was necessary to ensure that the previous fuel was fully replaced with the new blend. When the operating conditions were reached and reliably stabilized, the outcome values of torque output, fuel consumption rate and gas emission were recorded for three times in order to find the average values.

## 3. Results and Discussions

### 3.1 Physical/chemical properties

The tested results in Fig. 2 showed density values of diesel, BD10, BD20, BD30, BD40 and butanol, superimposed with the range of diesel standard. Since the density of butanol (0.814 $Kg/m^3$) is not so much different from that of diesel fuel (0.825 $kg/m^3$), its blends of up to 40% butanol in diesel are less than 1% variation from diesel density.

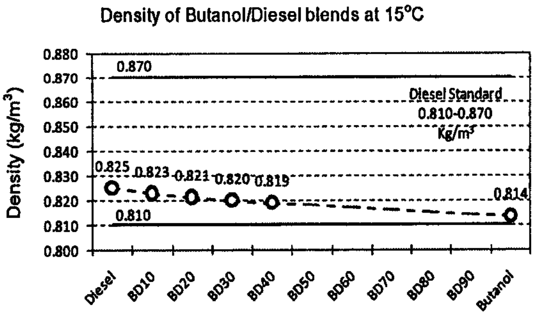


Fig. 2: Density of butanol/diesel blends at 15°C

Carbon residue and ash content results were within the standard values, namely carbon residue <0.05 %wt and ash content <0.01 %wt respectively. This implied that the tested diesel and butanol were free of noticeable impurities.

The heat of combustion results were exhibited in Fig. 3, which shows that the heating values (HV) tended to be decreased in a linear fashion with increasing blend fraction of butanol. The obtained HV values are also similar to those performed by another researcher [3]. Generally, diesel fuel and butanol have the HV of 45.6 MJ/kg and 34.9 MJ/kg respectively with the difference of 23.4%. The butanol/diesel blends contain higher heating value comparing to ethanol/diesel blends because butanol has longer chain with 4 atom carbon, and butanol can release more energy [7].

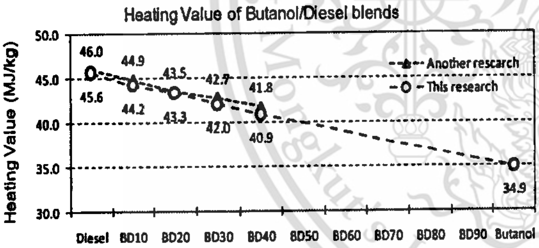


Fig. 3: Gross heat of combustion

In Fig. 4, kinematic visocisty of the blends shows non-linear reduction of viscosity with increasing butanol blend, especially for a large drop with small amount of butanol blend.

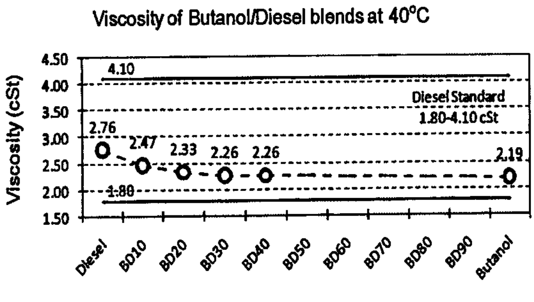


Fig. 4: Kinematic Viscosity

The results of water content exhibited in Fig. 5 show a steep increase until 40% butanol blend with gradual increase close to pure butanol. Diesel fuel has very little water content about 105 ppm. because water cannot dissolve into diesel fuel. On the other hand, since the purity of tested butanol is 99.9%, a little water of 1,871 ppm is acceptable. When butanol is blended with diesel fuel, water content will be increased with concentration of butanol.

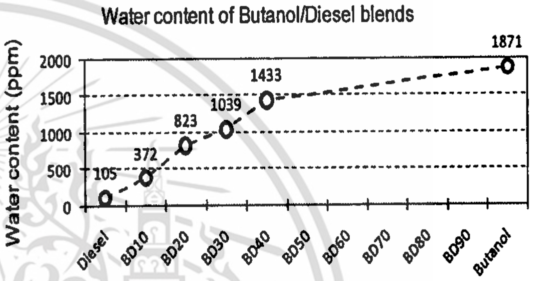


Fig. 5: Water content

All tested results of copper strip corrosion for butanol/diesel blends were in 1a level being also within the standard range (Number 1a-1c) so no corrosion is expected when used in the diesel engine.

Since flash point and lubricity are known problems for diesohol with ethanol, similar behavior was observed for butanol/diesel blend as shown in Fig 6 and 7. Low flash point property of diesohol can lead to the appearance of engine knock, which can destroy many internal engine parts such as piston, cylinder head, valve etc. The tested results of flash point property of butanol/diesel blends show the rapid reduction with the first 10% blend (from 64°C to 39°C) and afterward the property values are almost constant. This phenomenon was appeared for all blends (10% - 40%) and pure butanol (100%). This can be implied that the drop of flash point value in the fuels is not depending on the amount of added butanol. Due to a reduction of flash point, butanol in fuel blends was vaporized earlier with increasing fuel temperature, and hence the fire flashing was observed during flash point testing. The results of flash point property are exhibited in Fig. 6.

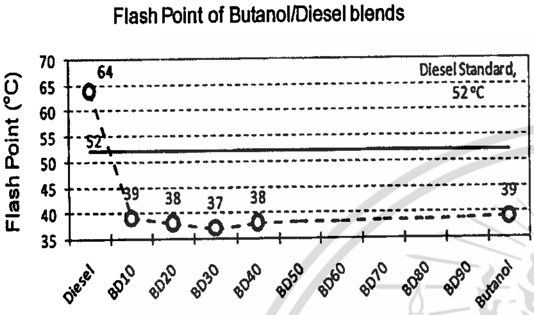


Fig. 6: Flash point

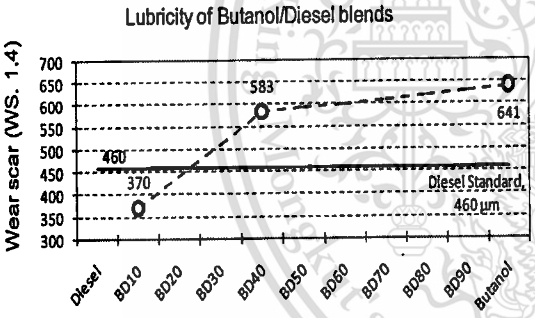


Fig. 7: Lubricity with WS.1.4

In Fig. 7, the tested results of lubricity show the immediate increase with BD40, outside the diesel standard level of 460 µm. The pure butanol shows highest value on wear scar (WS.1.4) because butanol is an eminent solvent, which deteriorates the lubricity. Addition of the butanol into diesel fuel caused the lubricity to reduce, depending on the concentration of butanol. Therefore the results showed that only BD10 was acceptable because the wear scar (WS. 1.4) was not over the standard value; while the BD40 and butanol was not acceptable. In addition, it might be possible that BD20 was also accepted in the standard.

### 3.2 Engine performance and fuel consumption

Previous investigation [8] was extended to cover BD35 and BD40 in the present engine testing. The turbo diesel engine with commonrail system was tested and evaluated in term of engine performance, fuel consumption, and gas emission.

As shown in Fig. 2 and Fig. 4, both density and viscosity properties are affected by butanol blend, which will directly affect the atomization characteristic of the fuel droplet once injected into the cylinder. Also, injection timing of the butanol/diesel blend may be different from that of pure diesel due to the ECM algorithm and feedback control, especially at the high load condition. However, the current study only focused on the adaptive capability of the unmodified ECM with the following results.

According to the Fig. 8, the torque and power of the engine were highest when it was powered by diesel fuel as it usually contains the highest heating value comparing to other tested fuels. It also shows that BD15 gave the results being closed to commercial diesel fuel, due to the engine compatibility by OEM ECM. However, for higher blends of BD20 up, the performance curves show some drop at 2,000 and 2,800 rpm, probably from the fact that ECM tried to adjust the engine operation. Additionally, the engine performance was much inferior when the BD25, BD30, BD35 and BD40 were applied because of the onset breakdown of ECM control.

For the brake specific fuel consumption (BSFC) values at full load, it was found that the BD05, BD10, BD15 and BD20 showed insignificant difference comparing with the diesel fuel as shown in Fig. 9. The BSFC curves of the blends of BD25, BD30, BD35 and BD40 show the irregularly peak at 2,800 rpm, due to ECM adjustment. Related to the tested results, the fuel consumption rate was generally optimized in the range of 1,000 – 3,000 rpm for the appearance of butanol in fuels up to 20%.

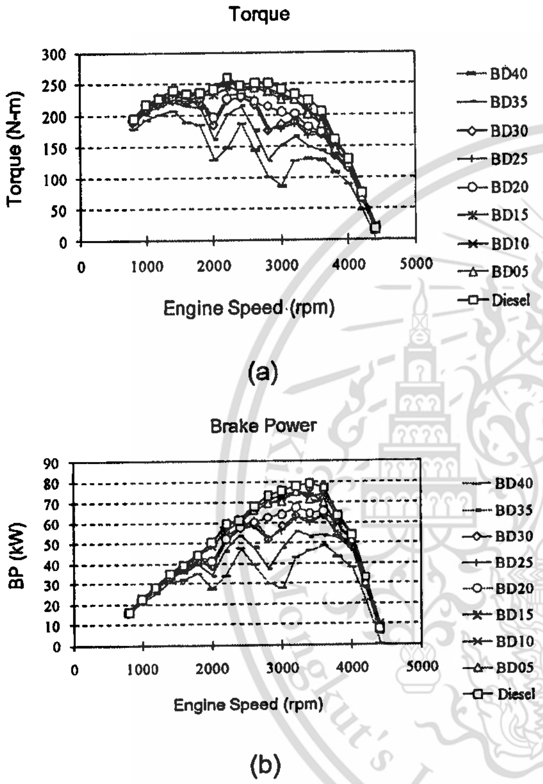


Fig. 8. Engine performance, (a) torque and (b) brake power, results at various butanol/diesel blends under full load condition

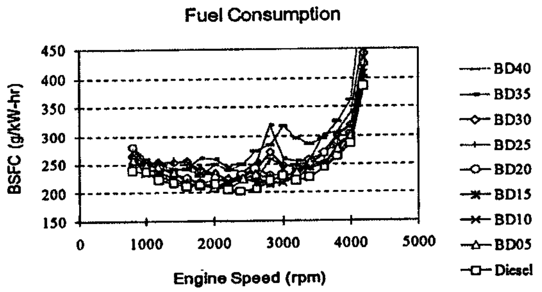
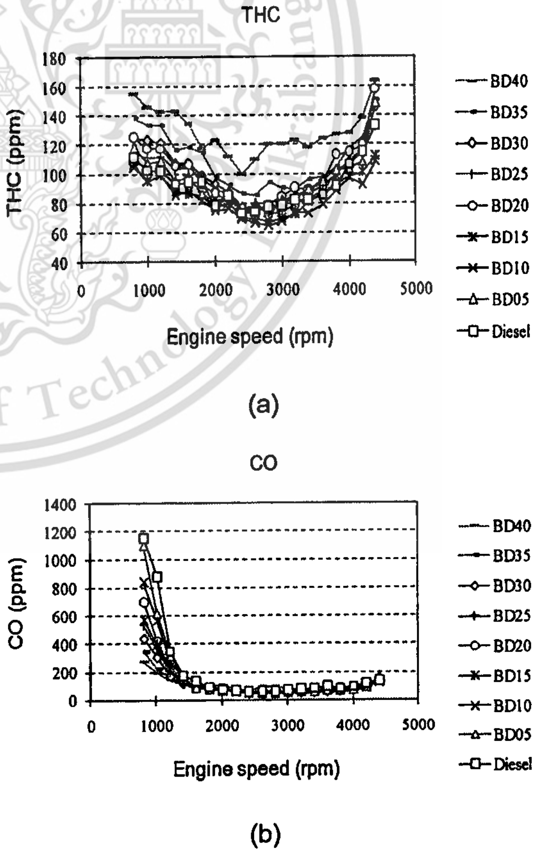


Fig. 9. Brake specific fuel consumption (BSFC) results at full load

### 3.3 Emission

Fig. 10(a) – 10(e) show the gas emission results of THC, CO, $CO_2$, $NO_x$ and $O_2$ at full load condition. According to the Fig. 10(a), all fuel blends produced THC emission similarly to the pure diesel at medium engine speed, excepting for BD35 and BD40. In Fig. 10(b), the results were similar to the engine speed of 1,600 rpm, in which there was no difference between BD and diesel. The combustion was quite complete due to little amount of CO values. The reason was that butanol (higher oxygen molecule content) in diesel fuel could improve the combustion by reducing CO emission. Furthermore, Fig. 10(c) further supported the complete combustion behavior when using the BD fuel.



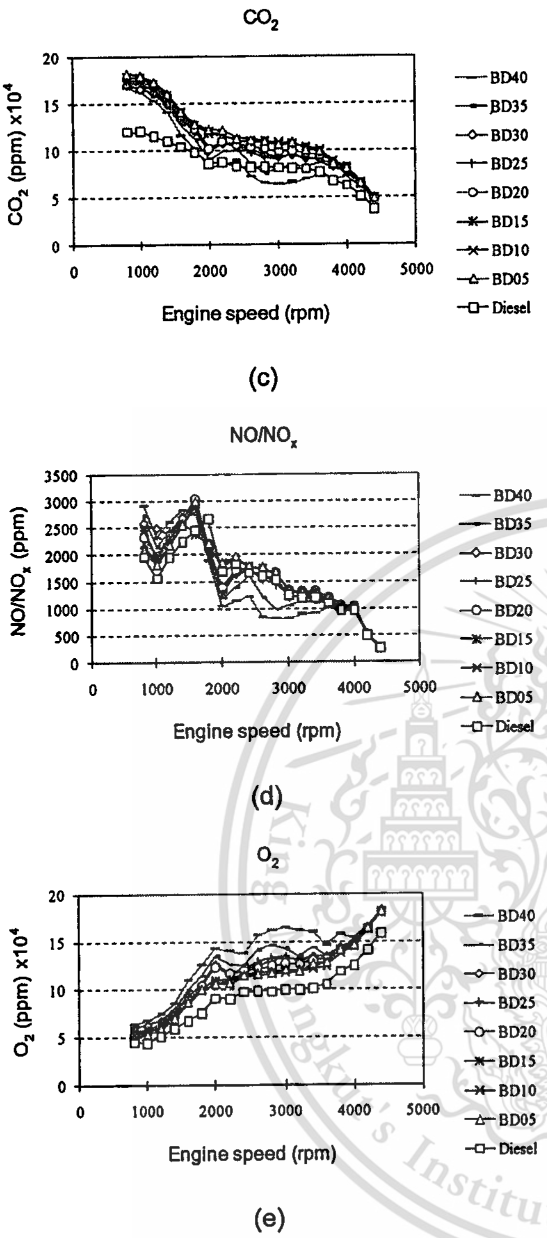


**Fig. 10.** Emission results of (a) THC, (b) CO, (c) CO$_2$, (d) NO/NO$_x$ and (e) O$_2$ at various butanol/diesel blends under full load condition

For NO/NO$_x$ emission results shown in Fig. 10(d), NO$_x$ emission was greater at higher loads and lower speed. Mostly, NO$_x$ trends of BD fuels were similar except for BD35 and BD40 due to irregular ECM behavior. Lastly, there was less O$_2$ emission left in the exhaust gas as the reduction of engine speed (higher loads) for all fuels (Fig. 10(e)).

## 4. Conclusion

The butanol/diesel blends of 10, 20, 30 and 40% were tested for their physical/chemical properties and engine compatibilities in terms of engine performance, fuel consumption and emission. The following conclusions were drawn:

1. The properties of density, carbon residue, ash and copper strip corrosion of butanol/diesel blends at 10, 20, 30 and 40% of butanol are not significantly different from those of diesel fuel.
2. The heating value of butanol/diesel blends is slightly less than that of diesel fuel by about 3 – 10%.
3. The viscosity of the butanol/diesel blend significantly drops with mere addition of 10% butanol or BD10, which could affect fuel spray pattern and atomization capability.
4. The flash point of butanol/diesel blends was closed to that of pure butanol, being in the range of 37 - 39 °C. This can lead to engine knocking problem.
5. Higher blend of butanol than 10% may jeopardize lubricity property beyond the standard limit.
6. Unmodified commonrail diesel engine can be fueled with butanol/diesel blends of between 5 – 20% without any significant drops in engine performances and fuel consumption.
7. The oxygen content in butanol molecule can enhance the complete combustion, resulting in lower CO and higher CO$_2$.

## 5. Acknowledgement

The authors gratefully acknowledge the contribution of Bioenergy Research Laboratory at National Metal and Materials Technology Center (MTEC), Faculty of Engineering at King Mongkut's Institute of Technology Ladkrabang, Faculty of Engineering, Tokyo Institute of Technology (TIT) and Thailand Advanced Institute of Science and Technology (TAIST) and Tokyo Institute of Technology for supports with the test instruments and technical assistance.

## 6. References

[1] Ministry of Energy, Thailand (2009). *Statistic Data*, available online: http://www.energy.go.th.

[2] Chollacoop, N. et al. "Research and Development Project on Bio-Ethanol Fuels for Diesel Vehicles in Thailand," 2nd Biomass Asia Workshop, Bangkok, December 13-15, 2005

[3] Leelanoi, P., The Performance Study of a Diesel Engine Using Buthanol Base Diesohol Fuel, Master thesis, M.Eng., Srinakharinwirot University, Thailand, May, 2007.

[4] Chotwichien, A., Luengnaruemitchai, A., Jai-In, S., Utilization of Palm Oil Alkyl Esters as an Additive in Diesel-Ethanol and Diesel-Butanol Blends, 3rd Energy Technology Network of Thailand (ENETT 2550), Bangkok, Thailand, May 23-25, 2007.

[5] Annual Book of ASTM Standard 2005, section five, petroleum product, lubricant, and fossil fuels, volume 05.01, 05.02, 50.03, ASTM International, West Conshohocken, PA 19428-2959.

[6] Fuels and Lubricants Test Equipment, HFRR Installation and Preparation Manual, PCS Instruments, London, UK.

[7] Wattanavichien, K., A Comparative Analysis of Engine's Combustion and Performance of an OEM I.D.I. Diesel engine fuelled with diesohol and diesel fuel, The 18th Conference of the Mechanical Engineering Network of Thailand (ME-NETT 18), Khon Kaen, Thailand, October 18-20, 2004.

[8] Thongchai, S., Chollacoop, N., Topaiboul, S., Charoenphonphanich,c., and Kamimoto, T., Effect of Butanol-Diesel Blends on Performance and Emission of Commonrail Engine, The 2nd Thammasat University International Conference on Chemical, Environmental and Energy Engineering (TU-ChEEE 2009), Bangkok, Thailand, March 3-4, 2009.

# APPENDIX B

# Tested Data under Full Load

## B-1: Engine Performance, BSFC and Temperature Data

**Table B1.1** Diesel results under full load (performance, BSFC and temperature)

Fuel type : Diesel

Test condition : Full load

| Speed (rpm) | Torque (N·m) | Fuel consumption (g/s) | Power (kW) | BSFC (g/kW·hr) | Exhaust gas temperature (°C) | Air inlet temperature (°C) | Lubricant temperature (°C) |
|---|---|---|---|---|---|---|---|
| 800 | 193.97 | 1.08 | 16.40 | 236.53 | 249.35 | 53.47 | 91.47 |
| 1000 | 216.05 | 1.47 | 22.43 | 235.45 | 253.67 | 54.23 | 95.47 |
| 1200 | 225.27 | 1.73 | 28.13 | 221.11 | 260.52 | 56.27 | 97.77 |
| 1400 | 238.63 | 2.10 | 35.05 | 216.00 | 268.13 | 59.17 | 99.33 |
| 1600 | 233.02 | 2.27 | 39.08 | 209.49 | 260.97 | 62.10 | 99.77 |
| 1800 | 234.05 | 2.63 | 44.18 | 214.61 | 265.12 | 69.00 | 100.90 |
| 2000 | 240.85 | 3.00 | 50.48 | 214.10 | 272.87 | 72.90 | 102.93 |
| 2200 | 258.50 | 3.39 | 59.78 | 204.03 | 290.03 | 82.73 | 105.30 |
| 2400 | 245.95 | 3.47 | 61.50 | 203.28 | 284.73 | 87.80 | 106.70 |
| 2600 | 249.92 | 3.92 | 68.18 | 207.00 | 293.67 | 91.70 | 107.83 |
| 2800 | 249.83 | 4.47 | 73.38 | 219.06 | 303.67 | 95.50 | 108.50 |
| 3000 | 240.50 | 4.77 | 75.67 | 227.10 | 309.03 | 96.17 | 108.57 |
| 3200 | 232.67 | 4.77 | 78.05 | 219.92 | 326.92 | 98.73 | 108.63 |
| 3400 | 222.22 | 4.94 | 79.12 | 224.98 | 339.47 | 99.73 | 107.90 |
| 3600 | 204.50 | 5.22 | 77.10 | 243.87 | 352.72 | 101.23 | 106.70 |
| 3800 | 159.97 | 4.66 | 63.65 | 263.51 | 339.13 | 100.27 | 106.10 |
| 4000 | 129.18 | 4.28 | 54.12 | 284.97 | 333.18 | 98.87 | 103.73 |
| 4200 | 75.32 | 3.54 | 33.12 | 384.65 | 316.52 | 95.00 | 100.90 |
| 4400 | 16.72 | 2.56 | 7.68 | 1,200.26 | 287.65 | 87.57 | 94.33 |

**Table B1.2** BD05 results under full load (performance, BSFC and temperature)

Fuel type : BD05 | Test condition : Full load

| Speed (rpm) | Torque (N·m) | Fuel consumption (g/s) | Power (kW) | BSFC (g/kW·hr) | Exhaust gas temperature (°C) | Air inlet temperature (°C) | Lubricant temperature (°C) |
|---|---|---|---|---|---|---|---|
| 800 | 195.85 | 1.17 | 16.43 | 256.11 | 272.98 | 52.97 | 91.77 |
| 1000 | 216.03 | 1.56 | 22.57 | 248.85 | 285.17 | 54.10 | 94.13 |
| 1200 | 227.77 | 1.91 | 28.08 | 244.97 | 294.20 | 55.17 | 95.53 |
| 1400 | 238.13 | 2.28 | 34.97 | 234.85 | 298.10 | 56.00 | 95.90 |
| 1600 | 232.62 | 2.36 | 39.05 | 217.95 | 298.25 | 64.47 | 96.90 |
| 1800 | 234.10 | 2.60 | 44.18 | 211.79 | 302.17 | 67.30 | 97.83 |
| 2000 | 239.50 | 2.90 | 49.97 | 208.97 | 310.17 | 72.17 | 98.87 |
| 2200 | 256.07 | 3.40 | 59.07 | 207.23 | 324.40 | 79.43 | 100.33 |
| 2400 | 239.92 | 3.78 | 60.75 | 223.72 | 314.15 | 84.53 | 101.20 |
| 2600 | 242.57 | 4.25 | 66.17 | 231.10 | 321.53 | 86.57 | 102.00 |
| 2800 | 236.55 | 4.31 | 69.48 | 223.56 | 334.80 | 91.50 | 103.70 |
| 3000 | 223.83 | 4.42 | 70.37 | 225.88 | 342.18 | 94.53 | 104.43 |
| 3200 | 223.65 | 4.90 | 75.03 | 234.90 | 354.78 | 95.63 | 105.13 |
| 3400 | 200.18 | 4.99 | 71.30 | 251.93 | 357.70 | 95.83 | 105.23 |
| 3600 | 185.45 | 4.88 | 69.90 | 251.46 | 360.52 | 97.90 | 105.27 |
| 3800 | 145.23 | 4.43 | 57.80 | 275.77 | 350.18 | 97.60 | 104.53 |
| 4000 | 122.42 | 4.29 | 51.30 | 301.23 | 345.87 | 96.73 | 103.57 |
| 4200 | 69.30 | 3.61 | 30.47 | 426.89 | 328.78 | 93.30 | 101.93 |
| 4400 | 15.78 | 2.68 | 7.25 | 1,332.28 | 308.80 | 90.33 | 100.23 |

**Table B1.3** BD10 results under full load (performance, BSFC and temperature)

Fuel type : BD10 | Test condition : Full load

| Speed (rpm) | Torque (N·m) | Fuel consumption (g/s) | Power (kW) | BSFC (g/kW·hr) | Exhaust gas temperature (°C) | Air inlet temperature (°C) | Lubricant temperature (°C) |
|---|---|---|---|---|---|---|---|
| 800 | 195.80 | 1.18 | 16.33 | 259.21 | 277.07 | 51.90 | 90.83 |
| 1000 | 215.67 | 1.47 | 22.62 | 233.49 | 289.12 | 53.00 | 94.00 |
| 1200 | 227.48 | 1.82 | 28.43 | 230.17 | 298.65 | 55.27 | 95.63 |
| 1400 | 238.33 | 2.14 | 35.07 | 219.45 | 303.10 | 58.63 | 96.20 |
| 1600 | 234.93 | 2.34 | 39.43 | 213.77 | 300.80 | 62.90 | 96.67 |
| 1800 | 234.47 | 2.61 | 44.27 | 212.66 | 305.95 | 68.17 | 97.60 |
| 2000 | 238.50 | 2.92 | 50.17 | 209.74 | 313.42 | 73.90 | 98.93 |
| 2200 | 250.60 | 3.54 | 57.82 | 220.48 | 322.30 | 78.20 | 99.80 |
| 2400 | 243.23 | 3.84 | 61.68 | 224.38 | 317.83 | 81.90 | 100.57 |
| 2600 | 245.03 | 4.05 | 66.82 | 218.04 | 329.87 | 86.57 | 101.82 |
| 2800 | 241.47 | 4.29 | 70.95 | 217.45 | 337.20 | 89.10 | 103.07 |
| 3000 | 233.33 | 4.40 | 73.38 | 215.92 | 348.47 | 92.07 | 104.37 |
| 3200 | 223.38 | 4.85 | 74.98 | 233.07 | 355.97 | 92.63 | 104.60 |
| 3400 | 203.68 | 4.94 | 72.55 | 245.09 | 359.95 | 92.60 | 104.90 |
| 3600 | 195.28 | 5.07 | 73.65 | 247.69 | 368.37 | 92.93 | 104.20 |
| 3800 | 154.12 | 4.52 | 61.33 | 265.05 | 357.68 | 95.77 | 103.50 |
| 4000 | 126.70 | 4.40 | 53.05 | 298.45 | 348.10 | 94.90 | 102.03 |
| 4200 | 73.62 | 3.57 | 32.40 | 396.81 | 333.93 | 91.70 | 100.03 |
| 4400 | 21.60 | 2.75 | 9.93 | 995.99 | 307.95 | 87.17 | 93.93 |

**Table B1.4** BD15 results under full load (performance, BSFC and temperature)

Fuel type : BD15 — Test condition : Full load

| Speed (rpm) | Torque (N·m) | Fuel consumption (g/s) | Power (kW) | BSFC (g/kW·hr) | Exhaust gas temperature (°C) | Air inlet temperature (°C) | Lubricant temperature (°C) |
|---|---|---|---|---|---|---|---|
| 800 | 193.30 | 1.21 | 16.22 | 269.52 | 280.25 | 49.40 | 88.53 |
| 1000 | 214.57 | 1.52 | 22.63 | 241.54 | 292.45 | 52.03 | 93.70 |
| 1200 | 224.60 | 1.82 | 27.92 | 235.12 | 303.88 | 54.37 | 95.80 |
| 1400 | 234.80 | 2.17 | 34.45 | 226.45 | 309.55 | 57.57 | 96.43 |
| 1600 | 231.75 | 2.32 | 38.85 | 214.59 | 308.48 | 62.17 | 96.93 |
| 1800 | 231.87 | 2.60 | 43.72 | 214.20 | 315.38 | 67.07 | 97.97 |
| 2000 | 231.47 | 2.83 | 48.60 | 209.73 | 322.53 | 73.00 | 99.20 |
| 2200 | 244.42 | 3.33 | 56.17 | 213.62 | 332.22 | 77.27 | 100.13 |
| 2400 | 241.33 | 3.82 | 60.67 | 226.49 | 327.52 | 82.27 | 100.60 |
| 2600 | 242.28 | 4.17 | 66.07 | 227.21 | 333.88 | 84.27 | 101.13 |
| 2800 | 238.07 | 4.14 | 69.92 | 213.18 | 344.83 | 88.70 | 102.67 |
| 3000 | 229.83 | 4.39 | 72.25 | 218.62 | 352.93 | 90.47 | 102.80 |
| 3200 | 224.90 | 4.68 | 75.42 | 223.56 | 360.98 | 91.27 | 102.13 |
| 3400 | 208.85 | 5.02 | 74.37 | 242.79 | 365.27 | 91.70 | 103.58 |
| 3600 | 186.17 | 4.86 | 70.18 | 249.54 | 367.55 | 96.90 | 105.03 |
| 3800 | 143.28 | 4.46 | 57.02 | 281.40 | 355.58 | 95.77 | 104.30 |
| 4000 | 122.17 | 4.26 | 51.10 | 299.88 | 350.53 | 95.40 | 103.10 |
| 4200 | 71.35 | 3.54 | 31.40 | 406.27 | 334.92 | 91.83 | 100.23 |
| 4400 | 17.07 | 2.67 | 7.83 | 1,227.44 | 308.58 | 86.57 | 95.57 |

**Table B1.5** BD20 results under full load (performance, BSFC and temperature)

Fuel type : BD20 — Test condition : Full load

| Speed (rpm) | Torque (N·m) | Fuel consumption (g/s) | Power (kW) | BSFC (g/kW·hr) | Exhaust gas temperature (°C) | Air inlet temperature (°C) | Lubricant temperature (°C) |
|---|---|---|---|---|---|---|---|
| 800 | 192.32 | 1.25 | 16.07 | 280.59 | 280.08 | 53.00 | 88.83 |
| 1000 | 211.00 | 1.52 | 21.88 | 250.10 | 291.27 | 55.40 | 93.33 |
| 1200 | 221.70 | 1.87 | 27.97 | 241.32 | 300.17 | 57.13 | 94.87 |
| 1400 | 230.40 | 2.19 | 33.83 | 233.52 | 305.50 | 60.47 | 95.53 |
| 1600 | 228.63 | 2.40 | 38.18 | 226.33 | 304.28 | 63.63 | 95.37 |
| 1800 | 226.97 | 2.57 | 42.82 | 215.79 | 308.77 | 67.60 | 95.90 |
| 2000 | 195.80 | 2.55 | 41.13 | 223.12 | 313.93 | 72.67 | 97.00 |
| 2200 | 224.78 | 3.17 | 51.85 | 220.10 | 323.07 | 79.00 | 98.33 |
| 2400 | 229.20 | 3.73 | 57.77 | 232.37 | 323.28 | 83.67 | 99.15 |
| 2600 | 221.02 | 4.02 | 60.25 | 240.46 | 327.97 | 86.53 | 99.97 |
| 2800 | 213.25 | 4.00 | 62.63 | 230.02 | 336.80 | 90.97 | 102.03 |
| 3000 | 204.07 | 4.13 | 64.17 | 231.70 | 345.22 | 93.20 | 102.77 |
| 3200 | 201.13 | 4.33 | 67.52 | 231.09 | 352.35 | 95.17 | 102.97 |
| 3400 | 181.37 | 4.61 | 64.57 | 257.27 | 356.17 | 96.63 | 103.00 |
| 3600 | 174.52 | 4.89 | 65.78 | 267.84 | 364.03 | 97.83 | 102.43 |
| 3800 | 144.38 | 4.55 | 57.47 | 285.05 | 355.45 | 95.83 | 99.37 |
| 4000 | 124.70 | 4.36 | 52.27 | 300.54 | 347.85 | 95.53 | 97.07 |
| 4200 | 70.92 | 3.68 | 31.18 | 424.68 | 329.43 | 89.60 | 92.73 |
| 4400 | 18.27 | 2.75 | 8.42 | 1,178.97 | 301.63 | 83.10 | 85.70 |

**Table B1.6** BD25 results under full load (performance, BSFC and temperature)

Fuel type : BD25 — Test condition : Full load

| Speed (rpm) | Torque (N·m) | Fuel consumption (g/s) | Power (kW) | BSFC (g/kW·hr) | Exhaust gas temperature (°C) | Air inlet temperature (°C) | Lubricant temperature (°C) |
|---|---|---|---|---|---|---|---|
| 800 | 190.08 | 1.14 | 15.87 | 259.83 | 281.27 | 52.27 | 89.57 |
| 1000 | 209.20 | 1.51 | 21.73 | 249.52 | 290.37 | 53.57 | 92.20 |
| 1200 | 217.38 | 1.92 | 27.37 | 252.30 | 300.52 | 55.43 | 94.30 |
| 1400 | 225.53 | 2.33 | 33.03 | 254.44 | 306.13 | 56.30 | 94.93 |
| 1600 | 222.65 | 2.64 | 37.35 | 254.04 | 304.62 | 60.00 | 94.90 |
| 1800 | 221.10 | 2.71 | 41.68 | 233.76 | 310.43 | 65.80 | 95.70 |
| 2000 | 191.20 | 2.57 | 39.97 | 231.20 | 311.00 | 71.83 | 97.07 |
| 2200 | 229.95 | 3.29 | 53.07 | 223.28 | 320.62 | 78.67 | 98.50 |
| 2400 | 230.83 | 3.60 | 58.32 | 222.49 | 321.45 | 82.50 | 99.13 |
| 2600 | 225.25 | 3.74 | 61.47 | 219.29 | 322.55 | 84.03 | 99.47 |
| 2800 | 177.30 | 3.74 | 52.10 | 258.49 | 314.45 | 85.93 | 100.13 |
| 3000 | 178.62 | 3.84 | 56.13 | 246.34 | 326.95 | 91.73 | 102.57 |
| 3200 | 185.92 | 4.29 | 62.37 | 247.87 | 337.62 | 93.67 | 103.17 |
| 3400 | 167.93 | 4.20 | 59.80 | 252.69 | 338.70 | 95.63 | 103.87 |
| 3600 | 168.50 | 4.66 | 63.52 | 264.16 | 352.40 | 97.60 | 103.90 |
| 3800 | 135.13 | 4.46 | 53.77 | 298.87 | 348.33 | 97.53 | 103.60 |
| 4000 | 116.18 | 4.28 | 48.67 | 316.39 | 344.18 | 95.73 | 101.13 |
| 4200 | 66.77 | 3.50 | 29.37 | 429.32 | 330.40 | 91.30 | 98.43 |
| 4400 | 15.60 | 2.61 | 7.15 | 1,316.69 | 306.87 | 87.30 | 95.27 |

**Table B1.7** BD30 results under full load (performance, BSFC and temperature)

Fuel type : BD30 — Test condition : Full load

| Speed (rpm) | Torque (N·m) | Fuel consumption (g/s) | Power (kW) | BSFC (g/kW·hr) | Exhaust gas temperature (°C) | Air inlet temperature (°C) | Lubricant temperature (°C) |
|---|---|---|---|---|---|---|---|
| 800 | 188.97 | 1.16 | 15.88 | 262.24 | 279.97 | 51.23 | 89.20 |
| 1000 | 207.22 | 1.51 | 21.65 | 251.69 | 289.05 | 52.37 | 92.73 |
| 1200 | 216.42 | 1.88 | 26.80 | 253.00 | 298.37 | 54.07 | 94.27 |
| 1400 | 223.27 | 2.31 | 32.83 | 253.53 | 303.23 | 56.63 | 94.87 |
| 1600 | 220.93 | 2.62 | 37.00 | 254.93 | 302.42 | 58.43 | 94.70 |
| 1800 | 218.25 | 2.73 | 41.18 | 238.86 | 308.77 | 66.77 | 96.13 |
| 2000 | 184.63 | 2.50 | 38.70 | 232.80 | 308.78 | 71.83 | 97.37 |
| 2200 | 222.78 | 3.15 | 51.45 | 220.39 | 319.85 | 77.37 | 98.50 |
| 2400 | 226.72 | 3.59 | 57.08 | 226.21 | 320.57 | 82.23 | 99.37 |
| 2600 | 216.33 | 3.92 | 59.00 | 239.48 | 320.33 | 83.53 | 99.67 |
| 2800 | 175.80 | 3.87 | 51.58 | 269.92 | 313.67 | 85.50 | 100.57 |
| 3000 | 185.35 | 4.00 | 58.28 | 247.19 | 334.25 | 91.40 | 102.87 |
| 3200 | 189.23 | 4.33 | 63.43 | 245.77 | 345.13 | 93.87 | 103.80 |
| 3400 | 173.87 | 4.23 | 61.93 | 245.99 | 346.30 | 95.87 | 104.40 |
| 3600 | 168.38 | 4.78 | 63.43 | 271.09 | 358.03 | 97.23 | 104.07 |
| 3800 | 134.83 | 4.49 | 53.65 | 301.61 | 351.95 | 96.17 | 104.03 |
| 4000 | 114.10 | 4.24 | 47.82 | 319.52 | 342.83 | 95.33 | 101.90 |
| 4200 | 65.25 | 3.51 | 28.68 | 440.68 | 329.82 | 92.43 | 99.57 |
| 4400 | 15.05 | 2.65 | 6.90 | 1,381.54 | 304.37 | 85.93 | 95.20 |

**Table B1.8** BD35 results under full load (performance, BSFC and temperature)

Fuel type : BD35 Test condition : Full load

| Speed (rpm) | Torque (N·m) | Fuel consumption (g/s) | Power (kW) | BSFC (g/kW·hr) | Exhaust gas temperature (°C) | Air inlet temperature (°C) | Lubricant temperature (°C) |
|---|---|---|---|---|---|---|---|
| 800 | 187.78 | 1.21 | 15.82 | 274.39 | 279.90 | 51.00 | 89.33 |
| 1000 | 204.72 | 1.51 | 21.47 | 253.78 | 287.87 | 52.03 | 92.43 |
| 1200 | 214.18 | 1.81 | 26.78 | 242.94 | 298.33 | 53.50 | 94.17 |
| 1400 | 221.72 | 2.16 | 32.52 | 239.34 | 303.75 | 55.17 | 94.47 |
| 1600 | 214.18 | 2.43 | 35.87 | 244.08 | 301.77 | 58.03 | 94.37 |
| 1800 | 211.37 | 2.88 | 39.85 | 259.82 | 304.00 | 59.90 | 94.37 |
| 2000 | 161.22 | 2.44 | 33.83 | 259.47 | 294.12 | 66.43 | 95.83 |
| 2200 | 200.72 | 3.10 | 46.13 | 242.38 | 312.85 | 73.13 | 97.30 |
| 2400 | 213.90 | 3.52 | 53.72 | 235.86 | 315.22 | 77.77 | 97.93 |
| 2600 | 175.17 | 3.39 | 47.82 | 255.68 | 308.10 | 76.20 | 97.87 |
| 2800 | 126.75 | 3.29 | 37.20 | 318.33 | 302.65 | 77.97 | 98.57 |
| 3000 | 151.30 | 3.41 | 47.58 | 257.89 | 319.33 | 88.70 | 101.97 |
| 3200 | 165.52 | 3.92 | 55.53 | 253.94 | 334.63 | 91.60 | 102.77 |
| 3400 | 149.03 | 3.75 | 53.08 | 254.16 | 333.57 | 93.20 | 103.47 |
| 3600 | 142.15 | 4.50 | 53.57 | 302.31 | 338.97 | 95.30 | 103.60 |
| 3800 | 130.87 | 4.44 | 52.07 | 307.19 | 349.32 | 96.37 | 103.23 |
| 4000 | 109.57 | 4.33 | 45.87 | 340.17 | 340.38 | 95.20 | 101.53 |
| 4200 | 61.70 | 3.56 | 27.10 | 472.78 | 322.13 | 90.47 | 98.97 |
| 4400 | 11.70 | 2.66 | 5.38 | 1,781.25 | 296.00 | 82.63 | 94.83 |

**Table B1.9** BD40 results under full load (performance, BSFC and temperature)

Fuel type : BD40 Test condition : Full load

| Speed (rpm) | Torque (N·m) | Fuel consumption (g/s) | Power (kW) | BSFC (g/kW·hr) | Exhaust gas temperature (°C) | Air inlet temperature (°C) | Lubricant temperature (°C) |
|---|---|---|---|---|---|---|---|
| 800 | 179.80 | 1.18 | 15.20 | 280.13 | 280.17 | 54.13 | 91.83 |
| 1,000 | 193.87 | 1.46 | 20.27 | 258.99 | 288.00 | 54.97 | 93.33 |
| 1,200 | 201.40 | 1.77 | 25.43 | 249.95 | 294.15 | 56.43 | 94.50 |
| 1,400 | 206.87 | 2.04 | 30.37 | 241.52 | 295.12 | 58.57 | 94.57 |
| 1,600 | 189.37 | 2.13 | 31.78 | 241.15 | 291.42 | 61.17 | 94.27 |
| 1,800 | 185.47 | 2.24 | 34.95 | 230.53 | 292.23 | 63.53 | 94.57 |
| 2,000 | 129.92 | 1.89 | 27.27 | 248.92 | 280.03 | 67.70 | 95.73 |
| 2,200 | 146.92 | 2.24 | 33.80 | 238.56 | 294.27 | 72.47 | 97.03 |
| 2,400 | 187.37 | 3.27 | 47.23 | 249.00 | 303.58 | 74.87 | 97.00 |
| 2,600 | 144.25 | 2.98 | 39.35 | 272.44 | 296.37 | 75.90 | 97.80 |
| 2,800 | 101.73 | 2.36 | 29.85 | 284.91 | 283.17 | 77.93 | 99.47 |
| 3,000 | 86.88 | 2.41 | 27.32 | 317.34 | 290.45 | 84.63 | 101.13 |
| 3,200 | 127.52 | 3.48 | 42.65 | 294.87 | 318.58 | 92.10 | 102.23 |
| 3,400 | 130.25 | 3.67 | 46.38 | 284.98 | 324.25 | 94.40 | 102.03 |
| 3,600 | 128.53 | 3.97 | 48.43 | 295.41 | 329.52 | 95.53 | 102.10 |
| 3,800 | 108.52 | 3.91 | 43.18 | 325.72 | 333.55 | 95.40 | 100.63 |
| 4,000 | 90.15 | 3.80 | 37.75 | 362.18 | 324.52 | 93.43 | 99.13 |
| 4,200 | 48.22 | 3.22 | 21.20 | 547.41 | 309.25 | 89.27 | 97.00 |
| 4,400 | 0.40 | 2.44 | 0.22 | 2,113.57 | 292.70 | 84.83 | 93.60 |

## B-2: Emission, Air/Fuel Ratio and Lambda Data

**Table B2.1** Diesel results under full load (exhaust gas emission, AFR and lambda)

Fuel type : Diesel

Test condition : Full load

| Speed | CO | $CO_2$ | NO/$NO_x$ | $O_2$ | THC | Spindt's formula | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (rpm) | (ppm) | (ppm) | (ppm) | (ppm) | (ppm) | $F_b$ | R | Q | S | $F_c$ | $F_h$ | $F_o$ | AFR | $\lambda$ |
| 800 | 1,159 | 120,256 | 1,966 | 44,874 | 111 | 0.999 | 0.010 | 0.373 | 0.016 | 0.867 | 0.133 | 0.000 | 18.35 | 1.26 |
| 1,000 | 884 | 121,112 | 1,564 | 43,985 | 103 | 0.999 | 0.007 | 0.363 | 0.013 | 0.867 | 0.133 | 0.000 | 18.22 | 1.26 |
| 1,200 | 347 | 116,088 | 1,958 | 51,109 | 102 | 0.999 | 0.003 | 0.440 | 0.017 | 0.867 | 0.133 | 0.000 | 18.99 | 1.31 |
| 1,400 | 173 | 110,469 | 2,232 | 58,703 | 94 | 0.999 | 0.002 | 0.531 | 0.020 | 0.867 | 0.133 | 0.000 | 19.91 | 1.37 |
| 1,600 | 131 | 104,213 | 2,447 | 67,062 | 94 | 0.999 | 0.001 | 0.644 | 0.023 | 0.867 | 0.133 | 0.000 | 21.04 | 1.45 |
| 1,800 | 89 | 97,956 | 2,663 | 75,421 | 94 | 0.999 | 0.001 | 0.770 | 0.027 | 0.867 | 0.133 | 0.000 | 22.32 | 1.54 |
| 2,000 | 70 | 86,602 | 1,684 | 90,558 | 78 | 0.999 | 0.001 | 1.046 | 0.019 | 0.867 | 0.133 | 0.000 | 25.02 | 1.72 |
| 2,200 | 66 | 87,290 | 1,822 | 89,576 | 85 | 0.999 | 0.001 | 1.026 | 0.021 | 0.867 | 0.133 | 0.000 | 24.83 | 1.71 |
| 2,400 | 56 | 82,783 | 1,656 | 97,077 | 74 | 0.999 | 0.001 | 1.173 | 0.020 | 0.867 | 0.133 | 0.000 | 26.29 | 1.81 |
| 2,600 | 55 | 82,003 | 1,603 | 98,281 | 75 | 0.999 | 0.001 | 1.199 | 0.020 | 0.867 | 0.133 | 0.000 | 26.54 | 1.83 |
| 2,800 | 56 | 82,613 | 1,535 | 97,443 | 77 | 0.999 | 0.001 | 1.180 | 0.019 | 0.867 | 0.133 | 0.000 | 26.35 | 1.82 |
| 3,000 | 68 | 81,559 | 1,242 | 98,939 | 78 | 0.999 | 0.001 | 1.213 | 0.015 | 0.867 | 0.133 | 0.000 | 26.67 | 1.84 |
| 3,200 | 76 | 81,299 | 1,191 | 99,305 | 82 | 0.999 | 0.001 | 1.221 | 0.015 | 0.867 | 0.133 | 0.000 | 26.75 | 1.84 |
| 3,400 | 82 | 80,149 | 1,190 | 100,819 | 81 | 0.999 | 0.001 | 1.258 | 0.015 | 0.867 | 0.133 | 0.000 | 27.11 | 1.87 |
| 3,600 | 97 | 77,321 | 1,088 | 104,768 | 86 | 0.999 | 0.001 | 1.355 | 0.014 | 0.867 | 0.133 | 0.000 | 28.07 | 1.93 |
| 3,800 | 80 | 67,381 | 959 | 118,639 | 91 | 0.999 | 0.001 | 1.761 | 0.014 | 0.867 | 0.133 | 0.000 | 32.10 | 2.21 |
| 4,000 | 91 | 62,740 | 954 | 125,048 | 107 | 0.998 | 0.001 | 1.993 | 0.015 | 0.867 | 0.133 | 0.000 | 34.40 | 2.37 |
| 4,200 | 117 | 51,361 | 482 | 140,609 | 115 | 0.998 | 0.002 | 2.738 | 0.009 | 0.867 | 0.133 | 0.000 | 41.76 | 2.88 |
| 4,400 | 135 | 38,031 | 250 | 158,648 | 133 | 0.997 | 0.004 | 4.172 | 0.007 | 0.867 | 0.133 | 0.000 | 55.93 | 3.85 |

**Table B2.2** DB05 results under full load (exhaust gas emission, AFR and lambda)

Fuel type : BD05

Test condition : Full load

| Speed | CO | $CO_2$ | $NO/NO_x$ | $O_2$ | THC | Spindt's formula | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (rpm) | (ppm) | (ppm) | (ppm) | (ppm) | (ppm) | $F_b$ | R | Q | S | $F_c$ | $F_h$ | $F_o$ | AFR | λ |
| 800 | 1,096 | 182,782 | 2,085 | 49,805 | 118 | 0.999 | 0.006 | 0.272 | 0.011 | 0.862 | 0.133 | 0.005 | 17.23 | 1.19 |
| 1,000 | 619 | 180,473 | 1,815 | 52,264 | 108 | 0.999 | 0.003 | 0.290 | 0.010 | 0.862 | 0.133 | 0.005 | 17.38 | 1.20 |
| 1,200 | 315 | 173,685 | 2,177 | 58,383 | 109 | 0.999 | 0.002 | 0.336 | 0.013 | 0.862 | 0.133 | 0.005 | 17.85 | 1.24 |
| 1,400 | 154 | 161,056 | 2,545 | 69,296 | 95 | 0.999 | 0.001 | 0.430 | 0.016 | 0.862 | 0.133 | 0.005 | 18.79 | 1.30 |
| 1,600 | 89 | 141,936 | 2,992 | 86,159 | 98 | 0.999 | 0.001 | 0.607 | 0.021 | 0.862 | 0.133 | 0.005 | 20.57 | 1.42 |
| 1,800 | 79 | 129,022 | 2,210 | 99,196 | 87 | 0.999 | 0.001 | 0.769 | 0.017 | 0.862 | 0.133 | 0.005 | 22.15 | 1.53 |
| 2,000 | 68 | 123,061 | 1,849 | 104,883 | 81 | 0.999 | 0.001 | 0.852 | 0.015 | 0.862 | 0.133 | 0.005 | 22.97 | 1.59 |
| 2,200 | 64 | 122,111 | 1,975 | 105,881 | 86 | 0.999 | 0.001 | 0.867 | 0.016 | 0.862 | 0.133 | 0.005 | 23.12 | 1.60 |
| 2,400 | 54 | 113,459 | 1,788 | 114,097 | 78 | 0.999 | 0.000 | 1.006 | 0.016 | 0.862 | 0.133 | 0.005 | 24.49 | 1.70 |
| 2,600 | 50 | 112,082 | 1,763 | 115,398 | 76 | 0.999 | 0.000 | 1.030 | 0.016 | 0.862 | 0.133 | 0.005 | 24.72 | 1.71 |
| 2,800 | 49 | 110,707 | 1,672 | 116,718 | 76 | 0.999 | 0.000 | 1.054 | 0.015 | 0.862 | 0.133 | 0.005 | 24.97 | 1.73 |
| 3,000 | 54 | 106,969 | 1,332 | 120,359 | 82 | 0.999 | 0.001 | 1.125 | 0.012 | 0.862 | 0.133 | 0.005 | 25.65 | 1.78 |
| 3,200 | 61 | 109,297 | 1,319 | 118,227 | 84 | 0.999 | 0.001 | 1.082 | 0.012 | 0.862 | 0.133 | 0.005 | 25.22 | 1.75 |
| 3,400 | 59 | 100,799 | 1,280 | 126,487 | 90 | 0.999 | 0.001 | 1.255 | 0.013 | 0.862 | 0.133 | 0.005 | 26.93 | 1.87 |
| 3,600 | 67 | 99,496 | 1,187 | 127,690 | 95 | 0.999 | 0.001 | 1.283 | 0.012 | 0.862 | 0.133 | 0.005 | 27.21 | 1.88 |
| 3,800 | 68 | 86,463 | 1,021 | 140,763 | 103 | 0.999 | 0.001 | 1.628 | 0.012 | 0.862 | 0.133 | 0.005 | 30.62 | 2.12 |
| 4,000 | 73 | 81,707 | 1,029 | 145,918 | 104 | 0.999 | 0.001 | 1.786 | 0.013 | 0.862 | 0.133 | 0.005 | 32.18 | 2.23 |
| 4,200 | 90 | 65,869 | 519 | 163,543 | 109 | 0.998 | 0.001 | 2.483 | 0.008 | 0.862 | 0.133 | 0.005 | 39.04 | 2.70 |
| 4,400 | 135 | 50,140 | 269 | 181,146 | 149 | 0.997 | 0.003 | 3.613 | 0.005 | 0.862 | 0.133 | 0.005 | 50.14 | 3.47 |

**Table B2.3** DB10 results under full load (exhaust gas emission, AFR and lambda)

Fuel type : BD10

Test condition : Full load

| Speed | CO | $CO_2$ | $NO/NO_x$ | $O_2$ | THC | Spindt's formula | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (rpm) | (ppm) | (ppm) | (ppm) | (ppm) | (ppm) | $F_b$ | R | Q | S | $F_c$ | $F_h$ | $F_o$ | AFR | λ |
| 800 | 840 | 179,143 | 2,209 | 51,768 | 105 | 0.999 | 0.005 | 0.289 | 0.012 | 0.857 | 0.133 | 0.009 | 17.30 | 1.20 |
| 1,000 | 562 | 178,149 | 1,816 | 52,805 | 95 | 0.999 | 0.003 | 0.296 | 0.010 | 0.857 | 0.133 | 0.009 | 17.36 | 1.21 |
| 1,200 | 275 | 171,305 | 2,212 | 58,803 | 99 | 0.999 | 0.002 | 0.343 | 0.013 | 0.857 | 0.133 | 0.009 | 17.83 | 1.24 |
| 1,400 | 148 | 159,575 | 2,537 | 69,051 | 86 | 0.999 | 0.001 | 0.433 | 0.016 | 0.857 | 0.133 | 0.009 | 18.72 | 1.30 |
| 1,600 | 87 | 140,434 | 2,954 | 86,098 | 89 | 0.999 | 0.001 | 0.613 | 0.021 | 0.857 | 0.133 | 0.009 | 20.52 | 1.43 |
| 1,800 | 78 | 127,413 | 2,182 | 99,236 | 81 | 0.999 | 0.001 | 0.779 | 0.017 | 0.857 | 0.133 | 0.009 | 22.13 | 1.54 |
| 2,000 | 66 | 120,944 | 1,858 | 105,495 | 75 | 0.999 | 0.001 | 0.872 | 0.015 | 0.857 | 0.133 | 0.009 | 23.04 | 1.60 |
| 2,200 | 61 | 116,964 | 1,917 | 109,326 | 76 | 0.999 | 0.001 | 0.935 | 0.016 | 0.857 | 0.133 | 0.009 | 23.66 | 1.65 |
| 2,400 | 52 | 112,012 | 1,775 | 114,068 | 70 | 0.999 | 0.000 | 1.018 | 0.016 | 0.857 | 0.133 | 0.009 | 24.48 | 1.70 |
| 2,600 | 49 | 110,694 | 1,735 | 115,424 | 67 | 0.999 | 0.000 | 1.043 | 0.016 | 0.857 | 0.133 | 0.009 | 24.72 | 1.72 |
| 2,800 | 49 | 110,023 | 1,639 | 116,097 | 65 | 0.999 | 0.000 | 1.055 | 0.015 | 0.857 | 0.133 | 0.009 | 24.84 | 1.73 |
| 3,000 | 56 | 108,481 | 1,323 | 117,722 | 68 | 0.999 | 0.001 | 1.085 | 0.012 | 0.857 | 0.133 | 0.009 | 25.12 | 1.75 |
| 3,200 | 61 | 107,286 | 1,279 | 118,916 | 74 | 0.999 | 0.001 | 1.108 | 0.012 | 0.857 | 0.133 | 0.009 | 25.35 | 1.76 |
| 3,400 | 61 | 104,074 | 1,292 | 121,967 | 74 | 0.999 | 0.001 | 1.172 | 0.012 | 0.857 | 0.133 | 0.009 | 25.98 | 1.81 |
| 3,600 | 71 | 101,242 | 1,172 | 124,848 | 79 | 0.999 | 0.001 | 1.233 | 0.012 | 0.857 | 0.133 | 0.009 | 26.57 | 1.85 |
| 3,800 | 68 | 88,167 | 1,031 | 137,801 | 88 | 0.999 | 0.001 | 1.563 | 0.012 | 0.857 | 0.133 | 0.009 | 29.81 | 2.08 |
| 4,000 | 73 | 81,623 | 1,022 | 144,907 | 97 | 0.999 | 0.001 | 1.775 | 0.013 | 0.857 | 0.133 | 0.009 | 31.90 | 2.22 |
| 4,200 | 85 | 65,760 | 517 | 162,549 | 92 | 0.999 | 0.001 | 2.472 | 0.008 | 0.857 | 0.133 | 0.009 | 38.73 | 2.70 |
| 4,400 | 125 | 49,245 | 248 | 181,216 | 108 | 0.998 | 0.003 | 3.680 | 0.005 | 0.857 | 0.133 | 0.009 | 50.56 | 3.52 |

**Table B2.4** DB15 results under full load (exhaust gas emission, AFR and lambda)

Fuel type : BD15

Test condition : Full load

| Speed | CO | $CO_2$ | $NO/NO_x$ | $O_2$ | THC | Spindt's formula | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (rpm) | (ppm) | (ppm) | (ppm) | (ppm) | (ppm) | $F_b$ | R | Q | S | $F_c$ | $F_h$ | $F_o$ | AFR | λ |
| 800 | 572 | 175,070 | 2,480 | 56,536 | 106 | 0.999 | 0.003 | 0.323 | 0.014 | 0.852 | 0.134 | 0.014 | 17.54 | 1.23 |
| 1,000 | 396 | 175,126 | 1,951 | 56,679 | 95 | 0.999 | 0.002 | 0.324 | 0.011 | 0.852 | 0.134 | 0.014 | 17.53 | 1.23 |
| 1,200 | 215 | 168,266 | 2,316 | 62,742 | 99 | 0.999 | 0.001 | 0.373 | 0.014 | 0.852 | 0.134 | 0.014 | 18.02 | 1.26 |
| 1,400 | 130 | 156,626 | 2,604 | 72,849 | 88 | 0.999 | 0.001 | 0.465 | 0.017 | 0.852 | 0.134 | 0.014 | 18.94 | 1.33 |
| 1,600 | 104 | 141,919 | 2,391 | 86,684 | 87 | 0.999 | 0.001 | 0.611 | 0.017 | 0.852 | 0.134 | 0.014 | 20.36 | 1.43 |
| 1,800 | 78 | 127,211 | 2,179 | 100,519 | 86 | 0.999 | 0.001 | 0.790 | 0.017 | 0.852 | 0.134 | 0.014 | 22.12 | 1.55 |
| 2,000 | 66 | 118,338 | 1,786 | 108,913 | 77 | 0.999 | 0.001 | 0.920 | 0.015 | 0.852 | 0.134 | 0.014 | 23.38 | 1.64 |
| 2,200 | 60 | 116,990 | 1,922 | 110,114 | 80 | 0.999 | 0.001 | 0.941 | 0.016 | 0.852 | 0.134 | 0.014 | 23.59 | 1.65 |
| 2,400 | 48 | 111,180 | 1,788 | 115,742 | 71 | 0.999 | 0.000 | 1.041 | 0.016 | 0.852 | 0.134 | 0.014 | 24.57 | 1.72 |
| 2,600 | 46 | 109,680 | 1,746 | 117,295 | 69 | 0.999 | 0.000 | 1.069 | 0.016 | 0.852 | 0.134 | 0.014 | 24.84 | 1.74 |
| 2,800 | 44 | 108,731 | 1,651 | 118,177 | 67 | 0.999 | 0.000 | 1.087 | 0.015 | 0.852 | 0.134 | 0.014 | 25.01 | 1.75 |
| 3,000 | 50 | 106,464 | 1,309 | 120,394 | 70 | 0.999 | 0.000 | 1.131 | 0.012 | 0.852 | 0.134 | 0.014 | 25.43 | 1.78 |
| 3,200 | 54 | 106,662 | 1,273 | 120,238 | 73 | 0.999 | 0.001 | 1.127 | 0.012 | 0.852 | 0.134 | 0.014 | 25.39 | 1.78 |
| 3,400 | 75 | 102,804 | 1,216 | 124,059 | 81 | 0.999 | 0.001 | 1.207 | 0.012 | 0.852 | 0.134 | 0.014 | 26.16 | 1.83 |
| 3,600 | 63 | 98,565 | 1,186 | 127,931 | 87 | 0.999 | 0.001 | 1.298 | 0.012 | 0.852 | 0.134 | 0.014 | 27.05 | 1.89 |
| 3,800 | 66 | 85,095 | 1,020 | 141,353 | 93 | 0.999 | 0.001 | 1.661 | 0.012 | 0.852 | 0.134 | 0.014 | 30.60 | 2.14 |
| 4,000 | 72 | 80,937 | 1,034 | 145,845 | 98 | 0.999 | 0.001 | 1.802 | 0.013 | 0.852 | 0.134 | 0.014 | 31.98 | 2.24 |
| 4,200 | 87 | 65,080 | 516 | 163,590 | 100 | 0.998 | 0.001 | 2.514 | 0.008 | 0.852 | 0.134 | 0.014 | 38.91 | 2.72 |
| 4,400 | 118 | 50,155 | 264 | 180,508 | 112 | 0.998 | 0.002 | 3.599 | 0.005 | 0.852 | 0.134 | 0.014 | 49.47 | 3.46 |

**Table B2.5** DB20 results under full load (exhaust gas emission, AFR and lambda)

Fuel type :BD20

Test condition : Full load

| Speed | CO | $CO_2$ | $NO/NO_x$ | $O_2$ | THC | Spindt's formula | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (rpm) | (ppm) | (ppm) | (ppm) | (ppm) | (ppm) | $F_b$ | R | Q | S | $F_c$ | $F_h$ | $F_o$ | AFR | λ |
| 800 | 700 | 178,037 | 2,329 | 52,754 | 125 | 0.999 | 0.004 | 0.296 | 0.013 | 0.847 | 0.134 | 0.020 | 17.17 | 1.21 |
| 1,000 | 416 | 176,093 | 1,988 | 54,847 | 118 | 0.999 | 0.002 | 0.311 | 0.011 | 0.847 | 0.134 | 0.020 | 17.30 | 1.22 |
| 1,200 | 223 | 168,957 | 2,354 | 61,130 | 118 | 0.999 | 0.001 | 0.362 | 0.014 | 0.847 | 0.134 | 0.020 | 17.80 | 1.25 |
| 1,400 | 130 | 156,952 | 2,679 | 71,583 | 106 | 0.999 | 0.001 | 0.456 | 0.017 | 0.847 | 0.134 | 0.020 | 18.73 | 1.32 |
| 1,600 | 88 | 138,258 | 3,048 | 88,202 | 106 | 0.999 | 0.001 | 0.638 | 0.022 | 0.847 | 0.134 | 0.020 | 20.52 | 1.45 |
| 1,800 | 82 | 124,289 | 2,190 | 102,508 | 94 | 0.999 | 0.001 | 0.825 | 0.018 | 0.847 | 0.134 | 0.020 | 22.32 | 1.57 |
| 2,000 | 74 | 102,689 | 1,401 | 123,562 | 87 | 0.999 | 0.001 | 1.203 | 0.014 | 0.847 | 0.134 | 0.020 | 25.98 | 1.83 |
| 2,200 | 61 | 109,621 | 1,723 | 116,461 | 82 | 0.999 | 0.001 | 1.062 | 0.016 | 0.847 | 0.134 | 0.020 | 24.62 | 1.73 |
| 2,400 | 50 | 106,484 | 1,743 | 119,824 | 76 | 0.999 | 0.000 | 1.125 | 0.016 | 0.847 | 0.134 | 0.020 | 25.23 | 1.78 |
| 2,600 | 47 | 104,407 | 1,730 | 121,777 | 75 | 0.999 | 0.000 | 1.166 | 0.017 | 0.847 | 0.134 | 0.020 | 25.63 | 1.80 |
| 2,800 | 46 | 102,038 | 1,663 | 124,098 | 80 | 0.999 | 0.000 | 1.216 | 0.016 | 0.847 | 0.134 | 0.020 | 26.12 | 1.84 |
| 3,000 | 52 | 99,250 | 1,336 | 126,963 | 85 | 0.999 | 0.001 | 1.279 | 0.013 | 0.847 | 0.134 | 0.020 | 26.71 | 1.88 |
| 3,200 | 58 | 99,858 | 1,312 | 126,381 | 90 | 0.999 | 0.001 | 1.266 | 0.013 | 0.847 | 0.134 | 0.020 | 26.58 | 1.87 |
| 3,400 | 55 | 96,298 | 1,316 | 129,892 | 88 | 0.999 | 0.001 | 1.349 | 0.014 | 0.847 | 0.134 | 0.020 | 27.39 | 1.93 |
| 3,600 | 62 | 94,984 | 1,206 | 131,317 | 94 | 0.999 | 0.001 | 1.383 | 0.013 | 0.847 | 0.134 | 0.020 | 27.71 | 1.95 |
| 3,800 | 72 | 86,444 | 1,059 | 139,835 | 113 | 0.999 | 0.001 | 1.618 | 0.012 | 0.847 | 0.134 | 0.020 | 29.98 | 2.11 |
| 4,000 | 79 | 80,823 | 1,034 | 146,079 | 115 | 0.999 | 0.001 | 1.807 | 0.013 | 0.847 | 0.134 | 0.020 | 31.83 | 2.24 |
| 4,200 | 91 | 65,080 | 513 | 163,632 | 120 | 0.998 | 0.001 | 2.514 | 0.008 | 0.847 | 0.134 | 0.020 | 38.66 | 2.72 |
| 4,400 | 144 | 49,475 | 244 | 181,457 | 159 | 0.997 | 0.003 | 3.668 | 0.005 | 0.847 | 0.134 | 0.020 | 49.78 | 3.50 |

**Table B2.6** DB25 results under full load (exhaust gas emission, AFR and lambda)

Fuel type : BD25

Test condition : Full load

| Speed | CO | $CO_2$ | $NO/NO_x$ | $O_2$ | THC | Spindt's formula | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (rpm) | (ppm) | (ppm) | (ppm) | (ppm) | (ppm) | $F_b$ | R | Q | S | $F_c$ | $F_b$ | $F_o$ | AFR | λ |
| 800 | 528 | 173,739 | 2,451 | 56,195 | 115 | 0.999 | 0.003 | 0.323 | 0.014 | 0.841 | 0.134 | 0.026 | 17.32 | 1.23 |
| 1,000 | 370 | 172,396 | 1,954 | 57,586 | 111 | 0.999 | 0.002 | 0.334 | 0.011 | 0.841 | 0.134 | 0.026 | 17.41 | 1.23 |
| 1,200 | 196 | 164,249 | 2,284 | 64,732 | 112 | 0.999 | 0.001 | 0.394 | 0.014 | 0.841 | 0.134 | 0.026 | 18.00 | 1.28 |
| 1,400 | 123 | 153,285 | 2,578 | 74,301 | 104 | 0.999 | 0.001 | 0.485 | 0.017 | 0.841 | 0.134 | 0.026 | 18.89 | 1.34 |
| 1,600 | 88 | 134,835 | 2,879 | 92,076 | 105 | 0.999 | 0.001 | 0.683 | 0.021 | 0.841 | 0.134 | 0.026 | 20.82 | 1.48 |
| 1,800 | 85 | 122,895 | 2,057 | 103,459 | 97 | 0.999 | 0.001 | 0.842 | 0.017 | 0.841 | 0.134 | 0.026 | 22.33 | 1.58 |
| 2,000 | 77 | 102,339 | 1,315 | 123,598 | 90 | 0.999 | 0.001 | 1.208 | 0.013 | 0.841 | 0.134 | 0.026 | 25.84 | 1.83 |
| 2,200 | 62 | 110,754 | 1,678 | 115,090 | 86 | 0.999 | 0.001 | 1.039 | 0.015 | 0.841 | 0.134 | 0.026 | 24.23 | 1.72 |
| 2,400 | 52 | 106,735 | 1,714 | 119,167 | 74 | 0.999 | 0.000 | 1.116 | 0.016 | 0.841 | 0.134 | 0.026 | 24.98 | 1.77 |
| 2,600 | 50 | 97,419 | 1,539 | 128,733 | 80 | 0.999 | 0.001 | 1.321 | 0.016 | 0.841 | 0.134 | 0.026 | 26.95 | 1.91 |
| 2,800 | 46 | 92,413 | 1,447 | 132,905 | 72 | 0.999 | 0.000 | 1.438 | 0.016 | 0.841 | 0.134 | 0.026 | 28.08 | 1.99 |
| 3,000 | 48 | 91,284 | 1,204 | 134,596 | 75 | 0.999 | 0.001 | 1.474 | 0.013 | 0.841 | 0.134 | 0.026 | 28.42 | 2.01 |
| 3,200 | 52 | 97,049 | 1,242 | 128,806 | 79 | 0.999 | 0.001 | 1.327 | 0.013 | 0.841 | 0.134 | 0.026 | 27.00 | 1.91 |
| 3,400 | 51 | 90,893 | 1,213 | 134,587 | 84 | 0.999 | 0.001 | 1.481 | 0.013 | 0.841 | 0.134 | 0.026 | 28.48 | 2.02 |
| 3,600 | 56 | 91,771 | 1,120 | 133,914 | 88 | 0.999 | 0.001 | 1.459 | 0.012 | 0.841 | 0.134 | 0.026 | 28.26 | 2.00 |
| 3,800 | 61 | 83,463 | 1,002 | 142,758 | 100 | 0.999 | 0.001 | 1.710 | 0.012 | 0.841 | 0.134 | 0.026 | 30.68 | 2.17 |
| 4,000 | 72 | 78,549 | 976 | 148,213 | 109 | 0.999 | 0.001 | 1.887 | 0.012 | 0.841 | 0.134 | 0.026 | 32.38 | 2.29 |
| 4,200 | 91 | 64,169 | 485 | 164,273 | 114 | 0.998 | 0.001 | 2.560 | 0.008 | 0.841 | 0.134 | 0.026 | 38.84 | 2.75 |
| 4,400 | 141 | 47,779 | 234 | 183,137 | 158 | 0.997 | 0.003 | 3.833 | 0.005 | 0.841 | 0.134 | 0.026 | 51.03 | 3.62 |

**Table B2.7** DB30 results under full load (exhaust gas emission, AFR and lambda)

Fuel type : BD30

Test condition : Full load

| Speed | CO | $CO_2$ | $NO/NO_x$ | $O_2$ | THC | Spindt's formula | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (rpm) | (ppm) | (ppm) | (ppm) | (ppm) | (ppm) | $F_b$ | R | Q | S | $F_c$ | $F_h$ | $F_o$ | AFR | λ |
| 800 | 436 | 170,474 | 2,584 | 58,783 | 125 | 0.999 | 0.003 | 0.345 | 0.015 | 0.834 | 0.134 | 0.032 | 17.41 | 1.24 |
| 1,000 | 302 | 166,041 | 2,488 | 62,696 | 123 | 0.999 | 0.002 | 0.378 | 0.015 | 0.834 | 0.134 | 0.032 | 17.72 | 1.26 |
| 1,200 | 168 | 161,608 | 2,392 | 66,610 | 121 | 0.999 | 0.001 | 0.412 | 0.015 | 0.834 | 0.134 | 0.032 | 18.05 | 1.29 |
| 1,400 | 115 | 150,395 | 2,693 | 76,452 | 107 | 0.999 | 0.001 | 0.508 | 0.018 | 0.834 | 0.134 | 0.032 | 18.98 | 1.35 |
| 1,600 | 88 | 133,612 | 2,940 | 92,840 | 107 | 0.999 | 0.001 | 0.695 | 0.022 | 0.834 | 0.134 | 0.032 | 20.79 | 1.48 |
| 1,800 | 83 | 121,100 | 2,101 | 104,788 | 99 | 0.999 | 0.001 | 0.865 | 0.017 | 0.834 | 0.134 | 0.032 | 22.40 | 1.60 |
| 2,000 | 77 | 99,600 | 1,323 | 125,987 | 94 | 0.999 | 0.001 | 1.265 | 0.013 | 0.834 | 0.134 | 0.032 | 26.21 | 1.87 |
| 2,200 | 61 | 107,824 | 1,640 | 117,383 | 88 | 0.999 | 0.001 | 1.089 | 0.015 | 0.834 | 0.134 | 0.032 | 24.53 | 1.75 |
| 2,400 | 50 | 105,002 | 1,703 | 120,411 | 77 | 0.999 | 0.000 | 1.147 | 0.016 | 0.834 | 0.134 | 0.032 | 25.09 | 1.79 |
| 2,600 | 48 | 101,271 | 1,645 | 124,186 | 78 | 0.999 | 0.000 | 1.226 | 0.016 | 0.834 | 0.134 | 0.032 | 25.85 | 1.84 |
| 2,800 | 46 | 94,837 | 1,488 | 130,756 | 75 | 0.999 | 0.000 | 1.379 | 0.016 | 0.834 | 0.134 | 0.032 | 27.31 | 1.95 |
| 3,000 | 48 | 92,963 | 1,224 | 132,787 | 79 | 0.999 | 0.001 | 1.428 | 0.013 | 0.834 | 0.134 | 0.032 | 27.77 | 1.98 |
| 3,200 | 50 | 95,094 | 1,240 | 130,657 | 85 | 0.999 | 0.001 | 1.374 | 0.013 | 0.834 | 0.134 | 0.032 | 27.25 | 1.94 |
| 3,400 | 50 | 91,286 | 1,230 | 134,011 | 86 | 0.999 | 0.001 | 1.468 | 0.013 | 0.834 | 0.134 | 0.032 | 28.15 | 2.01 |
| 3,600 | 55 | 91,069 | 1,127 | 134,462 | 91 | 0.999 | 0.001 | 1.476 | 0.012 | 0.834 | 0.134 | 0.032 | 28.23 | 2.01 |
| 3,800 | 58 | 82,626 | 1,011 | 143,775 | 100 | 0.999 | 0.001 | 1.740 | 0.012 | 0.834 | 0.134 | 0.032 | 30.74 | 2.19 |
| 4,000 | 66 | 77,446 | 989 | 149,533 | 108 | 0.999 | 0.001 | 1.931 | 0.013 | 0.834 | 0.134 | 0.032 | 32.57 | 2.32 |
| 4,200 | 86 | 63,969 | 495 | 164,647 | 116 | 0.998 | 0.001 | 2.574 | 0.008 | 0.834 | 0.134 | 0.032 | 38.69 | 2.76 |
| 4,400 | 147 | 49,109 | 252 | 181,538 | 146 | 0.997 | 0.003 | 3.697 | 0.005 | 0.834 | 0.134 | 0.032 | 49.37 | 3.52 |

**Table B2.8** DB35 results under full load (exhaust gas emission, AFR and lambda)

Fuel type : BD35

Test condition : Full load

| Speed | CO | $CO_2$ | $NO/NO_x$ | $O_2$ | THC | Spindt's formula | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (rpm) | (ppm) | (ppm) | (ppm) | (ppm) | (ppm) | $F_b$ | R | Q | S | $F_c$ | $F_h$ | $F_o$ | AFR | λ |
| 800 | 344 | 169,654 | 2,733 | 60,502 | 139 | 0.999 | 0.002 | 0.357 | 0.016 | 0.867 | 0.133 | 0.039 | 17.99 | 1.29 |
| 1,000 | 219 | 167,075 | 2,161 | 62,758 | 133 | 0.999 | 0.001 | 0.376 | 0.013 | 0.867 | 0.133 | 0.039 | 18.16 | 1.31 |
| 1,200 | 158 | 160,716 | 2,452 | 68,252 | 134 | 0.999 | 0.001 | 0.425 | 0.015 | 0.867 | 0.133 | 0.039 | 18.66 | 1.34 |
| 1,400 | 114 | 148,150 | 2,733 | 79,542 | 116 | 0.999 | 0.001 | 0.537 | 0.018 | 0.867 | 0.133 | 0.039 | 19.79 | 1.42 |
| 1,600 | 90 | 127,924 | 2,894 | 99,299 | 118 | 0.999 | 0.001 | 0.776 | 0.023 | 0.867 | 0.133 | 0.039 | 22.19 | 1.60 |
| 1,800 | 90 | 111,832 | 2,005 | 114,536 | 115 | 0.999 | 0.001 | 1.024 | 0.018 | 0.867 | 0.133 | 0.039 | 24.63 | 1.77 |
| 2,000 | 82 | 91,159 | 1,200 | 135,138 | 97 | 0.999 | 0.001 | 1.482 | 0.013 | 0.867 | 0.133 | 0.039 | 29.17 | 2.10 |
| 2,200 | 65 | 99,576 | 1,405 | 126,506 | 92 | 0.999 | 0.001 | 1.270 | 0.014 | 0.867 | 0.133 | 0.039 | 27.07 | 1.95 |
| 2,400 | 54 | 100,156 | 1,607 | 126,118 | 87 | 0.999 | 0.001 | 1.259 | 0.016 | 0.867 | 0.133 | 0.039 | 26.96 | 1.94 |
| 2,600 | 60 | 85,188 | 1,207 | 141,642 | 85 | 0.999 | 0.001 | 1.663 | 0.014 | 0.867 | 0.133 | 0.039 | 30.97 | 2.23 |
| 2,800 | 65 | 76,202 | 997 | 146,603 | 94 | 0.999 | 0.001 | 1.924 | 0.013 | 0.867 | 0.133 | 0.039 | 33.55 | 2.41 |
| 3,000 | 54 | 81,223 | 1,068 | 142,965 | 91 | 0.999 | 0.001 | 1.760 | 0.013 | 0.867 | 0.133 | 0.039 | 31.93 | 2.30 |
| 3,200 | 51 | 84,754 | 1,143 | 135,042 | 89 | 0.999 | 0.001 | 1.593 | 0.013 | 0.867 | 0.133 | 0.039 | 30.27 | 2.18 |
| 3,400 | 53 | 82,744 | 1,119 | 143,899 | 96 | 0.999 | 0.001 | 1.739 | 0.014 | 0.867 | 0.133 | 0.039 | 31.72 | 2.28 |
| 3,600 | 52 | 87,443 | 1,104 | 136,720 | 98 | 0.999 | 0.001 | 1.564 | 0.013 | 0.867 | 0.133 | 0.039 | 29.97 | 2.15 |
| 3,800 | 57 | 80,982 | 989 | 141,873 | 105 | 0.999 | 0.001 | 1.752 | 0.012 | 0.867 | 0.133 | 0.039 | 31.84 | 2.29 |
| 4,000 | 66 | 76,183 | 972 | 150,366 | 118 | 0.998 | 0.001 | 1.974 | 0.013 | 0.867 | 0.133 | 0.039 | 34.04 | 2.45 |
| 4,200 | 85 | 62,064 | 481 | 166,879 | 125 | 0.998 | 0.001 | 2.689 | 0.008 | 0.867 | 0.133 | 0.039 | 41.10 | 2.95 |
| 4,400 | 124 | 47,432 | 246 | 183,881 | 151 | 0.997 | 0.003 | 3.877 | 0.005 | 0.867 | 0.133 | 0.039 | 52.84 | 3.80 |

**Table B2.9** DB40 results under full load (exhaust gas emission, AFR and lambda)

Fuel type :BD40

Test condition : Full load

| Speed | CO | $CO_2$ | $NO/NO_x$ | $O_2$ | THC | Spindt's formula | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (rpm) | (ppm) | (ppm) | (ppm) | (ppm) | (ppm) | $F_b$ | R | Q | S | $F_c$ | $F_h$ | $F_o$ | AFR | λ |
| 800 | 271 | 166,947 | 2,925 | 63,517 | 155 | 0.999 | 0.002 | 0.380 | 0.018 | 0.867 | 0.133 | 0.046 | 18.20 | 1.32 |
| 1,000 | 193 | 162,792 | 2,316 | 67,294 | 146 | 0.999 | 0.001 | 0.413 | 0.014 | 0.867 | 0.133 | 0.046 | 18.51 | 1.34 |
| 1,200 | 143 | 153,930 | 2,620 | 74,350 | 143 | 0.999 | 0.001 | 0.483 | 0.017 | 0.867 | 0.133 | 0.046 | 19.21 | 1.39 |
| 1,400 | 115 | 141,566 | 2,835 | 85,022 | 143 | 0.999 | 0.001 | 0.601 | 0.020 | 0.867 | 0.133 | 0.046 | 20.40 | 1.48 |
| 1,600 | 98 | 116,490 | 2,768 | 109,821 | 135 | 0.999 | 0.001 | 0.943 | 0.024 | 0.867 | 0.133 | 0.046 | 23.82 | 1.73 |
| 1,800 | 100 | 101,646 | 1,896 | 125,370 | 118 | 0.999 | 0.001 | 1.233 | 0.019 | 0.867 | 0.133 | 0.046 | 26.68 | 1.93 |
| 2,000 | 100 | 81,694 | 1,050 | 143,841 | 123 | 0.998 | 0.001 | 1.761 | 0.013 | 0.867 | 0.133 | 0.046 | 31.89 | 2.31 |
| 2,200 | 82 | 85,572 | 1,145 | 140,639 | 113 | 0.999 | 0.001 | 1.644 | 0.013 | 0.867 | 0.133 | 0.046 | 30.73 | 2.23 |
| 2,400 | 70 | 89,385 | 1,224 | 137,526 | 100 | 0.999 | 0.001 | 1.539 | 0.014 | 0.867 | 0.133 | 0.046 | 29.69 | 2.15 |
| 2,600 | 90 | 72,405 | 833 | 156,536 | 110 | 0.998 | 0.001 | 2.162 | 0.012 | 0.867 | 0.133 | 0.046 | 35.87 | 2.60 |
| 2,800 | 94 | 65,364 | 812 | 162,608 | 120 | 0.998 | 0.001 | 2.488 | 0.012 | 0.867 | 0.133 | 0.046 | 39.11 | 2.83 |
| 3,000 | 89 | 64,149 | 818 | 164,843 | 120 | 0.998 | 0.001 | 2.570 | 0.013 | 0.867 | 0.133 | 0.046 | 39.92 | 2.89 |
| 3,200 | 77 | 66,542 | 902 | 162,869 | 123 | 0.998 | 0.001 | 2.448 | 0.014 | 0.867 | 0.133 | 0.046 | 38.71 | 2.81 |
| 3,400 | 70 | 70,034 | 905 | 160,586 | 118 | 0.998 | 0.001 | 2.293 | 0.013 | 0.867 | 0.133 | 0.046 | 37.18 | 2.69 |
| 3,600 | 66 | 75,128 | 1,021 | 146,722 | 125 | 0.998 | 0.001 | 1.953 | 0.014 | 0.867 | 0.133 | 0.046 | 33.80 | 2.45 |
| 3,800 | 74 | 70,275 | 931 | 157,695 | 127 | 0.998 | 0.001 | 2.244 | 0.013 | 0.867 | 0.133 | 0.046 | 36.69 | 2.66 |
| 4,000 | 89 | 72,543 | 979 | 154,160 | 128 | 0.998 | 0.001 | 2.125 | 0.014 | 0.867 | 0.133 | 0.046 | 35.51 | 2.57 |
| 4,200 | 117 | 60,516 | 497 | 166,387 | 138 | 0.998 | 0.002 | 2.749 | 0.008 | 0.867 | 0.133 | 0.046 | 41.67 | 3.02 |
| 4,400 | 139 | 48,440 | 273 | 182,572 | 164 | 0.997 | 0.003 | 3.769 | 0.006 | 0.867 | 0.133 | 0.046 | 51.73 | 3.75 |

# APPENDIX C

# Tested Data under Partial Load

## C-1: BSFC and Temperature Data

**Table C1.1** Diesel results under partial load (performance, BSFC and temperature)

Fuel type : Diesel — Test condition : Partial load

| Torque (N·m) | Speed (rpm) | Fuel consumption (g/s) | BSFC (g/kW·hr) | Exhaust gas temperature (°C) | Air Inlet temperature (°C) | Lubricant temperature (°C) |
|---|---|---|---|---|---|---|
| 50 | 1,000 | 0.43 | 305.19 | 158.57 | 67.00 | 80.90 |
| 50 | 1,500 | 0.65 | 307.49 | 186.45 | 73.13 | 84.70 |
| 50 | 2,000 | 0.89 | 305.10 | 224.55 | 83.50 | 86.80 |
| 50 | 2,500 | 1.16 | 324.92 | 247.87 | 81.73 | 89.37 |
| 50 | 3,000 | 1.43 | 336.93 | 231.23 | 82.00 | 91.70 |
| 50 | 3,500 | 2.17 | 436.92 | 260.65 | 81.67 | 98.73 |
| 100 | 1,000 | 0.73 | 251.83 | 204.33 | 66.50 | 86.73 |
| 100 | 1,500 | 1.04 | 242.06 | 213.65 | 67.53 | 86.73 |
| 100 | 2,000 | 1.43 | 245.96 | 256.47 | 74.07 | 89.87 |
| 100 | 2,500 | 1.81 | 252.98 | 275.35 | 77.17 | 91.53 |
| 100 | 3,000 | 2.23 | 258.34 | 276.90 | 89.93 | 94.63 |
| 100 | 3,500 | 3.09 | 307.12 | 292.55 | 90.50 | 100.07 |
| 150 | 1,000 | 1.00 | 232.36 | 239.25 | 59.87 | 89.60 |
| 150 | 1,500 | 1.41 | 217.82 | 234.32 | 57.90 | 91.50 |
| 150 | 2,000 | 1.90 | 220.13 | 277.28 | 59.83 | 91.83 |
| 150 | 2,500 | 2.42 | 223.46 | 281.92 | 68.87 | 93.47 |
| 150 | 3,000 | 3.00 | 230.55 | 287.62 | 82.07 | 95.27 |
| 150 | 3,500 | 3.28 | 215.82 | 318.75 | 95.33 | 102.00 |

**Table C1.2** BD05 results under partial load (performance, BSFC and temperature)

Fuel type : BD05

Test condition : Partial load

| Torque (N·m) | Speed (rpm) | Fuel consumption (g/s) | BSFC (g/kW·hr) | Exhaust gas temperature (°C) | Air Inlet temperature (°C) | Lubricant temperature (°C) |
|---|---|---|---|---|---|---|
| 50 | 1,000 | 0.47 | 333.27 | 169.52 | 61.90 | 85.87 |
| 50 | 1,500 | 0.66 | 314.57 | 188.25 | 68.07 | 84.87 |
| 50 | 2,000 | 0.89 | 313.23 | 224.52 | 75.97 | 85.37 |
| 50 | 2,500 | 1.20 | 337.61 | 257.25 | 77.87 | 86.90 |
| 50 | 3,000 | 1.47 | 345.20 | 242.02 | 77.27 | 90.27 |
| 50 | 3,500 | 2.06 | 414.72 | 265.58 | 75.00 | 93.50 |
| 100 | 1,000 | 0.79 | 277.00 | 222.32 | 72.87 | 90.57 |
| 100 | 1,500 | 1.10 | 254.66 | 236.68 | 69.07 | 87.80 |
| 100 | 2,000 | 1.38 | 239.03 | 276.67 | 72.57 | 89.07 |
| 100 | 2,500 | 1.86 | 257.09 | 285.02 | 72.97 | 90.10 |
| 100 | 3,000 | 2.22 | 258.36 | 291.03 | 84.13 | 93.20 |
| 100 | 3,500 | 3.16 | 315.00 | 309.23 | 88.03 | 99.07 |
| 150 | 1,000 | 1.02 | 235.78 | 258.73 | 65.60 | 91.57 |
| 150 | 1,500 | 1.48 | 229.78 | 263.50 | 59.30 | 90.23 |
| 150 | 2,000 | 2.08 | 239.72 | 291.12 | 61.20 | 91.97 |
| 150 | 2,500 | 2.55 | 234.89 | 300.30 | 63.80 | 93.43 |
| 150 | 3,000 | 2.99 | 229.25 | 303.57 | 78.80 | 95.03 |
| 150 | 3,500 | 3.83 | 252.88 | 336.70 | 92.30 | 100.23 |

**Table C1.3** BD10 results under partial load (performance, BSFC and temperature)

Fuel type : BD10

Test condition : Partial load

| Torque (N·m) | Speed (rpm) | Fuel consumption (g/s) | BSFC (g/kW·hr) | Exhaust gas temperature (°C) | Air Inlet temperature (°C) | Lubricant temperature (°C) |
|---|---|---|---|---|---|---|
| 50 | 1,000 | 0.49 | 343.04 | 164.82 | 61.23 | 83.47 |
| 50 | 1,500 | 0.69 | 321.70 | 187.15 | 65.70 | 83.57 |
| 50 | 2,000 | 0.87 | 306.83 | 220.45 | 72.93 | 84.43 |
| 50 | 2,500 | 1.15 | 324.72 | 245.18 | 72.90 | 85.70 |
| 50 | 3,000 | 1.46 | 342.76 | 240.93 | 75.67 | 89.57 |
| 50 | 3,500 | 2.08 | 419.51 | 265.17 | 75.00 | 94.10 |
| 100 | 1,000 | 0.73 | 258.20 | 228.88 | 74.30 | 91.63 |
| 100 | 1,500 | 1.07 | 248.64 | 237.35 | 69.67 | 87.50 |
| 100 | 2,000 | 1.41 | 244.45 | 270.45 | 70.03 | 88.07 |
| 100 | 2,500 | 1.86 | 260.13 | 287.47 | 73.67 | 91.07 |
| 100 | 3,000 | 2.32 | 269.07 | 286.75 | 77.23 | 92.10 |
| 100 | 3,500 | 2.94 | 292.21 | 304.23 | 85.10 | 97.53 |
| 150 | 1,000 | 1.02 | 234.67 | 266.18 | 70.87 | 94.17 |
| 150 | 1,500 | 1.48 | 228.52 | 260.38 | 56.87 | 90.37 |
| 150 | 2,000 | 1.94 | 227.69 | 289.73 | 57.67 | 91.03 |
| 150 | 2,500 | 2.62 | 242.17 | 298.03 | 62.10 | 92.17 |
| 150 | 3,000 | 3.01 | 231.84 | 306.82 | 80.00 | 95.17 |
| 150 | 3,500 | 3.84 | 253.30 | 330.60 | 89.20 | 98.53 |

**Table C1.4** BD15 results under partial load (performance, BSFC and temperature)

Fuel type : BD15 Test condition : Partial load

| Torque (N·m) | Speed (rpm) | Fuel consumption (g/s) | BSFC (g/kW·hr) | Exhaust gas temperature (°C) | Air Inlet temperature (°C) | Lubricant temperature (°C) |
|---|---|---|---|---|---|---|
| 50 | 1,000 | 0.50 | 351.58 | 165.15 | 61.10 | 83.73 |
| 50 | 1,500 | 0.65 | 301.51 | 198.62 | 67.10 | 84.00 |
| 50 | 2,000 | 0.88 | 313.99 | 232.42 | 74.93 | 85.00 |
| 50 | 2,500 | 1.20 | 336.59 | 254.88 | 75.43 | 86.70 |
| 50 | 3,000 | 1.48 | 347.16 | 243.92 | 79.17 | 90.60 |
| 50 | 3,500 | 2.08 | 417.38 | 266.85 | 75.00 | 94.07 |
| 100 | 1,000 | 0.74 | 259.09 | 227.00 | 70.23 | 90.20 |
| 100 | 1,500 | 1.07 | 244.27 | 241.70 | 67.93 | 88.30 |
| 100 | 2,000 | 1.51 | 263.63 | 278.10 | 67.50 | 89.77 |
| 100 | 2,500 | 1.86 | 259.30 | 290.80 | 71.73 | 90.90 |
| 100 | 3,000 | 2.19 | 254.66 | 290.65 | 80.67 | 92.87 |
| 100 | 3,500 | 2.95 | 294.53 | 307.88 | 83.07 | 96.90 |
| 150 | 1,000 | 1.10 | 253.57 | 257.45 | 58.13 | 90.00 |
| 150 | 1,500 | 1.49 | 229.96 | 261.82 | 54.23 | 89.13 |
| 150 | 2,000 | 1.97 | 228.36 | 290.83 | 57.27 | 90.13 |
| 150 | 2,500 | 2.67 | 247.28 | 305.53 | 65.63 | 93.33 |
| 150 | 3,000 | 3.04 | 234.19 | 310.43 | 81.10 | 95.73 |
| 150 | 3,500 | 3.86 | 255.84 | 340.05 | 91.77 | 100.90 |

**Table C1.5** BD20 results under partial load (performance, BSFC and temperature)

Fuel type : BD20 Test condition : Partial load

| Torque (N·m) | Speed (rpm) | Fuel consumption (g/s) | BSFC (g/kW·hr) | Exhaust gas temperature (°C) | Air Inlet temperature (°C) | Lubricant temperature (°C) |
|---|---|---|---|---|---|---|
| 50 | 1,000 | 0.56 | 393.08 | 172.98 | 64.70 | 85.67 |
| 50 | 1,500 | 0.72 | 341.00 | 199.58 | 68.00 | 84.70 |
| 50 | 2,000 | 0.88 | 311.21 | 224.35 | 76.33 | 85.33 |
| 50 | 2,500 | 1.24 | 347.78 | 247.32 | 77.23 | 86.90 |
| 50 | 3,000 | 1.49 | 349.58 | 241.02 | 80.23 | 90.03 |
| 50 | 3,500 | 2.11 | 427.07 | 267.03 | 77.93 | 93.37 |
| 100 | 1,000 | 0.77 | 268.30 | 223.02 | 70.13 | 87.80 |
| 100 | 1,500 | 1.08 | 251.05 | 239.93 | 69.13 | 86.93 |
| 100 | 2,000 | 1.51 | 266.18 | 270.67 | 69.83 | 88.47 |
| 100 | 2,500 | 1.88 | 264.29 | 285.08 | 71.33 | 89.63 |
| 100 | 3,000 | 2.22 | 260.76 | 291.98 | 83.07 | 93.00 |
| 100 | 3,500 | 3.01 | 298.64 | 311.48 | 89.80 | 98.33 |
| 150 | 1,000 | 1.15 | 265.40 | 256.97 | 60.43 | 88.80 |
| 150 | 1,500 | 1.52 | 231.44 | 264.58 | 56.90 | 89.33 |
| 150 | 2,000 | 2.02 | 234.51 | 292.02 | 60.53 | 91.03 |
| 150 | 2,500 | 2.74 | 254.11 | 307.87 | 70.37 | 94.87 |
| 150 | 3,000 | 3.04 | 239.87 | 306.38 | 80.97 | 96.50 |
| 150 | 3,500 | 3.90 | 258.00 | 333.48 | 94.20 | 100.43 |

**Table C1.6** BD25 results under partial load (performance, BSFC and temperature)

Fuel type : BD25 — Test condition : Partial load

| Torque (N·m) | Speed (rpm) | Fuel consumption (g/s) | BSFC (g/kW·hr) | Exhaust gas temperature (°C) | Air Inlet temperature (°C) | Lubricant temperature (°C) |
|---|---|---|---|---|---|---|
| 50 | 1,000 | 0.47 | 334.28 | 167.45 | 64.50 | 81.63 |
| 50 | 1,500 | 0.70 | 325.04 | 183.95 | 67.13 | 82.43 |
| 50 | 2,000 | 0.92 | 324.11 | 234.90 | 79.13 | 85.00 |
| 50 | 2,500 | 1.19 | 335.08 | 255.68 | 79.00 | 88.93 |
| 50 | 3,000 | 1.54 | 360.57 | 244.12 | 82.60 | 90.30 |
| 50 | 3,500 | 2.13 | 430.42 | 265.85 | 74.93 | 93.20 |
| 100 | 1,000 | 0.79 | 274.43 | 220.97 | 66.17 | 86.80 |
| 100 | 1,500 | 1.08 | 249.67 | 245.47 | 70.00 | 86.17 |
| 100 | 2,000 | 1.46 | 254.87 | 270.93 | 69.43 | 87.37 |
| 100 | 2,500 | 1.87 | 261.34 | 286.92 | 72.07 | 89.53 |
| 100 | 3,000 | 2.28 | 263.88 | 292.05 | 84.73 | 93.27 |
| 100 | 3,500 | 2.95 | 296.17 | 299.28 | 88.03 | 98.20 |
| 150 | 1,000 | 1.11 | 256.18 | 262.62 | 64.63 | 92.63 |
| 150 | 1,500 | 1.52 | 235.06 | 260.88 | 55.13 | 88.83 |
| 150 | 2,000 | 2.04 | 236.73 | 287.77 | 57.53 | 89.63 |
| 150 | 2,500 | 2.66 | 245.73 | 299.67 | 61.90 | 91.23 |
| 150 | 3,000 | 3.04 | 233.40 | 305.23 | 79.10 | 95.20 |
| 150 | 3,500 | 3.92 | 259.52 | 330.02 | 92.07 | 98.10 |

**Table C1.7** BD30 results under partial load (performance, BSFC and temperature)

Fuel type : BD30 — Test condition : Partial load

| Torque (N·m) | Speed (rpm) | Fuel consumption (g/s) | BSFC (g/kW·hr) | Exhaust gas temperature (°C) | Air Inlet temperature (°C) | Lubricant temperature (°C) |
|---|---|---|---|---|---|---|
| 50 | 1,000 | 0.53 | 371.11 | 166.18 | 64.10 | 80.80 |
| 50 | 1,500 | 0.68 | 320.79 | 197.00 | 66.10 | 82.30 |
| 50 | 2,000 | 0.93 | 327.34 | 235.35 | 79.50 | 85.10 |
| 50 | 2,500 | 1.27 | 357.51 | 254.82 | 82.43 | 88.53 |
| 50 | 3,000 | 1.59 | 373.56 | 243.23 | 80.60 | 90.83 |
| 50 | 3,500 | 2.15 | 433.78 | 270.98 | 77.43 | 94.60 |
| 100 | 1,000 | 0.78 | 273.60 | 225.97 | 71.90 | 91.07 |
| 100 | 1,500 | 1.11 | 257.05 | 232.28 | 66.67 | 88.33 |
| 100 | 2,000 | 1.50 | 261.09 | 268.08 | 66.87 | 88.50 |
| 100 | 2,500 | 1.96 | 272.90 | 288.78 | 69.27 | 90.57 |
| 100 | 3,000 | 2.49 | 293.63 | 290.00 | 81.20 | 93.73 |
| 100 | 3,500 | 3.06 | 303.47 | 305.37 | 85.87 | 97.13 |
| 150 | 1,000 | 1.14 | 264.81 | 263.33 | 66.80 | 92.70 |
| 150 | 1,500 | 1.57 | 241.14 | 263.38 | 59.60 | 90.70 |
| 150 | 2,000 | 2.06 | 238.29 | 291.80 | 59.00 | 90.67 |
| 150 | 2,500 | 2.86 | 264.36 | 307.43 | 67.43 | 93.57 |
| 150 | 3,000 | 3.19 | 244.52 | 308.73 | 80.97 | 97.13 |
| 150 | 3,500 | 3.69 | 261.44 | 324.63 | 89.87 | 100.00 |

**Table C1.8** BD35 results under partial load (performance, BSFC and temperature)

Fuel type : BD35 | Test condition : Partial load

| Torque (N·m) | Speed (rpm) | Fuel consumption (g/s) | BSFC (g/kW·hr) | Exhaust gas temperature (°C) | Air Inlet temperature (°C) | Lubricant temperature (°C) |
|---|---|---|---|---|---|---|
| 50 | 1,000 | 0.47 | 329.48 | 163.20 | 64.70 | 79.63 |
| 50 | 1,500 | 0.71 | 334.63 | 196.43 | 66.60 | 81.53 |
| 50 | 2,000 | 0.95 | 337.50 | 230.87 | 77.60 | 84.43 |
| 50 | 2,500 | 1.27 | 357.47 | 257.75 | 76.73 | 86.30 |
| 50 | 3,000 | 1.56 | 366.23 | 238.77 | 76.73 | 87.67 |
| 50 | 3,500 | 2.21 | 445.77 | 265.38 | 74.20 | 93.17 |
| 100 | 1,000 | 0.75 | 265.70 | 227.77 | 74.17 | 91.70 |
| 100 | 1,500 | 1.10 | 255.33 | 236.12 | 66.87 | 88.53 |
| 100 | 2,000 | 1.55 | 269.52 | 272.83 | 66.40 | 89.40 |
| 100 | 2,500 | 1.96 | 274.14 | 287.43 | 68.43 | 91.00 |
| 100 | 3,000 | 2.39 | 278.44 | 279.15 | 77.80 | 95.57 |
| 100 | 3,500 | 3.17 | 318.35 | 302.10 | 85.37 | 97.83 |
| 150 | 1,000 | 1.29 | 296.60 | 263.25 | 59.97 | 92.80 |
| 150 | 1,500 | 1.57 | 239.19 | 262.38 | 56.27 | 90.27 |
| 150 | 2,000 | 2.10 | 243.80 | 293.43 | 56.77 | 90.90 |
| 150 | 2,500 | 2.72 | 252.25 | 307.93 | 65.23 | 93.97 |
| 150 | 3,000 | 3.43 | 270.42 | 316.55 | 82.20 | 98.93 |
| 150 | 3,500 | - | - | - | - | - |

**Table C1.9** BD40 results under partial load (performance, BSFC and temperature)

Fuel type : BD40 | Test condition : Partial load

| Torque (N·m) | Speed (rpm) | Fuel consumption (g/s) | BSFC (g/kW·hr) | Exhaust gas temperature (°C) | Air Inlet temperature (°C) | Lubricant temperature (°C) |
|---|---|---|---|---|---|---|
| 50 | 1,000 | 0.51 | 341.27 | 179.60 | 69.07 | 86.13 |
| 50 | 1,500 | 0.74 | 352.03 | 196.40 | 69.37 | 84.95 |
| 50 | 2,000 | 0.97 | 339.10 | 215.67 | 74.37 | 86.52 |
| 50 | 2,500 | 1.33 | 373.08 | 241.07 | 78.00 | 88.28 |
| 50 | 3,000 | 1.65 | 382.79 | 244.45 | 81.10 | 91.63 |
| 50 | 3,500 | 2.14 | 433.21 | 257.15 | 74.47 | 93.10 |
| 100 | 1,000 | 0.92 | 285.00 | 238.68 | 76.22 | 92.68 |
| 100 | 1,500 | 1.19 | 268.00 | 237.98 | 67.83 | 90.48 |
| 100 | 2,000 | 1.50 | 262.86 | 267.00 | 63.80 | 90.70 |
| 100 | 2,500 | 1.94 | 270.52 | 275.75 | 63.33 | 92.10 |
| 100 | 3,000 | 2.41 | 278.68 | 273.58 | 73.63 | 94.63 |
| 100 | 3,500 | 3.15 | 312.56 | 296.22 | 82.37 | 96.10 |
| 150 | 1,000 | 1.20 | 275.73 | 269.32 | 67.87 | 94.45 |
| 150 | 1,500 | 1.54 | 237.84 | 276.63 | 61.57 | 92.83 |
| 150 | 2,000 | 2.12 | 242.50 | 281.83 | 61.33 | 93.57 |
| 150 | 2,500 | 2.57 | 238.50 | 290.25 | 65.87 | 93.60 |
| 150 | 3,000 | 3.25 | 249.54 | 304.30 | 81.37 | 95.83 |
| 150 | 3,500 | - | - | - | - | - |

## C-2: Emission, Air/Fuel Ratio and Lambda Data

**Table C2.1** Diesel results under partial load (exhaust gas emission, AFR and lambda)

Fuel type : Diesel

Test condition : Partial load

| Torque | Speed | CO | $CO_2$ | $NO/NO_x$ | $O_2$ | THC | Spindt's formula | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (N·m) | (rpm) | (ppm) | (ppm) | (ppm) | (ppm) | (ppm) | $F_b$ | R | Q | S | $F_c$ | $F_h$ | $F_o$ | AFR | λ |
| 50 | 1,000 | 221 | 58,651 | 264 | 130,349 | 212 | 0.996 | 0.004 | 2.222 | 0.004 | 0.867 | 0.133 | 0.000 | 36.57 | 2.52 |
| 50 | 1,500 | 366 | 69,112 | 120 | 115,202 | 242 | 0.997 | 0.005 | 1.667 | 0.002 | 0.867 | 0.133 | 0.000 | 31.05 | 2.14 |
| 50 | 2,000 | 536 | 80,158 | 77 | 99,661 | 268 | 0.997 | 0.007 | 1.243 | 0.001 | 0.867 | 0.133 | 0.000 | 26.85 | 1.85 |
| 50 | 2,500 | 306 | 67,534 | 160 | 117,376 | 216 | 0.997 | 0.005 | 1.738 | 0.002 | 0.867 | 0.133 | 0.000 | 31.77 | 2.19 |
| 50 | 3,000 | 324 | 59,967 | 128 | 127,934 | 163 | 0.997 | 0.005 | 2.133 | 0.002 | 0.867 | 0.133 | 0.000 | 35.71 | 2.46 |
| 50 | 3,500 | 86 | 38,108 | 524 | 157,991 | 119 | 0.997 | 0.002 | 4.146 | 0.014 | 0.867 | 0.133 | 0.000 | 55.73 | 3.84 |
| 100 | 1,000 | 162 | 82,483 | 628 | 96,204 | 154 | 0.998 | 0.002 | 1.166 | 0.008 | 0.867 | 0.133 | 0.000 | 26.14 | 1.80 |
| 100 | 1,500 | 194 | 79,035 | 259 | 101,043 | 150 | 0.998 | 0.002 | 1.278 | 0.003 | 0.867 | 0.133 | 0.000 | 27.24 | 1.88 |
| 100 | 2,000 | 198 | 80,706 | 292 | 98,578 | 160 | 0.998 | 0.002 | 1.221 | 0.004 | 0.867 | 0.133 | 0.000 | 26.67 | 1.84 |
| 100 | 2,500 | 148 | 76,483 | 287 | 104,749 | 129 | 0.998 | 0.002 | 1.370 | 0.004 | 0.867 | 0.133 | 0.000 | 28.15 | 1.94 |
| 100 | 3,000 | 229 | 75,922 | 218 | 105,555 | 133 | 0.998 | 0.003 | 1.390 | 0.003 | 0.867 | 0.133 | 0.000 | 28.35 | 1.95 |
| 100 | 3,500 | 73 | 50,637 | 832 | 140,817 | 108 | 0.998 | 0.001 | 2.781 | 0.016 | 0.867 | 0.133 | 0.000 | 42.23 | 2.91 |
| 150 | 1,000 | 93 | 86,636 | 2,477 | 88,985 | 123 | 0.999 | 0.001 | 1.027 | 0.029 | 0.867 | 0.133 | 0.000 | 24.87 | 1.71 |
| 150 | 1,500 | 84 | 77,228 | 1,372 | 103,609 | 115 | 0.999 | 0.001 | 1.342 | 0.018 | 0.867 | 0.133 | 0.000 | 27.94 | 1.93 |
| 150 | 2,000 | 89 | 76,033 | 859 | 105,382 | 111 | 0.999 | 0.001 | 1.386 | 0.011 | 0.867 | 0.133 | 0.000 | 28.35 | 1.95 |
| 150 | 2,500 | 108 | 70,017 | 470 | 113,854 | 96 | 0.999 | 0.002 | 1.626 | 0.007 | 0.867 | 0.133 | 0.000 | 30.72 | 2.12 |
| 150 | 3,000 | 117 | 75,620 | 397 | 105,788 | 100 | 0.999 | 0.002 | 1.399 | 0.005 | 0.867 | 0.133 | 0.000 | 28.46 | 1.96 |
| 150 | 3,500 | 61 | 61,839 | 984 | 125,140 | 100 | 0.998 | 0.001 | 2.024 | 0.016 | 0.867 | 0.133 | 0.000 | 34.71 | 2.39 |

## **Table C2.2** DB05 results under partial load (exhaust gas emission, AFR and lambda)

Fuel type : BD05

Test condition : Partial load

| Torque | Speed | CO | $CO_2$ | NO/$NO_x$ | $O_2$ | THC | Spindt's formula | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (N·m) | (rpm) | (ppm) | (ppm) | (ppm) | (ppm) | (ppm) | $F_b$ | R | Q | S | $F_c$ | $F_h$ | $F_o$ | AFR | λ |
| 50 | 1,000 | 230 | 78,033 | 286 | 149,651 | 140 | 0.998 | 0.003 | 1.918 | 0.004 | 0.862 | 0.133 | 0.005 | 33.43 | 2.31 |
| 50 | 1,500 | 487 | 97,748 | 117 | 128,792 | 199 | 0.998 | 0.005 | 1.318 | 0.001 | 0.862 | 0.133 | 0.005 | 27.48 | 1.90 |
| 50 | 2,000 | 806 | 116,065 | 71 | 110,507 | 242 | 0.998 | 0.007 | 0.952 | 0.001 | 0.862 | 0.133 | 0.005 | 23.87 | 1.65 |
| 50 | 2,500 | 333 | 90,604 | 183 | 135,858 | 190 | 0.998 | 0.004 | 1.499 | 0.002 | 0.862 | 0.133 | 0.005 | 29.28 | 2.03 |
| 50 | 3,000 | 371 | 81,566 | 137 | 145,286 | 157 | 0.998 | 0.005 | 1.781 | 0.002 | 0.862 | 0.133 | 0.005 | 32.07 | 2.22 |
| 50 | 3,500 | 89 | 49,627 | 574 | 181,215 | 106 | 0.998 | 0.002 | 3.652 | 0.012 | 0.862 | 0.133 | 0.005 | 50.59 | 3.50 |
| 100 | 1,000 | 148 | 116,378 | 791 | 110,669 | 149 | 0.999 | 0.001 | 0.951 | 0.007 | 0.862 | 0.133 | 0.005 | 23.89 | 1.65 |
| 100 | 1,500 | 241 | 123,077 | 205 | 104,172 | 162 | 0.999 | 0.002 | 0.846 | 0.002 | 0.862 | 0.133 | 0.005 | 22.83 | 1.58 |
| 100 | 2,000 | 225 | 119,047 | 301 | 107,785 | 169 | 0.999 | 0.002 | 0.905 | 0.003 | 0.862 | 0.133 | 0.005 | 23.42 | 1.62 |
| 100 | 2,500 | 164 | 108,889 | 296 | 117,263 | 129 | 0.999 | 0.002 | 1.077 | 0.003 | 0.862 | 0.133 | 0.005 | 25.12 | 1.74 |
| 100 | 3,000 | 258 | 110,101 | 207 | 116,449 | 133 | 0.999 | 0.002 | 1.058 | 0.002 | 0.862 | 0.133 | 0.005 | 24.93 | 1.73 |
| 100 | 3,500 | 70 | 67,144 | 892 | 161,336 | 97 | 0.999 | 0.001 | 2.403 | 0.013 | 0.862 | 0.133 | 0.005 | 38.28 | 2.65 |
| 150 | 1,000 | 93 | 123,092 | 2,701 | 104,243 | 123 | 0.999 | 0.001 | 0.847 | 0.022 | 0.862 | 0.133 | 0.005 | 22.94 | 1.59 |
| 150 | 1,500 | 99 | 117,093 | 1,190 | 110,089 | 105 | 0.999 | 0.001 | 0.940 | 0.010 | 0.862 | 0.133 | 0.005 | 23.81 | 1.65 |
| 150 | 2,000 | 91 | 107,705 | 932 | 119,261 | 98 | 0.999 | 0.001 | 1.107 | 0.009 | 0.862 | 0.133 | 0.005 | 25.45 | 1.76 |
| 150 | 2,500 | 57 | 94,781 | 959 | 131,928 | 93 | 0.999 | 0.001 | 1.392 | 0.010 | 0.862 | 0.133 | 0.005 | 28.28 | 1.96 |
| 150 | 3,000 | 120 | 108,385 | 413 | 118,425 | 95 | 0.999 | 0.001 | 1.093 | 0.004 | 0.862 | 0.133 | 0.005 | 25.29 | 1.75 |
| 150 | 3,500 | 56 | 83,604 | 1,105 | 143,411 | 84 | 0.999 | 0.001 | 1.715 | 0.013 | 0.862 | 0.133 | 0.005 | 31.49 | 2.18 |

## **Table C2.3** DB10 results under partial load (exhaust gas emission, AFR and lambda)

Fuel type : BD10

Test condition : Partial load

| Torque | Speed | CO | $CO_2$ | NO/$NO_x$ | $O_2$ | THC | Spindt's formula | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (N·m) | (rpm) | (ppm) | (ppm) | (ppm) | (ppm) | (ppm) | $F_b$ | R | Q | S | $F_c$ | $F_h$ | $F_o$ | AFR | λ |
| 50 | 1,000 | 223 | 77,895 | 271 | 148,770 | 132 | 0.998 | 0.003 | 1.910 | 0.003 | 0.857 | 0.133 | 0.009 | 33.17 | 2.31 |
| 50 | 1,500 | 470 | 98,266 | 114 | 126,815 | 191 | 0.998 | 0.005 | 1.291 | 0.001 | 0.857 | 0.133 | 0.009 | 27.07 | 1.88 |
| 50 | 2,000 | 824 | 116,243 | 66 | 108,033 | 233 | 0.998 | 0.007 | 0.929 | 0.001 | 0.857 | 0.133 | 0.009 | 23.52 | 1.64 |
| 50 | 2,500 | 360 | 86,977 | 189 | 138,215 | 171 | 0.998 | 0.004 | 1.589 | 0.002 | 0.857 | 0.133 | 0.009 | 30.01 | 2.09 |
| 50 | 3,000 | 337 | 80,140 | 138 | 145,446 | 144 | 0.998 | 0.004 | 1.815 | 0.002 | 0.857 | 0.133 | 0.009 | 32.23 | 2.24 |
| 50 | 3,500 | 88 | 49,143 | 551 | 179,825 | 99 | 0.998 | 0.002 | 3.659 | 0.011 | 0.857 | 0.133 | 0.009 | 50.40 | 3.51 |
| 100 | 1,000 | 150 | 115,966 | 735 | 109,473 | 137 | 0.999 | 0.001 | 0.944 | 0.006 | 0.857 | 0.133 | 0.009 | 23.69 | 1.65 |
| 100 | 1,500 | 227 | 120,556 | 207 | 105,218 | 145 | 0.999 | 0.002 | 0.873 | 0.002 | 0.857 | 0.133 | 0.009 | 22.97 | 1.60 |
| 100 | 2,000 | 207 | 115,513 | 312 | 109,657 | 154 | 0.999 | 0.002 | 0.949 | 0.003 | 0.857 | 0.133 | 0.009 | 23.73 | 1.65 |
| 100 | 2,500 | 161 | 110,292 | 278 | 114,771 | 119 | 0.999 | 0.001 | 1.041 | 0.003 | 0.857 | 0.133 | 0.009 | 24.63 | 1.71 |
| 100 | 3,000 | 219 | 103,800 | 219 | 121,074 | 119 | 0.999 | 0.002 | 1.166 | 0.002 | 0.857 | 0.133 | 0.009 | 25.87 | 1.80 |
| 100 | 3,500 | 65 | 66,115 | 895 | 161,345 | 93 | 0.999 | 0.001 | 2.440 | 0.014 | 0.857 | 0.133 | 0.009 | 38.44 | 2.68 |
| 150 | 1,000 | 88 | 123,344 | 2,819 | 102,554 | 116 | 0.999 | 0.001 | 0.831 | 0.023 | 0.857 | 0.133 | 0.009 | 22.67 | 1.58 |
| 150 | 1,500 | 91 | 113,140 | 1,307 | 112,821 | 100 | 0.999 | 0.001 | 0.997 | 0.012 | 0.857 | 0.133 | 0.009 | 24.25 | 1.69 |
| 150 | 2,000 | 88 | 106,009 | 927 | 119,207 | 93 | 0.999 | 0.001 | 1.124 | 0.009 | 0.857 | 0.133 | 0.009 | 25.49 | 1.77 |
| 150 | 2,500 | 56 | 94,479 | 917 | 131,305 | 87 | 0.999 | 0.001 | 1.390 | 0.010 | 0.857 | 0.133 | 0.009 | 28.10 | 1.96 |
| 150 | 3,000 | 93 | 100,396 | 497 | 125,378 | 84 | 0.999 | 0.001 | 1.249 | 0.005 | 0.857 | 0.133 | 0.009 | 26.70 | 1.86 |
| 150 | 3,500 | 54 | 82,039 | 1,074 | 142,475 | 81 | 0.999 | 0.001 | 1.737 | 0.013 | 0.857 | 0.133 | 0.009 | 31.53 | 2.19 |

**Table C2.4** DB15 results under partial load (exhaust gas emission, AFR and lambda)

Fuel type : BD15

Test condition : Partial load

| Torque | Speed | CO | $CO_2$ | $NO/NO_x$ | $O_2$ | THC | Spindt's formula | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (N·m) | (rpm) | (ppm) | (ppm) | (ppm) | (ppm) | (ppm) | $F_b$ | R | Q | S | $F_c$ | $F_h$ | $F_o$ | AFR | λ |
| 50 | 1,000 | 215 | 75,274 | 305 | 152,426 | 133 | 0.998 | 0.003 | 2.025 | 0.004 | 0.852 | 0.134 | 0.014 | 34.11 | 2.39 |
| 50 | 1,500 | 556 | 97,350 | 97 | 128,330 | 203 | 0.998 | 0.006 | 1.318 | 0.001 | 0.852 | 0.134 | 0.014 | 27.18 | 1.90 |
| 50 | 2,000 | 798 | 111,783 | 74 | 114,093 | 234 | 0.998 | 0.007 | 1.021 | 0.001 | 0.852 | 0.134 | 0.014 | 24.28 | 1.70 |
| 50 | 2,500 | 428 | 88,957 | 191 | 135,937 | 188 | 0.998 | 0.005 | 1.528 | 0.002 | 0.852 | 0.134 | 0.014 | 29.24 | 2.05 |
| 50 | 3,000 | 363 | 80,555 | 144 | 146,503 | 152 | 0.998 | 0.005 | 1.819 | 0.002 | 0.852 | 0.134 | 0.014 | 32.08 | 2.25 |
| 50 | 3,500 | 92 | 49,426 | 545 | 179,058 | 102 | 0.998 | 0.002 | 3.623 | 0.011 | 0.852 | 0.134 | 0.014 | 49.74 | 3.48 |
| 100 | 1,000 | 152 | 115,221 | 739 | 110,748 | 142 | 0.999 | 0.001 | 0.961 | 0.006 | 0.852 | 0.134 | 0.014 | 23.73 | 1.66 |
| 100 | 1,500 | 218 | 117,996 | 222 | 108,749 | 147 | 0.999 | 0.002 | 0.922 | 0.002 | 0.852 | 0.134 | 0.014 | 23.32 | 1.63 |
| 100 | 2,000 | 192 | 109,346 | 431 | 117,236 | 156 | 0.999 | 0.002 | 1.072 | 0.004 | 0.852 | 0.134 | 0.014 | 24.80 | 1.74 |
| 100 | 2,500 | 154 | 105,012 | 337 | 120,643 | 127 | 0.999 | 0.001 | 1.149 | 0.003 | 0.852 | 0.134 | 0.014 | 25.55 | 1.79 |
| 100 | 3,000 | 215 | 104,501 | 234 | 121,022 | 124 | 0.999 | 0.002 | 1.158 | 0.002 | 0.852 | 0.134 | 0.014 | 25.64 | 1.79 |
| 100 | 3,500 | 68 | 66,470 | 879 | 161,727 | 97 | 0.999 | 0.001 | 2.433 | 0.013 | 0.852 | 0.134 | 0.014 | 38.15 | 2.67 |
| 150 | 1,000 | 90 | 121,719 | 2,776 | 105,542 | 122 | 0.999 | 0.001 | 0.867 | 0.023 | 0.852 | 0.134 | 0.014 | 22.89 | 1.60 |
| 150 | 1,500 | 93 | 111,938 | 1,324 | 114,931 | 115 | 0.999 | 0.001 | 1.027 | 0.012 | 0.852 | 0.134 | 0.014 | 24.40 | 1.71 |
| 150 | 2,000 | 92 | 105,803 | 912 | 120,406 | 109 | 0.999 | 0.001 | 1.138 | 0.009 | 0.852 | 0.134 | 0.014 | 25.47 | 1.78 |
| 150 | 2,500 | 58 | 95,695 | 922 | 131,372 | 100 | 0.999 | 0.001 | 1.373 | 0.010 | 0.852 | 0.134 | 0.014 | 27.77 | 1.94 |
| 150 | 3,000 | 94 | 101,257 | 511 | 124,422 | 92 | 0.999 | 0.001 | 1.229 | 0.005 | 0.852 | 0.134 | 0.014 | 26.34 | 1.84 |
| 150 | 3,500 | 54 | 83,186 | 1,092 | 143,630 | 80 | 0.999 | 0.001 | 1.727 | 0.013 | 0.852 | 0.134 | 0.014 | 31.25 | 2.19 |

**Table C2.5** DB20 results under partial load (exhaust gas emission, AFR and lambda)

Fuel type : BD20

Test condition : Partial load

| Torque | Speed | CO | $CO_2$ | $NO/NO_x$ | $O_2$ | THC | Spindt's formula | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (N·m) | (rpm) | (ppm) | (ppm) | (ppm) | (ppm) | (ppm) | $F_b$ | R | Q | S | $F_c$ | $F_h$ | $F_o$ | AFR | λ |
| 50 | 1,000 | 224 | 75,886 | 321 | 151,220 | 150 | 0.998 | 0.003 | 1.993 | 0.004 | 0.847 | 0.134 | 0.020 | 33.57 | 2.36 |
| 50 | 1,500 | 533 | 92,720 | 124 | 130,673 | 217 | 0.998 | 0.006 | 1.409 | 0.001 | 0.847 | 0.134 | 0.020 | 27.90 | 1.96 |
| 50 | 2,000 | 914 | 111,720 | 75 | 112,972 | 266 | 0.998 | 0.008 | 1.011 | 0.001 | 0.847 | 0.134 | 0.020 | 24.04 | 1.69 |
| 50 | 2,500 | 756 | 89,975 | 170 | 134,047 | 237 | 0.997 | 0.008 | 1.490 | 0.002 | 0.847 | 0.134 | 0.020 | 28.68 | 2.02 |
| 50 | 3,000 | 404 | 80,425 | 153 | 144,920 | 174 | 0.998 | 0.005 | 1.802 | 0.002 | 0.847 | 0.134 | 0.020 | 31.71 | 2.23 |
| 50 | 3,500 | 98 | 49,906 | 579 | 179,722 | 114 | 0.998 | 0.002 | 3.601 | 0.012 | 0.847 | 0.134 | 0.020 | 49.21 | 3.46 |
| 100 | 1,000 | 165 | 116,309 | 695 | 109,443 | 162 | 0.999 | 0.001 | 0.941 | 0.006 | 0.847 | 0.134 | 0.020 | 23.38 | 1.65 |
| 100 | 1,500 | 218 | 115,555 | 258 | 109,919 | 165 | 0.999 | 0.002 | 0.951 | 0.002 | 0.847 | 0.134 | 0.020 | 23.46 | 1.65 |
| 100 | 2,000 | 205 | 108,786 | 377 | 116,536 | 170 | 0.998 | 0.002 | 1.071 | 0.003 | 0.847 | 0.134 | 0.020 | 24.63 | 1.73 |
| 100 | 2,500 | 156 | 102,821 | 369 | 122,425 | 125 | 0.999 | 0.002 | 1.191 | 0.004 | 0.847 | 0.134 | 0.020 | 25.80 | 1.82 |
| 100 | 3,000 | 179 | 97,266 | 306 | 128,203 | 123 | 0.999 | 0.002 | 1.318 | 0.003 | 0.847 | 0.134 | 0.020 | 27.03 | 1.90 |
| 100 | 3,500 | 69 | 67,697 | 958 | 159,584 | 97 | 0.999 | 0.001 | 2.357 | 0.014 | 0.847 | 0.134 | 0.020 | 37.18 | 2.62 |
| 150 | 1,000 | 94 | 121,668 | 2,729 | 104,719 | 126 | 0.999 | 0.001 | 0.861 | 0.022 | 0.847 | 0.134 | 0.020 | 22.68 | 1.60 |
| 150 | 1,500 | 94 | 110,749 | 1,389 | 115,400 | 127 | 0.999 | 0.001 | 1.042 | 0.013 | 0.847 | 0.134 | 0.020 | 24.40 | 1.72 |
| 150 | 2,000 | 86 | 102,595 | 1,068 | 123,426 | 114 | 0.999 | 0.001 | 1.203 | 0.010 | 0.847 | 0.134 | 0.020 | 25.95 | 1.83 |
| 150 | 2,500 | 50 | 90,393 | 1,132 | 135,773 | 94 | 0.999 | 0.001 | 1.502 | 0.013 | 0.847 | 0.134 | 0.020 | 28,87 | 2.03 |
| 150 | 3,000 | 71 | 88,810 | 722 | 136,115 | 88 | 0.999 | 0.001 | 1.533 | 0.008 | 0.847 | 0.134 | 0.020 | 29.15 | 2.05 |
| 150 | 3,500 | 57 | 83,574 | 1,149 | 141,253 | 87 | 0.999 | 0.001 | 1.690 | 0.014 | 0.847 | 0.134 | 0.020 | 30.70 | 2.16 |

**Table C2.6** DB25 results under partial load (exhaust gas emission, AFR and lambda)

Fuel type : BD25

Test condition : Partial load

| Torque | Speed | CO | $CO_2$ | $NO/NO_x$ | $O_2$ | THC | Spindt's formula | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (N·m) | (rpm) | (ppm) | (ppm) | (ppm) | (ppm) | (ppm) | $F_b$ | R | Q | S | $F_c$ | $F_h$ | $F_o$ | AFR | λ |
| 50 | 1,000 | 226 | 75,916 | 295 | 150,644 | 144 | 0.998 | 0.003 | 1.984 | 0.004 | 0.841 | 0.134 | 0.026 | 33.27 | 2.36 |
| 50 | 1,500 | 605 | 95,779 | 102 | 128,895 | 218 | 0.998 | 0.006 | 1.346 | 0.001 | 0.841 | 0.134 | 0.026 | 27.10 | 1.92 |
| 50 | 2,000 | 912 | 112,644 | 70 | 111,398 | 260 | 0.998 | 0.008 | 0.989 | 0.001 | 0.841 | 0.134 | 0.026 | 23.66 | 1.68 |
| 50 | 2,500 | 512 | 89,718 | 184 | 135,475 | 210 | 0.998 | 0.006 | 1.510 | 0.002 | 0.841 | 0.134 | 0.026 | 28.68 | 2.03 |
| 50 | 3,000 | 426 | 80,585 | 138 | 144,662 | 172 | 0.998 | 0.005 | 1.795 | 0.002 | 0.841 | 0.134 | 0.026 | 31.44 | 2.23 |
| 50 | 3,500 | 90 | 49,428 | 548 | 180,970 | 115 | 0.998 | 0.002 | 3.661 | 0.011 | 0.841 | 0.134 | 0.026 | 49.45 | 3.50 |
| 100 | 1,000 | 167 | 114,937 | 672 | 110,868 | 146 | 0.999 | 0.001 | 0.965 | 0.006 | 0.841 | 0.134 | 0.026 | 23.45 | 1.66 |
| 100 | 1,500 | 188 | 111,223 | 512 | 114,622 | 165 | 0.999 | 0.002 | 1.031 | 0.005 | 0.841 | 0.134 | 0.026 | 24.08 | 1.71 |
| 100 | 2,000 | 210 | 107,509 | 352 | 118,375 | 185 | 0.998 | 0.002 | 1.101 | 0.003 | 0.841 | 0.134 | 0.026 | 24.75 | 1.75 |
| 100 | 2,500 | 166 | 103,432 | 331 | 122,250 | 143 | 0.999 | 0.002 | 1.182 | 0.003 | 0.841 | 0.134 | 0.026 | 25.54 | 1.81 |
| 100 | 3,000 | 204 | 102,374 | 234 | 122,503 | 139 | 0.999 | 0.002 | 1.197 | 0.002 | 0.841 | 0.134 | 0.026 | 25.68 | 1.82 |
| 100 | 3,500 | 63 | 66,307 | 896 | 161,894 | 106 | 0.998 | 0.001 | 2.442 | 0.014 | 0.841 | 0.134 | 0.026 | 37.73 | 2.67 |
| 150 | 1,000 | 112 | 122,474 | 2,708 | 103,709 | 127 | 0.999 | 0.001 | 0.847 | 0.022 | 0.841 | 0.134 | 0.026 | 22.40 | 1.59 |
| 150 | 1,500 | 101 | 111,948 | 1,830 | 113,888 | 116 | 0.999 | 0.001 | 1.017 | 0.016 | 0.841 | 0.134 | 0.026 | 24.02 | 1.70 |
| 150 | 2,000 | 89 | 101,422 | 953 | 124,067 | 106 | 0.999 | 0.001 | 1.223 | 0.009 | 0.841 | 0.134 | 0.026 | 25.97 | 1.84 |
| 150 | 2,500 | 59 | 92,034 | 959 | 133,642 | 98 | 0.999 | 0.001 | 1.452 | 0.010 | 0.841 | 0.134 | 0.026 | 28.18 | 2.00 |
| 150 | 3,000 | 85 | 93,053 | 576 | 131,905 | 95 | 0.999 | 0.001 | 1.418 | 0.006 | 0.841 | 0.134 | 0.026 | 27.83 | 1.97 |
| 150 | 3,500 | 59 | 82,352 | 1,041 | 143,336 | 94 | 0.999 | 0.001 | 1.741 | 0.013 | 0.841 | 0.134 | 0.026 | 30.98 | 2.19 |

**Table C2.7** DB30 results under partial load (exhaust gas emission, AFR and lambda)

Fuel type : BD30

Test condition : Partial load

| Torque | Speed | CO | $CO_2$ | $NO/NO_x$ | $O_2$ | THC | Spindt's formula | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (N·m) | (rpm) | (ppm) | (ppm) | (ppm) | (ppm) | (ppm) | $F_b$ | R | Q | S | $F_c$ | $F_h$ | $F_o$ | AFR | λ |
| 50 | 1,000 | 247 | 74,790 | 290 | 151,300 | 165 | 0.998 | 0.003 | 2.023 | 0.004 | 0.834 | 0.134 | 0.032 | 33.39 | 2.38 |
| 50 | 1,500 | 1,007 | 107,400 | 66 | 118,300 | 309 | 0.997 | 0.009 | 1.101 | 0.001 | 0.834 | 0.134 | 0.032 | 24.56 | 1.75 |
| 50 | 2,000 | 1,160 | 113,900 | 62 | 110,400 | 317 | 0.997 | 0.010 | 0.969 | 0.001 | 0.834 | 0.134 | 0.032 | 23.30 | 1.66 |
| 50 | 2,500 | 726 | 88,790 | 180 | 134,800 | 269 | 0.997 | 0.008 | 1.518 | 0.002 | 0.834 | 0.134 | 0.032 | 28.54 | 2.04 |
| 50 | 3,000 | 485 | 80,470 | 137 | 144,100 | 193 | 0.998 | 0.006 | 1.791 | 0.002 | 0.834 | 0.134 | 0.032 | 31.16 | 2.22 |
| 50 | 3,500 | 86 | 49,340 | 566 | 177,300 | 118 | 0.998 | 0.002 | 3.593 | 0.011 | 0.834 | 0.134 | 0.032 | 48.43 | 3.46 |
| 100 | 1,000 | 200 | 103,512 | 410 | 121,861 | 172 | 0.998 | 0.002 | 1.177 | 0.004 | 0.834 | 0.134 | 0.032 | 25.31 | 1.81 |
| 100 | 1,500 | 206 | 106,708 | 284 | 118,375 | 153 | 0.999 | 0.002 | 1.109 | 0.003 | 0.834 | 0.134 | 0.032 | 24.66 | 1.76 |
| 100 | 2,000 | 172 | 100,933 | 365 | 124,061 | 140 | 0.999 | 0.002 | 1.229 | 0.004 | 0.834 | 0.134 | 0.032 | 25.81 | 1.84 |
| 100 | 2,500 | 138 | 95,158 | 445 | 129,746 | 127 | 0.999 | 0.001 | 1.363 | 0.005 | 0.834 | 0.134 | 0.032 | 27.10 | 1.93 |
| 100 | 3,000 | 174 | 95,646 | 286 | 122,824 | 130 | 0.999 | 0.002 | 1.284 | 0.003 | 0.834 | 0.134 | 0.032 | 26.33 | 1.88 |
| 100 | 3,500 | 63 | 66,379 | 898 | 161,696 | 105 | 0.998 | 0.001 | 2.436 | 0.014 | 0.834 | 0.134 | 0.032 | 37.40 | 2.67 |
| 150 | 1,000 | 83 | 110,045 | 2,598 | 93,377 | 115 | 0.999 | 0.001 | 0.849 | 0.024 | 0.834 | 0.134 | 0.032 | 22.26 | 1.59 |
| 150 | 1,500 | 89 | 104,887 | 1,707 | 121,005 | 119 | 0.999 | 0.001 | 1.154 | 0.016 | 0.834 | 0.134 | 0.032 | 25.15 | 1.79 |
| 150 | 2,000 | 84 | 99,508 | 1,044 | 126,351 | 114 | 0.999 | 0.001 | 1.270 | 0.010 | 0.834 | 0.134 | 0.032 | 26.23 | 1.87 |
| 150 | 2,500 | 48 | 88,869 | 1,118 | 133,813 | 92 | 0.999 | 0.001 | 1.506 | 0.013 | 0.834 | 0.134 | 0.032 | 28.51 | 2.03 |
| 150 | 3,000 | 53 | 80,405 | 923 | 146,846 | 88 | 0.999 | 0.001 | 1.826 | 0.011 | 0.834 | 0.134 | 0.032 | 31.57 | 2.25 |
| 150 | 3,500 | 50 | 88,775 | 1,061 | 136,373 | 91 | 0.999 | 0.001 | 1.536 | 0.012 | 0.834 | 0.134 | 0.032 | 28.79 | 2.05 |

**Table C2.8** DB35 results under partial load (exhaust gas emission, AFR and lambda)

Fuel type : BD35

Test condition : Partial load

| Torque (N·m) | Speed (rpm) | CO (ppm) | $CO_2$ (ppm) | $NO/NO_x$ (ppm) | $O_2$ (ppm) | THC (ppm) | Spindt's formula | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | $F_b$ | R | Q | S | $F_c$ | $F_h$ | $F_o$ | AFR | λ |
| 50 | 1,000 | 280 | 73,855 | 288 | 153,535 | 171 | 0.998 | 0.004 | 2.079 | 0.004 | 0.867 | 0.133 | 0.039 | 35.02 | 2.52 |
| 50 | 1,500 | 879 | 92,891 | 108 | 131,744 | 273 | 0.997 | 0.009 | 1.418 | 0.001 | 0.867 | 0.133 | 0.039 | 28.45 | 2.05 |
| 50 | 2,000 | 1,576 | 112,477 | 64 | 111,915 | 425 | 0.996 | 0.014 | 0.995 | 0.001 | 0.867 | 0.133 | 0.039 | 24.24 | 1.74 |
| 50 | 2,500 | 1,312 | 89,880 | 167 | 134,200 | 436 | 0.995 | 0.015 | 1.493 | 0.002 | 0.867 | 0.133 | 0.039 | 29.16 | 2.10 |
| 50 | 3,000 | 784 | 80,375 | 133 | 144,936 | 254 | 0.997 | 0.010 | 1.803 | 0.002 | 0.867 | 0.133 | 0.039 | 32.27 | 2.32 |
| 50 | 3,500 | 115 | 49,542 | 531 | 180,139 | 125 | 0.997 | 0.002 | 3.636 | 0.011 | 0.867 | 0.133 | 0.039 | 50.51 | 3.63 |
| 100 | 1,000 | 155 | 111,338 | 831 | 114,377 | 161 | 0.999 | 0.001 | 1.027 | 0.007 | 0.867 | 0.133 | 0.039 | 24.60 | 1.77 |
| 100 | 1,500 | 217 | 105,392 | 304 | 120,577 | 166 | 0.998 | 0.002 | 1.144 | 0.003 | 0.867 | 0.133 | 0.039 | 25.74 | 1.85 |
| 100 | 2,000 | 248 | 105,154 | 363 | 120,505 | 181 | 0.998 | 0.002 | 1.146 | 0.003 | 0.867 | 0.133 | 0.039 | 25.76 | 1.85 |
| 100 | 2,500 | 253 | 101,884 | 376 | 123,571 | 137 | 0.999 | 0.002 | 1.213 | 0.004 | 0.867 | 0.133 | 0.039 | 26.44 | 1.90 |
| 100 | 3,000 | 138 | 80,850 | 437 | 145,236 | 127 | 0.998 | 0.002 | 1.796 | 0.005 | 0.867 | 0.133 | 0.039 | 32.24 | 2.32 |
| 100 | 3,500 | 69 | 66,446 | 886 | 160,523 | 108 | 0.998 | 0.001 | 2.416 | 0.013 | 0.867 | 0.133 | 0.039 | 38.43 | 2.76 |
| 150 | 1,000 | 94 | 117,689 | 2,365 | 107,831 | 126 | 0.999 | 0.001 | 0.916 | 0.020 | 0.867 | 0.133 | 0.039 | 23.57 | 1.69 |
| 150 | 1,500 | 97 | 106,129 | 1,542 | 119,651 | 129 | 0.999 | 0.001 | 1.127 | 0.015 | 0.867 | 0.133 | 0.039 | 25.64 | 1.84 |
| 150 | 2,000 | 100 | 101,848 | 960 | 123,029 | 123 | 0.999 | 0.001 | 1.208 | 0.009 | 0.867 | 0.133 | 0.039 | 26.41 | 1.90 |
| 150 | 2,500 | 52 | 89,385 | 1,083 | 136,123 | 94 | 0.999 | 0.001 | 1.523 | 0.012 | 0.867 | 0.133 | 0.039 | 29.56 | 2.13 |
| 150 | 3,000 | 53 | 78,829 | 989 | 147,650 | 88 | 0.999 | 0.001 | 1.873 | 0.013 | 0.867 | 0.133 | 0.039 | 33.05 | 2.38 |
| 150 | 3,500 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |

**Table C.9** DB40 results under partial load (exhaust gas emission, AFR and lambda)

Fuel type : BD40

Test condition : Partial load

| Torque (N·m) | Speed (rpm) | CO (ppm) | $CO_2$ (ppm) | $NO/NO_x$ (ppm) | $O_2$ (ppm) | THC (ppm) | Spindt's formula | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | $F_b$ | R | Q | S | $F_c$ | $F_b$ | $F_o$ | AFR | λ |
| 50 | 1,000 | 294 | 57,863 | 285 | 136,855 | 193 | 0.997 | 0.005 | 2.365 | 0.005 | 0.867 | 0.133 | 0.046 | 37.81 | 2.74 |
| 50 | 1,500 | 936 | 71,729 | 107 | 116,496 | 311 | 0.996 | 0.013 | 1.624 | 0.001 | 0.867 | 0.133 | 0.046 | 30.43 | 2.21 |
| 50 | 2,000 | 1,809 | 84,463 | 55 | 98,484 | 514 | 0.994 | 0.021 | 1.166 | 0.001 | 0.867 | 0.133 | 0.046 | 25.87 | 1.88 |
| 50 | 2,500 | 1,659 | 69,578 | 123 | 119,052 | 579 | 0.992 | 0.024 | 1.711 | 0.002 | 0.867 | 0.133 | 0.046 | 31.22 | 2.26 |
| 50 | 3,000 | 754 | 62,912 | 149 | 129,306 | 253 | 0.996 | 0.012 | 2.055 | 0.002 | 0.867 | 0.133 | 0.046 | 34.72 | 2.52 |
| 50 | 3,500 | 125 | 40,635 | 580 | 159,981 | 144 | 0.996 | 0.003 | 3.937 | 0.014 | 0.867 | 0.133 | 0.046 | 53.44 | 3.87 |
| 100 | 1,000 | 157 | 81,504 | 976 | 102,840 | 183 | 0.998 | 0.002 | 1.262 | 0.012 | 0.867 | 0.133 | 0.046 | 26.91 | 1.95 |
| 100 | 1,500 | 212 | 79,760 | 331 | 107,852 | 198 | 0.998 | 0.003 | 1.352 | 0.004 | 0.867 | 0.133 | 0.046 | 27.76 | 2.01 |
| 100 | 2,000 | 194 | 73,576 | 517 | 115,849 | 185 | 0.997 | 0.003 | 1.575 | 0.007 | 0.867 | 0.133 | 0.046 | 29.98 | 2.17 |
| 100 | 2,500 | 143 | 66,961 | 576 | 124,750 | 151 | 0.998 | 0.002 | 1.863 | 0.009 | 0.867 | 0.133 | 0.046 | 32.86 | 2.38 |
| 100 | 3,000 | 114 | 59,961 | 519 | 134,242 | 134 | 0.998 | 0.002 | 2.239 | 0.009 | 0.867 | 0.133 | 0.046 | 36.60 | 2.65 |
| 100 | 3,500 | 73 | 53,382 | 881 | 142,845 | 118 | 0.998 | 0.001 | 2.676 | 0.016 | 0.867 | 0.133 | 0.046 | 40.98 | 2.97 |
| 150 | 1,000 | 95 | 90,649 | 2,560 | 91,252 | 146 | 0.998 | 0.001 | 1.007 | 0.028 | 0.867 | 0.133 | 0.046 | 24.46 | 1.77 |
| 150 | 1,500 | 100 | 75,231 | 1,727 | 113,487 | 131 | 0.998 | 0.001 | 1.509 | 0.023 | 0.867 | 0.133 | 0.046 | 29.43 | 2.13 |
| 150 | 2,000 | 95 | 67,367 | 1,021 | 124,122 | 120 | 0.998 | 0.001 | 1.842 | 0.015 | 0.867 | 0.133 | 0.046 | 32.71 | 2.37 |
| 150 | 2,500 | 71 | 62,997 | 873 | 130,063 | 110 | 0.998 | 0.001 | 2.065 | 0.014 | 0.867 | 0.133 | 0.046 | 34.91 | 2.53 |
| 150 | 3,000 | 58 | 62,114 | 996 | 130,990 | 109 | 0.998 | 0.001 | 2.109 | 0.016 | 0.867 | 0.133 | 0.046 | 35.36 | 2.56 |
| 150 | 3,500 | 60 | 63,689 | 1,021 | 129,091 | 109 | 0.998 | 0.001 | 2.027 | 0.016 | 0.867 | 0.133 | 0.046 | 34.54 | 2.50 |

# APPENDIX D

# ASTM AND CEC STANDARD

## D-1: Flash Point (ASTM D93)

This flash point test method is a dynamic test method, which depends on specified rates of heating to be able to meet the precision of the test method. The rate of heating may not in all cases give the precision quoted in the test method because of the low thermal conductivity of some materials. Flash point values are a function of the apparatus design, the condition of the apparatus used, and the operational procedure carried out. Flash point can therefore only be defined in terms of a standard test method, and no general valid correlation can be guaranteed between results obtained by different test methods, or with test apparatus different from that specified. The apparatus specifications are showed in Figure D1.

These test methods cover the determination of the flash point of petroleum products in the temperature range from 40 to 360°C by a manual Pensky-Martens closed-cup apparatus or an automated Pensky-Martens closed-cup apparatus. There are two procedures for this test method. First, procedure A is applicable to distillate fuels (diesel, kerosene, heating oil, turbine fuels), new lubricating oils, and other homogeneous petroleum liquids not included in the scope of Procedure B. Second, Procedure B is applicable to residual fuel oils, cutback residua, used lubricating oils, mixtures of petroleum liquids with solids, petroleum liquids that tend to form a surface film under test conditions, or is petroleum liquids of such kinematic viscosity that they are not uniformly heated

For calculating flash point value, the barometric pressure used in this calculation is the ambient pressure for the laboratory at the time of the test. Many aneroid barometers, such as those used at weather stations and airports, are precorrected to give sea level readings and would not give the correct reading for this test. Observe and record the ambient barometric pressure at the time of the test. When the pressure differs from 101.3 kPa (760 mm Hg), correct the flash point as follows:

$$\text{Corrected flash point} = C + 0.25\,(101.3 - K) \quad \text{(d1)}$$

$$\text{Corrected flash point} = F + 0.06\,(760 - P) \quad \text{(d2)}$$

$$\text{Corrected flash point} = C + 0.033\,(760 - P) \quad \text{(d3)}$$

Where: $C$ = observed flash point, °C

$F$ = observed flash point, °F

$P$ = ambient barometric pressure, mm Hg, and

$K$ = ambient barometric pressure, kPa.

After correction for barometric pressure, round the temperature to the nearest 0.5°C (1°F) and record

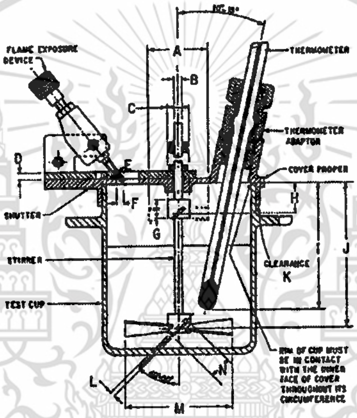


**Figure D1** Test Cup and Cover Assembly.

## D-2: Copper Strip Corrosion (ASTM D130)

This test method covers the determination of the corrosiveness by copper of aviation gasoline, aviation turbine fuel, automotive gasoline, cleaners solvent, kerosine, diesel fuel, distillate fuel oil, lubricating oil, and natural gasoline or other hydrocarbons having a vapor pressure no greater than 124 kPa (18 psi) at 37.8°C. Interpret the corrosiveness of the sample in accordance with one of the classifications of the ASTM Copper Strip Corrosion Standard as listed in Table D1.

**Table D1** Copper strip classifications (ASTM D130)

| Classification | Designation | Description[A] |
|---|---|---|
| Freshly polished strip | .. | [B] |
| 1 | slight tarnish | a. Light orange, almost the same as freshly polished strip |
| | | b. Dark orange |
| 2 | moderate tarnish | a. Claret red |
| | .. | b. Lavender |
| | .. | c. Multicolored with lavender blue or silver, or both, overlaid on claret red |
| | ... | d. Silvery |
| | ... | e. Brassy or gold |
| 3 | dark tarnish | a. Magenta overcast on brassy strip |
| | .. | b. Multicolored with red and green showing (peacock), but no gray |
| 4 | corrosion | a. Transparent black, dark gray or brown with peacock green barely showing |
| | ... | b. Graphite or lusterless black |
| | .. | c. Glossy or jet black |

[A] The ASTM Copper Strip Corrosion Standard is a colored reproduction of strips characteristic of these descriptions.

[B] The freshly polished strip is included in the series only as an indication of the appearance of a properly polished strip before a test run; it is not possible to duplicate this appearance after a test even with a completely noncorrosive sample.

## D-3: Carbon Residue (ASTM D524)

This test method covers the determination of the amount of carbon residue left after evaporation and pyrolysis of an oil, and it is intended to provide some indication of relative coke-forming propensity. This test method is generally applicable to relatively nonvolatile petroleum products, which partially decompose on distillation at atmospheric pressure. This test method also covers the determination of carbon residue on 10% (v/v) distillation residues. Petroleum products, containing ash-forming constituents as determined by Test Method D482, will have an erroneously high carbon residue, depending upon the amount of ash formed.

Calculate the carbon residue of the sample or of the 10 % distillation residue as follows:

$$\text{Carbon residue} = (A \times 100)/W \tag{d4}$$

where: A = mass of carbon residue, gram, and

W = mass of sample, gram.

## D-4: Heat of Combustion (ASTM D240)

This test method covers the determination of the heat of combustion of liquid hydrocarbon fuels ranging in volatility from that of light distillates to that of residual fuels. The heat of combustion is a measure of the energy available from a fuel. A knowledge of this value is essential when considering the thermal efficiency of equipment for producing either power or heat.

D-4.1 Gross Heat of Combustion, compute the gross heat of combustion by substituting in the following equation:

$$Q_g = (tW\text{-}e_1\text{-}e_2\text{-}e_3\text{-}e_4)/1{,}000\ g \qquad \text{(d5)}$$

where: $Q_g$ = gross heat of combustion, at constant volume expressed as MJ/kg,

t = corrected temperature rise (in D-4.2 or D-4.3), °C,

W = energy equivalent of calorimeter, MJ/°C (in D-4.5),

$e_1$, $e_2$, $e_3$, $e_4$ = corrections as prescribed (in D-4.4), and

g = weight of sample, g.

D-4.2 Temperature Rise in Adiabatic Jacket Calorimeter, using data obtained as prescribed to compute the temperature rise, t, in an adiabatic jacket calorimeter as follows:

$$t = t_f - t_\alpha \qquad \text{(d6)}$$

where: t = corrected temperature rise,

$t_\alpha$ = temperature when charge was fired, corrected for thermometer error , and

$t_f$ = final equilibrium temperature, corrected for the thermometer error.

D-4.3 Temperature Rise in Isothermal Jacket Calorimeter, using data obtained as prescribed, compute the temperature rise, t, in an isothermal jacket calorimeter as follows:

$$t = t_c\text{-}t_\alpha - r_1(b\text{-}a)\text{-}r_2(c\text{-}b) \qquad \text{(d7)}$$

where: t = corrected temperature rise,

a = time of firing,

b = time (to nearest 0.1 min) when the temperature rise reaches 60% of total,

c = time at beginning of period in which the rate of temperature change with time has become constant (after combustion),

$t_\alpha$ = temperature at time of firing, corrected for thermometer error,

$t_c$ = temperature at time, c, corrected for thermometer error,

$r_1$ = rate (temperature units per minute) at which temperature was rising during 5-min period before firing, and

$r_2$ = rate (temperature units per minute) at which temperature was rising during the 5-min period after time c. If the temperature is falling, $r_2$ is negative and the quantity, $r_2(c - b)$ is positive.

D-4.4 Thermo-chemical Corrections compute the following for each test:

$e_1$ = correction for heat of formation of nitric acid ($HNO_3$), MJ = $cm^3$ of standard (0.0866 N) NaOH solution used in titration x $5/10^6$,

$e_2$ = correction for heat of formation of sulfuric acid ($H_2SO_4$). MJ = 58.0 x percentage of sulfur in sample x mass of sample/106,

$e_3$ = correction for heat of combustion of firing wire, MJ,

= 1.13 x millimetres of iron wire consumed/$10^6$,

= 0.96 x millimetres of Chromel C wire consumed/$10^6$, and

$e_4$ = correction for heat of combustion of pressure-sensitive tape or gelatin capsule and mineral oil, MJ = mass of tape or capsule oil, g x heat of combustion of tape or capsule/oil, MJ/kg/$10^6$.

D-4.5 Determine the Energy Equivalent of the Calorimeter, average not less than six tests using standard benzoic acid. These tests should be spaced over a period of not less than three days. Use not less than 0.9 g or more than 1.1 g of standard benzoic acid ($C_6H_6COOH$). Make each determination according to the procedure and compute the corrected temperature rise, t, as described in D-4.2 or D-4.3 Determine the corrections for nitric acid ($HNO_3$) and firing wire as described in 4 and substitute in the following equation:

$$W = (Q \times g + e_1 + e_2)/t \qquad \text{(d8)}$$

where: W = energy equivalent of calorimeter, MJ/°C,

Q = heat of combustion of standard benzoic acid, MJ/g, calculated from the certified value,

g = weight of standard benzoic acid sample, g,

t = corrected temperature rise, as calculated in D.4.2 or D4.3,°C,

$e_1$ = correction for heat of formation of nitric acid, MJ, and

$e_2$ = correction for heat of combustion of firing wire, MJ.

## D-5: Kinematic Viscosity (ASTM D445)

Dynamic viscosity ($\mu$), viscosity describes a fluids resistance to flow. Dynamic viscosity (sometimes referred to as Absolute viscosity) is obtained by dividing the Shear stress by the rate of shear strain. The units of dynamic viscosity are: force/area x time. The Pascal unit (Pa) is used to describe pressure or stress = force per area. This unit can be combined with time (sec) to define dynamic viscosity, which is $\mu$ = Pa•s (1.0 Pa•s = 10 Poise = 1,000 Centipoise).

Kinematic Viscosity ($\nu$), sometimes viscosity is measured by timing the flow of a known volume of fluid from a viscosity measuring cup. The timings can be used along with a formula to estimate the kinematic viscosity value of the fluid in Centistokes (cSt). The motive force driving the fluid out of the cup is the head of fluid. This fluid head is also part of the equation that makes up the volume of the fluid. Rationalizing the equations the fluid head term is eliminated leaving the units of Kinematic viscosity as area/time, which is $\nu = m^2/s$ ($1.0\ m^2/s$ = 10,000 Stokes = 1,000,000 Centistokes) and the kinematic viscosity can also be determined by dividing the dynamic viscosity by the fluid density.

For this test method specifies a procedure for the determination of the kinematic viscosity, $\nu$ , of liquid petroleum products, both transparent and opaque, by measuring the time for a volume of liquid to flow under gravity through a calibrated glass capillary viscometer. The dynamic viscosity, $\eta$, can be obtained by multiplying the kinematic viscosity, $\nu$, by the density, $\rho$, of the liquid.

The result obtained from this test method is dependent upon the behavior of the sample, and is intended for application to liquids for which primarily the shear stress and shear rates are proportional (Newtonian flow behavior). If, however, the viscosity varies significantly with the rate of shear, different results may be obtained from viscometers of different capillary diameters. The procedure and precision values for residual fuel oils, which under some conditions exhibit non-Newtonian behavior, have been included.

Calculate each of the determined kinematic viscosity values, $\nu_1$ and $\nu_2$, from the measured flow times, $t_1$ and $t_2$, and the viscometer constant, C, by means of the following equation:

$$\nu_{1,2} = C \cdot t_{1,2} \qquad \text{(d9)}$$

where: $\nu_{1,2}$ = determined kinematic viscosity values for $\nu_1$ and $\nu_2$, $mm^2/s$,

$C$ = calibration constant of the viscometer, $mm^2/s^2$, and

$t_{1,2}$ = measured flow times for $t_1$ and $t_2$, respectively, s.

Calculate the dynamic viscosity, $\eta$, from the calculated kinematic viscosity, $\nu$, and the density, $\rho$, by means of the following equation:

$$\eta = \nu \times \rho \times 10^{-3} \tag{d10}$$

where: $\eta$ = dynamic viscosity, mPa·s,

$\rho$ = density, $kg/m^3$, at the same temperature used for the determination of the kinematic viscosity, and

$\nu$ = kinematic viscosity, $mm^2/s$.

## D-6: Ash Content (ASTM D482)

This test method covers the determination of ash in the range 0.001–0.180 mass %, from distillate and residual fuels, gas turbine fuels, crude oils, lubricating oils, waxes, and other petroleum products, in which any ash-forming materials are normally considered to be undesirable impurities or contaminants. The test method is limited to petroleum products, which are free from added ash-forming additives, including certain phosphorus compounds.

Calculate the mass of the ash as a percentage of the original samples as follows:

$$\text{Ash, mass \%} = (w/W) \times 100 \tag{d11}$$

where: $w$ = mass of ash, g, and

$W$ = mass of sample, g.

## D-7: Density (ASTM D4052)

This test method covers the determination of the density, relative density, and API Gravity of petroleum distillates and viscous oils that can be handled in a normal fashion as liquids at the temperature of test, utilizing either manual or automated sample injection equipment. Its application is restricted to liquids with total vapor pressures typically below 100 kPa and viscosities typically below about 15,000 $mm^2/s$ at the temperature of test. The total vapor pressure limitation however can be extended 100 kPa provided that it is first ascertained that no bubbles form in the U-shaped, oscillating tube, which can affect the density determination. Some examples of products that may be tested by this procedure include: gasoline and gasoline-oxygenate blends, diesel, jet, basestocks, waxes, and lubricating oils.

Calculating Density Analyzers, using the observed T-value for the sample, and the T-value for water and appropriate instrument constants determined in Eq. d14 or d15, calculate the density or relative density using Eq. 2.2.12 and 2.2.13. Carry out all calculations to six significant figures and round the final results to four.

For density: density, g/mL (kg/m$^3$) at $t = d_w + K_1(T_s^2 - T_w^2)$ (d12)

relative density, $t/t = 1 + K_2(T_s^2 - T_w^2)$ (d13)

where: $T_w$ = observed period of oscillation for cell containing water,

$T_s$ = observed period of oscillation for cell containing sample,

$d_w$ = density of water at test temperature,

$K_1$ = instrument constant for density,

$K_2$ = instrument constant for relative density, and

T = temperature of test, °C.

Using the observed T-values and the reference values for water and air (Eq. d16), calculate the instrument constant K using the following equations:

For density: $K_1 = [d_w - d_a][T_w^2 - T_a^2]$ (d14)

For relative density: $K_2 = [1.0 - d_a]\,[T_w^2 - T_a^2]$ (d15)

where: $T_w$ = observed period of oscillation for cell containing water,

$T_a$ = observed period of oscillation for cell containing air,

$d_w$ = density of water at test temperature, and

$d_a$ = density of air at test temperature.

Calculate the density of air at the temperature of test using the following equation:

$d_a$, g/mL = 0.001293[273.15/T][P/760] (d16)

where: T = temperature, K, and

P = barometric pressure, torr.

## D-8: Water Content (ASTM D6304)

This test method covers the direct determination of water in the range of 10 to 25,000 mg/kg entrained water in petroleum products and hydrocarbons using automated instrumentation.

This test method also covers the indirect analysis of water thermally removed from samples and swept with dry inert gas into the Karl Fischer titration cell.

Calculate the water concentration in mg/kg or µL/mL of the sample as follows:

$$\text{water, mg/kg or } \mu g/g = W_1/W_2 \qquad \text{or} \tag{d17}$$

$$\text{water, } \mu L/mL = V_1/V_2 \tag{d18}$$

and calculate the water concentration, in mass or volume %, of the sample as follows:

$$\text{water, mass \%} = W_1/(10{,}000 \text{x} W_2) \qquad \text{or} \tag{d19}$$

$$\text{volume \%} = V_1/(10 \text{x} V_2) \tag{d20}$$

where: $W_1$ = mass of water titrated, mg or µg (as appropriate),

$W_2$ = mass of sample used, kg or g (as appropriate),

$V_1$ = volume of water titrated, µL, and

$V_2$ = volume of sample used, mL.

Use the following equations for calculating the water content of the sample in units of volume % from mass %, or mass % from volume %.

$$\text{water, (volume\%)} = \text{mass\% x [density of sample at t / density of water at t]} \tag{d21}$$

$$\text{water, (mass\%)} = \text{volume \% x [density of sample at t / density of water at t ]} \tag{d22}$$

where: t = test temperature.

## D-9: Lubricity (CEC F-06-A-96)

For calculation of test results for corrected wear scar diameter (WS1.4), it is necessary to calculate the mean water vapor pressure at the start and the end of each test, and to apply a humidity correction factor (HCF) which normalizes the test result to a standard vapor pressure of 1.4 kPa because the absolute humidity affects the results of the HFRR test. The corrected wear scar diameter, WS1.4, is calculated as follow.

Initial vapor pressure, from the value of temperature in °C ($T_1$) and relative humidity ($\%HR_1$) at the start of the test are calculated the initial absolute vapor pressure ($AVP_1$).

$$APV_1 = \frac{\%RH_1 \times 10^{\nu}}{760} \qquad \text{kPa} \tag{d23}$$

where: $$\nu = 8.017352 - \frac{1{,}705.984}{231.8636 + T_1} \tag{d24}$$

The 'X' and 'Y' is used uncorrected mean ware scar diameter values on the upper specimen to calculate the mean wear scar diameter (MWSD).

$$\text{MWSD} = (\text{X}+\text{Y})/2 \tag{d25}$$

Final vapor pressure uses the values of temperature ($T_2$) and relative humidity ($\%RH_2$) at the end of the test to calculate the absolute vapor pressure ($APV_2$).

$$APV_2 = \frac{\%RH_2 \times 10^{\nu}}{760} \quad \text{kPa} \tag{d26}$$

where: $$\nu = 8.017352 - \frac{1{,}705.984}{231.8636 + T_2} \tag{d27}$$

The mean absolute vapor pressure during the test is given by.

$$APV = \left(APV_1 - APV_2\right)/2 \quad \text{kPa} \tag{d28}$$

Therefore, the corrected wear scar diameter (WS1.4) is given by.

$$WS1.4 = MWSD + HCF(1.4 - APV) \quad \text{microns} \tag{d29}$$

where: HFC is the humidity correction factor in µm/kPa

HFC = 60.0 for unknown fuel samples

HFC = 130 for RF-74-T-95 (low lubricity reference fluid)

HFC = 3.0 for RF-90-A-92 (high lubricity reference fluid)

# APPENDIX E

# Diesel Standard of Department of Energy Business

**Table E1** Characteristic and quality of Diesel fuel (Department of Energy Business, 1997)

| Item | Description | Rates (low-high) | Diesel | | |
|---|---|---|---|---|---|
| | | | High Speed | | Low speed |
| | | | Normal | B5 | |
| 1 | Specific Gravity at 15.6 °C | Not lower than | 0.81 | 0.81 | - |
| | | And not higher than | 0.87 | 0.87 | 0.92 |
| 2 | Cetane Number | | | | |
| | or Calculated Cetane Index | | | | |
| | Before January 1, 2012 | Not lower than | 47 | 47 | 45 |
| | Form January 1, 2012 | Not lower than | 50 | 50 | 45 |
| 3 | Viscosity, cSt | | | | |
| | 3.1 at 40 °C or | Not lower than | 1.8 | 1.8 | - |
| | | And not higher than | 4.1 | 4.1 | 8 |
| | 3.2 at 50 °C | Not higher than | - | - | 6 |
| 4 | Pour Point, °C | Not higher than | 10 | 10 | 16 |
| 5 | Sulphur, %wt. | | | | |
| | Before January 1, 2012 | Not higher than | 0.035 | 0.035 | 1.5 |
| | Form January 1, 2012 | Not higher than | 0.005 | 0.005 | 1.5 |
| 6 | Copper Strip Corrosion | Not higher than | N. 1 | N. 1 | - |
| 7 | Oxidation Stability, g/m$^3$ | Not higher than | - | 25 | - |
| 8 | Carbon Residue, %wt | Not higher than | 0.05 | 0.05 | - |
| 9 | Water and Sediment, %vol | Not higher than | 0.05 | 0.05 | 0.3 |
| 10 | Ash, %wt | Not higher than | 0.01 | 0.01 | 0.02 |
| 11 | Flash Point, °C | Not higher than | 52 | 52 | 52 |
| 12 | Distillation (90% recovered), °C | Not higher than | 357 | 357 | - |
| 13 | Polycyclic Aromatic Hydrocarbon, % wt | | | | |
| | Before January 1, 2012 | - | - | - | - |
| | Form January 1, 2012 | Not higher than | 11 | 11 | - |
| 14 | Colour | | | | |
| | 14.1 Hue | | - | Blue | - |
| | 14.2 Dye , mg/L | Not lower than | - | 7.0 | - |
| | 14.3 Intensity | Not lower than | - | - | 4.5 |
| | | And not higher than | 4.0 | - | 7.5 |
| 15 | Methyl Ester of Fatty Acid, %vol | Not lower than | 1.5 | 4 | - |
| | | And not higher than | 2 | 5 | - |
| 16 | Lubricity, µm | Not higher than | 460 | 460 | - |
| 17 | Additive | According to the regulation of Department of Energy Business | | | |

# APPENDIX F

# Life-Cycle Assessment of Corn-Based Butanol

Wu *et al.* (2007) have studied butanol produced from bio-sources (such as corn) could have attractive properties as a transportation fuel. Production of butanol through a fermentation process called acetone-butanol-ethanol (ABE) has been the focus of increasing research and development efforts. Advances in ABE process development in recent years have led to drastic increases in ABE productivity and yields, making butanol production worthy of evaluation for use in motor vehicles. Consequently, chemical/fuel industries have announced their intention to produce butanol from bio-based materials. The purpose of this study is to estimate the potential life-cycle energy and emission effects associated with using bio-butanol as a transportation fuel. The study employs a well-to-wheels analysis tool (the Greenhouse Gases, Regulated Emissions and Energy Use in Transportation (GREET) model developed at Argonne National Laboratory) and the Aspen Plus® model developed by AspenTech. The study describes the butanol production from corn, including grain processing, fermentation, gas stripping, distillation, and adsorption for products separation. The Aspen® results that we obtained for the corn-to-butanol production process provide the basis for GREET modeling to estimate life-cycle energy use and greenhouse gas emissions. The GREET model was expanded to simulate the bio-butanol life cycle, from agricultural chemical production to butanol use in motor vehicles.

Figure F1 depicts the GREET modeling boundary for this study. The life cycle of bio-butanol is divided into five stages: 1. Corn farming, 2. Corn transportation, 3. Bio-butanol production, 4. Bio-butanol transportation and distribution, and 5. Bio-butanol use in gasoline vehicles (GVs). The results can summarize that Corn-based butanol, produced by means of the current ABE process, could offer substantial fossil energy savings and moderate reductions in GHG emissions relative to petroleum gasoline on a WTW basis, when co-products are credited by energy allocation. The energy benefits associated with bio-butanol are significant when co-product corn-acetone is credited with displacement method. When acetone is credited by energy allocation, life-cycle energy benefits for corn butanol are less promising than those of corn ethanol generated from conventional dry milling processes. GHG emissions generated from bio-butanol life cycle are higher than those generated from corn ethanol.

In addition, while the use of corn-based butanol achieves energy benefits and reduces greenhouse gas emissions, the results are affected by the methods used to treat the acetone that is co-produced in butanol plants.

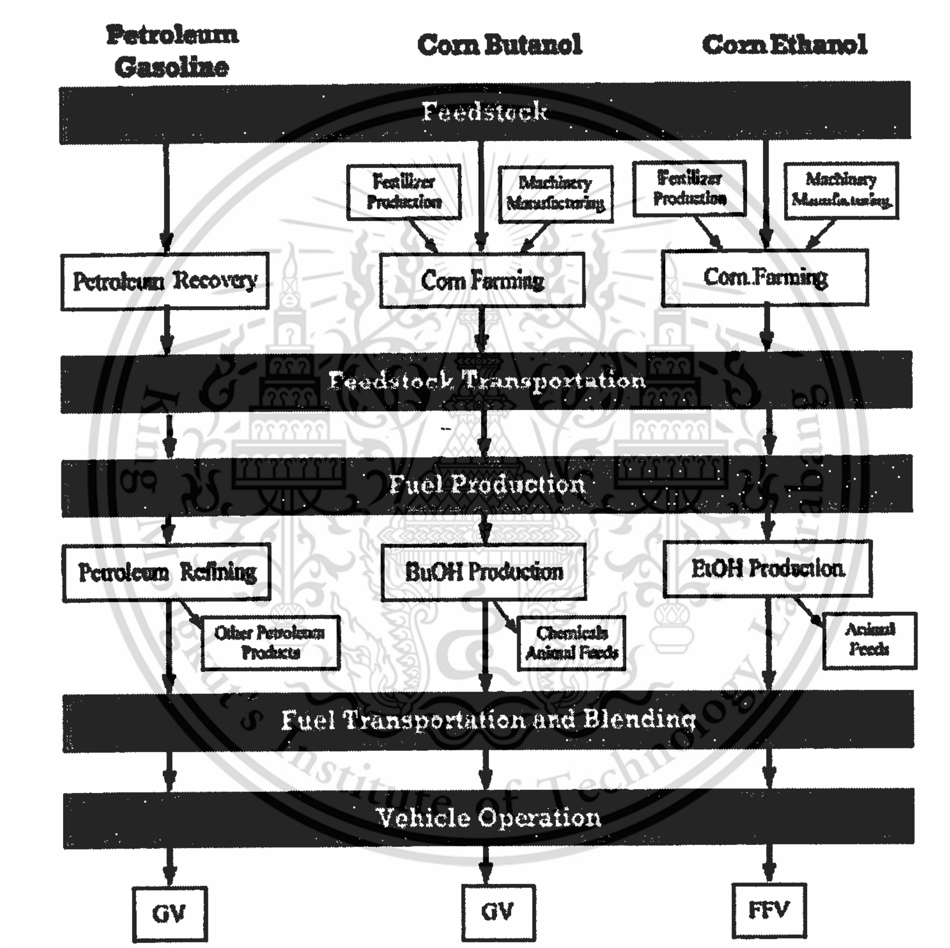


**Figure F1** Schematic representation of WTW analysis system boundaries for butanol, ethanol, and gasoline.

# BIOGRAPHY

| | |
|---|---|
| **Name:** | Mr. Sakda Thongchai |
| **Date of Birth:** | October 1, 1978 |
| **Place of Birth:** | Nongkhai, Thailand |

**Education:**

| | |
|---|---|
| 1978-1999 | B. Eng. in Mechanical Engineering, King Mongkut's Institute of Technology Ladkrabang (KMITL) |
| 2004 – 2006 | M.B.A. in Agribusiness and Food Industry Management, King Mongkut's Institute of Technology Ladkrabang (KMITL) |
| 2007-2010 | M. Eng. in Automotive Engineering (International program), International College, King Mongkut's Institute of Technology Ladkrabang (KMITL) |

**Scholarships:**

| | |
|---|---|
| 2007-2009 | Full scholarship for study in the master degree from National Science and Technology Development Agency (NSTDA) |

**Publications:**

1. Thongchai, S., Chollacoop, N., Topaiboul, S., Charoenphonphanich,c., and Kamimoto, T., Effect of Butanol-Diesel Blends on Performance and Emission of Commonrail Engine, The 2nd Thammasat University International Conference on Chemical, Environmental and Energy Engineering (TU-ChEEE 2009), Bangkok, Thailand, March 3-4, 2009.
2. Thongchai, S., Chollacoop, N., Topaiboul, S., Suwannakij, K., Charoenphonphanich, c., and Hanamura, K., Feasibility Study of Using High Butanol-Diesel Blends in Commonrail Engine, The 23rd Conference of the Mechanical Engineering Network of Thailand, Chiang Mai, November 4 – 7, 2009.