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Investigation of Abnormal Combustion Characteristics of Dual Fuel Engine Using Natural Gas and Diesel as Fuels

Nawee Nuntapap [1], Himashu Singh [2], Amornrat Kaewpradap [1] and Yossapong Laoonual [1],*

[1] Combustion and Engines Research Laboratory (CERL), Department of Mechanical Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, 126 Pracha Uthit Road, Bang Mod, Thung Kru, Bangkok, 10140, Thailand

[2] Internship Student, Indian Institute of Technology Kanpur, India 208016

*Corresponding Author: E-mail: yossapong.lao@kmutt.ac.th, +66 2470 9123; Fax: +66 2470 9111

Abstract

This paper investigates abnormal combustion characteristics of dual fuel engines using both natural gas and diesel. Amodified, single cylinder diesel engine is used for the experiment. The diesel injection system allows for fuel variance by pump adjustment, while the gas injection system is controlled by an electronic control unit (ECU). For all experiments, the following parameters are kept constant: injection timing, engine speed, torque and power output. The mixing ratio between natural gas and diesel fuel (Z) is varied from 70% to 92%. Combustion characteristics and heat release rate were analysed by in-cylinder pressure measurements. An increased mixing ratio (Z) leads to increased heat release rate during the mixed control phase. Cylinder peak pressure decreases when the mixing ratio (Z) increases. For abnormal DDF combustion, variation in Indicated Mean Effective Pressure (IMEP) is expected due to partial burning of fuel. Start of combustion takes place after top dead center (TDC), which is a considerably longer ignition delay for all cycles

Keywords: Abnormal Combustion, Knock, Diesel Dual Fuel (DDF)

1. Introduction

The demand for energy is increasing daily. It has led to a quest for alternative fuels which are cheaper and more widely available. There have been efforts to increase usage of natural gas in place of conventional fuels. A dual fuel engine is one in which a diesel engine can be modified for the use of gaseous fuels.

Unlike SI and CI engines, which are based on Otto and Diesel cycles, a dual fuel cycle has been modelled using a Sabathe cycle by Pawlack [1]. As shown in Fig. 1, heat is applied at constant pressure and volume. The experiment was performed for engine speeds (1200, 1400, 1800, 2200, 2600, 3000 and 3200 rpm). The engine theoretical efficiency was calculated for four compression ratio values: 10, 12, 14 and 16. The total amount of heat applied remained constant, but the amount of heat applied at constant volume was different for each cycle. At constant volume, the efficiency ranged between 0.4 to 0.6 when no heat was applied. It increased to 0.7 if all heat was applied at constant volume. In practice, heat applied at constant volume is limited by maximum cylinder pressure ($p_{max.}$= 10MPa).

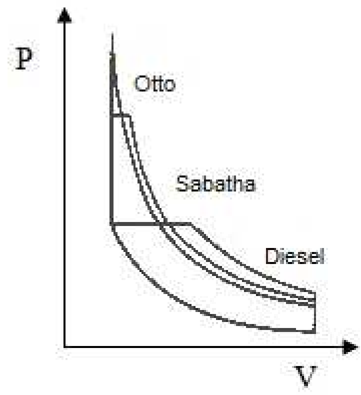

Fig.1 P-V diagram showing a comparison among the ideal Otto, Diesel and Sabathe's cycle for same compression ratio [2]

Hence, it is difficult to obtain a compromise between engine efficiency and smooth engine run without knocking.It has been found previously that dual fuel engines suffer from low efficiencies at partial-load operations [3, 4]. However, they are considered to be more efficient than diesel engines at full-load operations [5]. With DDF engines, it is possible to switch to pure diesel operation at low loads, thereby increasing the overall engine efficiency. Abnormal combustion has been studied in detail for both spark and compression ignition engines. Heywood [6] classified abnormal combustion in spark-ignition engines into two categories: knocking and surface ignition. He defined knocking as the noise transmitted through the engine structure due to spontaneous ignition process. Karim cite all. [7] describe knocking as the phenomenon of loss of combustion control whereby the power output cannot be controlled cycle pressure with little change in mixture strength. However, in DDF engines, the terms 'abnormal combustion' and 'knocking' are highly subjective to the quality and quantity of fuel. It has been shown by Liu and Karim [8] that with methane and natural gas, knocking is primarily due to auto-ignition, but with hydrogen, it may be due to a very high heat release rate. Knocking is often described as loss of combustion control where more power output cannot be obtained by adding more gas. It has been shown by Selim [9] that while keeping engine speed, pilot fuel quantity and pilot fuel injection timing constant, and increasing the amount of gaseous fuel, there occurs a point at which the maximum torque output starts decreasing. This isreferred to as 'onset of knock'. Saidi cite all. [10] explained that knocking in dual fuel engines cannot be solely defined on the basis of either SI or CI knocking as it uses diesel fuel for the pilot ignition process, and gaseous fuels as the main fuel. Here, the diesel fuel is considered to be acting only as an ignition source for the gaseous fuels [4]. There is an ignition delay period associated with the combustion of the pilot diesel fuel. This delay period will depend on the quantity of the pilot fuel injected with respect to the gaseous fuel and its cetane number. The ignition characteristics of the gaseous fuel will depend on its octane number.

According to Karim [3], the limits for the normal operation of a DDF engine can be estimated by calculating the unburned fuel in the engine. This research work focuses on combustion characteristics, e.g. IMEP or COV to differentiate between normal and abnormal DDF.

2. Experimental Section

2.1 Apparatus

The experiment was performed using a Kubota RT140 single cylinder, 4-stroke diesel engine. The specifications of the engine are described in Table 1. The amount of gaseous fuel was measured using an ECU control unit, while the pilot fuel injection was controlled using an injection pump. The specifications of the pump are mentioned in Table 2. The power output and torque were controlled using an eddy current dynamometer Nishishiba NEDZ-113. The pressure inside the combustion chamber was measured using the Kistler 6061B pressure transducer. The data obtained from the transducer was passed through a charge amplifier and sent to a data acquisition system for further processing. The amount of diesel input was measured using a digital weight scale. Gas flow rate was measured using a gas flow meter. The amount of gas consumed was measured by balancing the weight and was converted into an electrical signal by the Load Cell. The signal was then sent for further analysis to the data acquisition system. The schematic of the experimental apparatus can be seen in Fig. 2.

Table 1. Specifications of the diesel engine

ENGINE SPECIFICATIONS	
MODEL	Kubota RT140
Engine Type	1 cylinder
Combustion Chamber Type	Direct Injection
Bore x Stroke	97 x 96 mm
Displacement Volume	709 cc
Compression Ratio	18:1
Maximum power output	14 hp at 2400 rpm
Continuous rated power output	12 hp at 2400 rpm
Maximum Torque	5 kg_f-m at 1600 rpm

Table 2. Specifications of the injection pump

Injection pump type	In-line pump
Governor Type	Mechanical
Injection Timing	18 degree BTDC
Injection Nozzle Opening Pressure	210 kg_f/cm^2

Table 3. Typical natural gas composition for Bangkok metropolitan area known as East source [11]

Composition	Amount in % by mole
CH_4	76.57
C_2H_6	5.14
C_3H_8	1.67
C_4H_{10}	0.37
C_5H_{12}	0.14
C_6H_{14}	0.06
N_2	1.99
CO_2	13.76

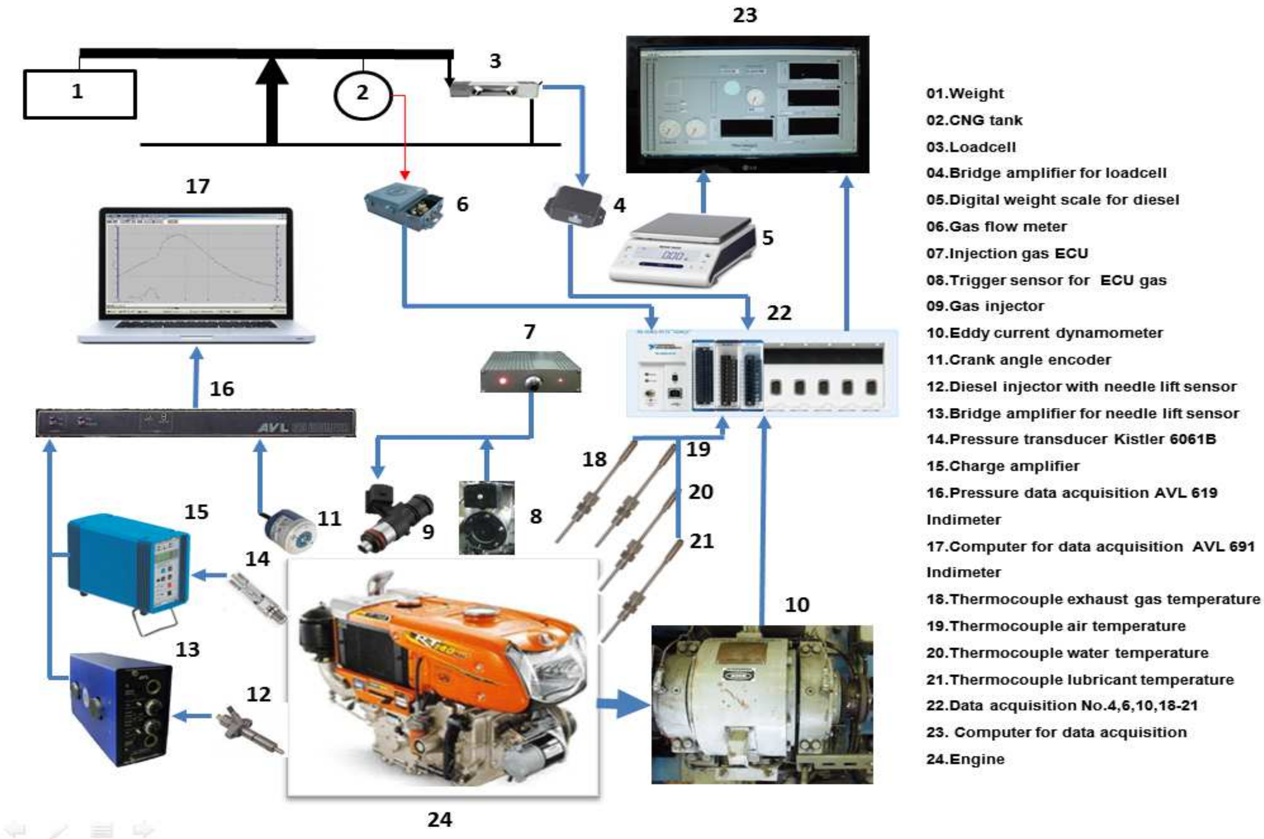

Fig. 2 Schematic diagram of the experimental setup

2.2 Methodology

The natural gas used in this experiment is the east gas and its composition is described In this experiment, the torque and engine speed are kept constant at 24.5 Nm and 2000 rpm, respectively. At first, the engine is run under full diesel operation and the amount of gas is varied by increasing the mixing ratio (Z). is increased until it reaches a point where further improvement is not possible under normal engine operation. The mixing ratio (Z) can be calculated by using the Eq. (1).

$$Z\% = \frac{\dot{m}_{CNG}}{\dot{m}_D + \dot{m}_{CNG}} \times 100 \qquad . (1)$$

Energy component of natural gas with respect to the total energy can be found using Eq. (2).

$$CNG\% = \frac{\dot{m}_{CNG} \times LHV_{CNG}}{\dot{m}_D \times LHV_D + \dot{m}_{CNG} \times LHV_{CNG}} \qquad (2)$$

The pressure was measured in accordance with the crank angle for different values of Z. Then, pressure rise rate and heat release were obtained from the measured pressure. Heat release rate was calculated using Eq. (3)

$$\frac{dQ_{net}}{d\theta} = \left(\frac{\gamma}{\gamma-1}\right) P \frac{dV}{d\theta} + \left(\frac{1}{\gamma-1}\right) V \frac{dP}{d\theta} \qquad (3)$$

Pressure rise rate and heat release rate were plotted against crank angle. Coefficient of variation (COV) was established using the following correlatic: where σ_{IMEP} is the standard deviation of the cycle work and μ_{IMEP} is the mean work output from the cycles.

$$COV_{IMEP} = \frac{\sigma_{IMEP}}{\mu_{IMEP}} \qquad (4)$$

Table 4. Details of mass flow rate and the energy component of diesel and gas fuel

Condition	Gas (kg/hr)	Diesel (kg/hr)	Z%	Diesel (KJ)	Gas(KJ)	CNG (%)	Efficiency (%)
Diesel	0	1.47	0	18.66	0.00	0.00	27.33
Z= 70%	1.81	0.76	70	9.73	19.61	66.84	17.38
Z= 82%	1.84	0.38	82	4.85	19.89	80.39	20.60
Z(max.)= 88%	1.93	0.25	88	3.17	20.88	86.82	21.20

The mass flow rates and energy component of the diesel and the gaseous fuel are described in the Table 4. The lower heating values for diesel and natural gas were taken to be 45.56 MJ/Kg and 39.037 MJ/kg, respectively .

3.Results And Discussion

3.1 Normal operation

From Fig. 3, it can be seen that the maximum cylinder pressure for pure diesel was higher than with dual fuel operation. This is due to lower heating value of natural gas compared to diesel. However, the change in ignition delay was not significant when Z was further increased from 70% to 80%, and further to 88%. Hence, we can see that ignition delay is not directly proportional to the partial pressure of the gas. Rather, after a certain amount of gas, it is not much affected by a further gas increase. The maximum rate of pressure rise is proportional to the amount of diesel fuel. It is at its maximum for pure diesel operation and decreases with the increase of gas. Fig. 3 also suggests that the combustion in dual fuel starts after TDC whereas in pure diesel operation, the combustion starts before TDC. For all three d amounts of the pilot diesel fuel, the combustion starts at roughly the same time. It can be seen that the premixed combustion phase, which is a characteristic phase of diesel engines, is found to be missing in dual fuel operation.

3.2 Abnormal Operation

The engine was operated under the same engine speed and power output with a mixing ratio (Z) of 92%. The process was analyzed cycle by cycle. From Fig. 4, it can be seen that the peak pressure for the abnormal DDF operation was fluctuating about the peak pressure for pure diesel operation. The ignition delay was much more significant for the abnormal operation of the DDF than what was recorded for normal DDF operation. It can be seen that the cycles with less ignition delay had higher peak pressures and pressure rise rates. The heat release rates were also different for the various cycles. However, for most of the cycles it was greater than for pure diesel operation. Also, the combustion starts after TDC for the abnormal DDF engine. The pre-mixed phase of combustion was completely missing from abnormal DDF operation and shows some similarity with the spark ignition engine. The curves obtained for normal operation were smoother than those obtained for abnormal combustion. Fig. 5 shows that the IMEP for the abnormal DDF engine

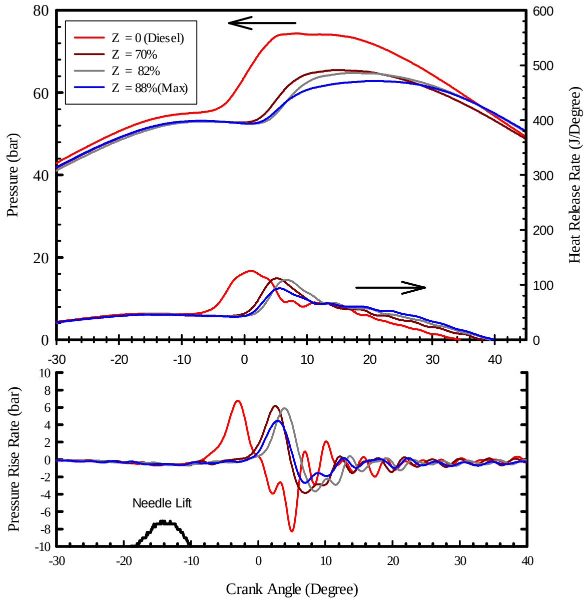

Fig. 3 Comparison between Diesel and DDF engine operating under normal combustion process: Variation of pressure; heat release rate and pressure rise rate with crank angle N=2000 rpm; T= 24.5 N

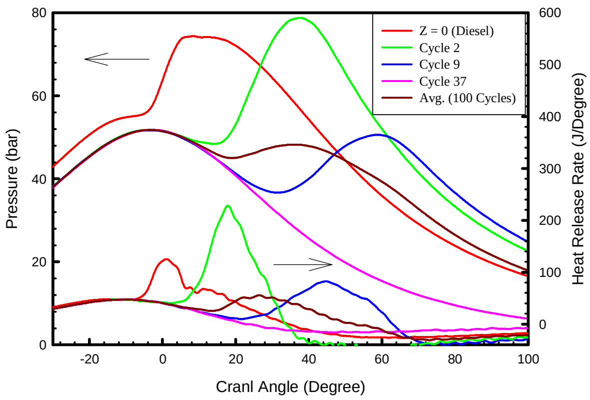

Fig. 4 Comparison between Diesel and DDF engine operating under abnormal combustion process: Variation of pressure and heat release rate with crank angle at N=2000 rpm; T= 24.5 N

Table 5 shows that $COV_{(IMEP)}$ values for pure diesel and normal DDF operation are comparable. COV values for abnormal DDF operation are quite due to late combustion in some cycles.

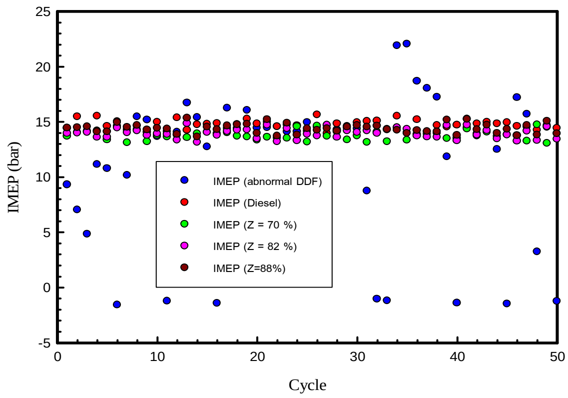

Fig. 5 Comparison between IMEP for diesel, normal and abnormal DDF operation

exhibits significant variation for different cycles while with diesel operation, it is stable for all cycles, as IMEP ranges from 14 to 16.

4.Conclusion

This study compares pure diesel under normal and abnormal DDF operations. It also investigates heat release rate and peak pressures achieved during operation of an abnormal DDF engine. The results are:

- Exhaust temperature increases along with increased mixing ratio (Z).
- For normal operation of a DDF engine (Z in between 70% to 88 %), the combustion starts very near TDC.
- An increase in mixing ratio (Z) leads to increase in heat release rate during the mixed control phase.
- Cylinder peak pressure decreases along with an increased mixing ratio (Z).
- For abnormal DDF combustion,
  - Variation of IMEP expected due to incomplete burning of fuel.
- Start of combustion takes place after TDC, which is a considerably longer ignition delay for all cycles.

Table 5. Details of exhaust temperature and COV for different values of Z at N=2000 rpm, T= 24.5 Nm, Power output=5.1kW

Condition	Temp EX.	Temp Air	$COV_{(IMEP)}$
Diesel	333.2	38.8	0.028
Z= 70%	341.3	40.5	0.021
Z= 82%	354.0	40.7	0.022
Z(max.)= 88%	368.2	41.4	0.024
Z(abnormal)= 92%	372.5	41.8	0.640

5. Acknowledgement

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