Fuel 140 (2015) 164–170

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Investigation of operating range in a methanol fumigated diesel engine

Quangang Wang, Lijiang Wei, Wang Pan, Chunde Yao *

State Key Laboratory of Engines, Tianjin University, Tianjin 300072, China

HIGHLIGHTS

- Operating range is identified on a methanol fumigated diesel engine.
- DMDF range is restricted to partial burn, misfire, roar combustion and knock.
- Systematic analysis of combustion characteristics on each bound of the range.
- DMDF mode worsens the BTE at low load while boosting it at medium and high load.

ARTICLE INFO

Article history:
Received 20 June 2014
Received in revised form 13 September 2014
Accepted 19 September 2014
Available online 7 October 2014

Keywords:
Dual fuel
Diesel engine
Methanol fumigation
Operating range
Combustion characteristics

ABSTRACT

An experimental study was conducted to investigate the operating range and combustion characteristics in a methanol fumigated diesel engine. The test engine was a six-cylinder, turbocharged direct injection engine with methanol injected into the intake manifold of each cylinder. The experimental results showed that the viable diesel methanol dual fuel (DMDF) operating range in terms of load and methanol substitution percent (MSP) was achieved over a load range from 6% to 100%. The operating range was restricted by four bounds: partial burning, misfire, roar combustion and knock. The lower bound of the operating range was the partial burn bound, which occurred under very low load conditions with high MSP. As the load increased to medium load, MSP reached its maximum value of about 76%, and the onset of misfire provided the right bound for normal operation. At medium to high load, maximum MSP began to decrease. DMDF combustion with excessive MSP was extremely loud with high pressure rise rate, which defined the roar combustion bound. As it increased to nearly full load, measured pressure traces in-cylinder showed strong acoustic oscillations. The appearance of knock provided the upper bound of the operating range. In general, as the load increased, the characters of the combustion changed from partial burn to misfire to roar combustion and to knocking. The range between these four bounds and the neat diesel combustion bound constituted the viable operating range. Over the viable operating range, DMDF combustion worsened the brake thermal efficiency (BTE) at light load while boosted it at medium and high load.

1. Introduction

Compared with spark-ignition engine, researchers are more interested in compression–ignition (CI) engine due to its better fuel economy with high compression ratio and no throttling loss. However, the conventional CI engine sustains with high nitrogen oxides (NO_x) and particulate matter (PM) emissions. In addition, improving the fuel efficiency is always a goal because of the direct connection to carbon dioxide (CO_2) emissions and crude oil usage. Hence, the heavy-duty CI diesel engine has been a topic of research over the last two decades. Moreover, the sources of fossil fuel are dwindling with time's going, which causes the price of petroleum oil becoming higher on a daily basis. These all pose challenges to the availability of fossil fuel. Under these circumstances, the demand of alternative fuels is increasing as a substitute of conventional fossil fuel in transportation sector to address energy security issues. Among the alternative fuels, methanol and ethanol have received considerable attention as suitable diesel fuel replacement. In particular, methanol is readily available from the conversion of

---

Abbreviations: CI, compression–ignition; NO_x, nitrogen oxides; PM, particulate matter; CO_2, carbon dioxide; DMDF, diesel methanol dual fuel; MSP, methanol substitution percent; BTE, brake thermal efficiency; DMCC, diesel methanol compound combustion; ECU, electronic control unit; CA, crank angle; ATDC, after top dead center; BTDC, before top dead center; AHRR, apparent heat release rate; PPRR, peak pressure rise rate; PCP, peak cylinder pressure; COV, coefficient of variation; IMEP, indicated mean effective pressure.

* Corresponding author. Tel.: +86 22 2740 6649; fax: +86 22 2738 3362.
E-mail address: arcdyao@tju.edu.cn (C. Yao).

http://dx.doi.org/10.1016/j.fuel.2014.09.067

biomass, coal and natural gas [1]. The storage, transportation, distribution, and application of methanol are similar to those of traditional gasoline and diesel fuels as a liquid. Therefore, the substitution of diesel fuel with methanol is of significant economic and environmental importance in countries like China which has large coal reserve, and in particular, huge amount of coke-oven gas resources.

The foremost drawback for the utilization of methanol in diesel engines is probably its low cetane number, which, depending on the measurement method, typically ranges from 2 to 12 [2]. The much high latent heat of vaporization also weakens its auto-ignition ability [3]. In spite of these drawbacks, methanol has been used in diesel engines primarily in one of the following ways: blends, neat methanol and dual fuel. Recently, the team of Huang investigated on the emissions and combustion characteristics of a single-cylinder diesel engine running on a stabilized diesel–methanol mixture with up to 18% by weight of methanol. And smoke emission decreases with the increase of the oxygen mass fraction in the blends without increasing the NO_x emission [4,5]. However the blending of methanol with diesel fuel requires additives for stabilizing the mixed fuel and there is a limitation on the amount of methanol that can be premixed with diesel fuel for stable operation [6]. Actually, the diesel–methanol blending has been made possible only by the addition of surfactants in order to form micro-emulsions, rather than real solutions [7]. Moreover, the use of neat methanol in diesel engines usually requires the addition of relatively large amount of expensive ignition-improving compounds and very high compression ratios [8].

In this regard, dual fuel combustion has received renewed interest due to its adaptability for alternative fuels and due to its excellent performance and ultra-low emissions compared to conventional diesel combustion. Dual fuel combustion is an approach that utilizes a high cetane number fuel such as diesel, biodiesel to ignite a low cetane number fuel such as alcohol [9]. Separate fuels direct injection [10], dual fuel injector [11] and fumigation [12] are used for diesel methanol dual fuel (DMDF) operation. However, the use of two separate fuels injection system is more complicated because it involves significant engine modifications as the methanol injector is placed at the top of combustion chamber. Using only one injector to inject two fuels in an engine is only reported by the system developed by Westport Corp., called HPDI [11]. In this regard, fumigation is favored currently, because it requires a minimum of modification to the engine since methanol injectors is placed at the intake manifold. However methanol fumigation is unfavorable for cold start and low load operation. Based on the method of fumigation, Yao et al. [13,14] developed a diesel/methanol compound combustion (DMCC) system. Under DMCC mode, at cold start and low speed conditions, the engine operates on diesel alone to ensure cold starting capability and to avoid aldehydes production under these conditions. At medium to high loads, the engine operates on diesel methanol dual fuel (DMDF) mode, of which methanol is fumigated into intake manifold and the homogeneous air/methanol mixture is ignited by the diesel directly injected [14]. The advantage of DMCC system is that there is no cold start difficulty when the engine operates at dual fuel mode. Furthermore, in case of lacking methanol fuel supply, this engine still runs according to the diesel cycle by switching from dual fuel mode to neat diesel mode [15]. Unlike natural gas dual fuel engine, there is no simultaneous reduction of air supply [16]. Hence, the compression pressure and the mean effective pressure of the engine are not decreased and even boosted with methanol fumigation.

Many previous investigations were performed with a DMCC system. Recently, using a 4-cylinder direct-injection diesel engine with fumigation methanol, Cheng et al. [17] showed that the concentration of nitrogen oxides is significantly reduced except under full load conditions. There is also a reduction in the smoke opacity and the particulate matter mass concentration. With the same engine setup and operating conditions, Zhang et al. [18] found that under low engine loads, the brake thermal efficiency (BTE) decreases with the increase of fumigation methanol; but under high loads, it is slightly boosted with the increase of fumigation methanol. Using the same engine with the present study, Geng et al. [19] observed that the mass and number concentrations of particulate matter significantly decrease at low and medium loads, while they increase when the tested engine operated at high loads. Li et al. [20] developed a multi-dimensional model to investigate the combustion and emission characteristics of a fumigated methanol and diesel reactivity controlled compression ignition engine. They found that methanol addition is an effective way to achieve the efficient and clean combustion and all the emissions are reduced with moderate methanol addition.

The above brief survey of the relevant literatures shows that, though many studies have examined DMDF combustion on single-cylinder naturally aspirated light-duty engines, few researchers have reported DMDF combustion results from multi-cylinder turbocharged heavy duty engines. Furthermore, hardly any researchers have focused on the operating range and combustion characteristics of DMDF combustion. Based on the authors' previous studies on DMDF engines, methanol substitution percent (MSP) and brake thermal efficiency (BTE) of DMDF combustion depended greatly on engine load. In order to further understand the effect of MSP on a DMDF engine, this work concentrated on establishing the operating range with regard to MSP and engine load on a methanol fumigated six-cylinder turbocharged heavy duty diesel engine and investigated the combustion characteristics of conditions at each range bound.

2. Experimental apparatus and methods

2.1. Test engine and fuels

The original engine was an in-line six-cylinder, direct injection, turbocharged diesel engine with an electronically controlled unit injection pump. Technical specifications of the engine are listed in Table 1. Fig. 1 shows the schematic of the engine layout. The engine was modified to run on DMDF mode with introducing the methanol fuel by 6 electronically controlled methanol injectors fixed at the intake manifold of each cylinder. The methanol was injected at a pressure of 0.4 MPa and the mass of methanol injected was controlled by an electronic control unit (ECU) developed by ourselves. The engine was coupled to an electronically controlled hydraulic dynamometer. The engine speed and torque could be controlled by the EMC2020 heavy diesel engine test system, which allowed to changing engine speed and load as required.

The pressure trace in-cylinder was measured with a Kistler 6025C piezoelectric pressure transducer in series with an AVL 612 IndiSmart combustion analyzer, which had a signal amplifier for piezo inputs. For each engine operating point, 100 consecutive cycles of cylinder pressure data were recorded. The collected cycles

Table 1
Parameters of the engine.

Parameters	Value
Number of cylinders	Six in-line
Displacement (L)	7.14
Bore × stoke (mm)	130 × 108
Compression ratio	18:1
Number of nozzle holes	6
Nozzle hole diameter (mm)	0.235
IVC(° ATDC)	−124.5
EVO(° ATDC)	79.6