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Full Length Article

Experimental investigation into the combustion characteristics of a methanol-Diesel heavy duty engine operated in RCCI mode

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ABSTRACT

This study examines combustion in a dual-fuel methanol-Diesel heavy duty engine using three different methanol injection configurations: port injection into the intake manifold; direct injection during the intake stroke (DI_E) and direct injection during the compression stroke (DI_L). The latter two methanol direct injection configurations were used in the attempt to reduce HC and CO emissions, which were considerably high in the port-injected high-octane fuel RCCI combustion. Engine experiments were performed using a double Diesel injection strategy with two pilot Diesel injections (PI1 and PI2) and a constant engine speed of 1500 rpm. The effects of three parameters – the PI1 and PI2 injection timings, and the PI2/PI1 duration ratio – were investigated at 5 bar IMEP for the three methanol injection configurations. The onset of unstable combustion and excessive combustion phasing advancement imposed lower or upper limits on the sweeps over the studied parameters. The DI_L configuration achieved lower net indicated thermal efficiencies than the other two methanol injection configurations. The influences of the methanol injection pressure and methanol substitution percentage (MSP) were also investigated for the DI_L configuration at 5 bar IMEP, revealing that the combustion process was relatively insensitive to the methanol injection pressure but was adversely affected by increasing the MSP. Finally, the port and DI_L configurations were tested at various loads. Neither configuration offered any advantage over pure Diesel combustion in terms of net indicated thermal efficiency nor emissions of HC and CO, but both offered lower greenhouse gas emissions at all load points. However, only the methanol port injection configuration achieved ultra-low NO_x and soot emissions at 12 bar IMEP.

1. Introduction

The global automotive industry is highly dependent on conventional fossil fuels. However, because of limited petroleum resources and concerns about environmental pollution, there is growing interest in alternative fuels such as alcohols, CNG, hydrogen and vegetable oils, all of which have been studied as Diesel engine fuels for several decades [1–4]. Methanol has attracted particular attention as an alternative fuel because of its low production cost, high fuel security, high oxygen content and already established manufacturing plants.

Methanol can be used in Diesel engines as a blend with conventional Diesel fuel, by fumigation, or by direct injection. Most studies on methanol combustion in Diesel engines have focused on fuel blends. Because methanol is poorly soluble in Diesel, such blended fuels require additives, and the proportion of methanol must be low. Huang et al. [5] investigated the effect of methanol mass fraction and the start of injection on engine performance when using blended fuels. They found that increasing the methanol mass fraction increased the level of premixed combustion as a proportion of total combustion, and that advancing the start of injection increased the peak pressure and maximum pressure rise rate. Ingle et al. [6] investigated engine performance at three different methanol substitution ratios (MSR, and demonstrated the feasibility of using methanol-Diesel blends in Diesel engines, showing that the output power, torque and specific fuel consumption for Diesel fuel were lower than those for various methanol-Diesel blends over a wide range of engine speeds. Sayin et al. [7] explored engine performance and emissions for three different methanol-Diesel blends (M5, M10 and M15), and found that smoke opacity, hydrocarbons (HC) emissions and carbon monoxide (CO) emissions were all reduced by using methanol-Diesel blends instead of Diesel. They also identified an optimum injection pressure that minimized break specific fuel consumption (BSFC).

Methanol fumigation methods have also been investigated extensively. Popa et al. [8] studied two different injection systems, one using premixed methanol injected through a carburetor with direct injection of Diesel; and one using a single injector to directly inject both

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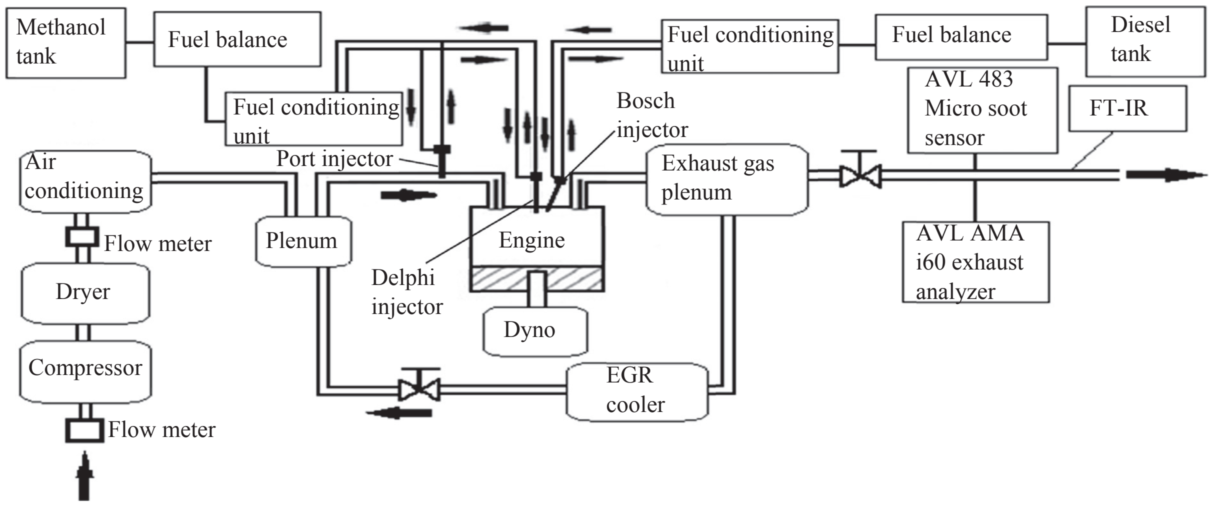

Fig. 1. Schematic layout of the engine.

methanol and Diesel. Only NO_x and smoke emissions were measured. The first injection system significantly reduced NO_x levels at all engine loads. However, smoke levels were only reduced at high engine loads (> 50%). Wang et al. [9] investigated the operating range of a methanol-fumigated Diesel engine, and identified four key operating bounds: partial burn, misfire, roar combustion (noisy combustion) and knock, respectively. At the maximum methanol substitution ratio (MSR), these bounds were quite load dependent. Wei et al. [10] reported experiments on a turbocharged six-cylinder Diesel engine that explored the effects of pilot Diesel injection on methanol-Diesel dual-fuel combustion. Their results indicated that pilot injection could improve combustion stability at low loads and high (MSR) values. They concluded that this happened because the pilot injection increased the in-cylinder pressure and temperature before the main combustion. Methanol fumigation increased emissions of various regulated and unregulated substances, but not those of NO_x and carbon dioxide (CO_2). To avoid poor combustion when using methanol fumigation under cold start or low load conditions, Yao et al. [11] proposed a methanol-Diesel compound combustion (DMCC) system that uses Diesel fuel during engine start and at low speeds, but employs a homogenous methanol/air mixture with a pilot Diesel injection at moderate and high loads. The DMCC method simultaneously reduced soot and NO_x emissions but increased HC and CO emissions. Yao et al. [12] investigated the effect of methanol injecting position on cylinder-to-cylinder variation in the methanol Diesel dual-fuel engine. Three different methanol injection positions were used in the paper: at the intake manifold (Case 1); at distal end of inlet duct (Case 2) and at neat end of inlet duct (Case 3). All three cases used port-injected methanol. They concluded that the unevenness degree of 4 cylinder is better when methanol injectors are fixed at Case 1 and Case 2 than that of Case 3. The methanol fumigation method mentioned above suffers from high levels of unburned HC and CO mainly due to methanol tapped in the crevice regions. In an effort to reduce HC and CO emissions from methanol fumigation, direct injection of both methanol and Diesel might show certain potential. So far, only one study was found to use direct injection of both methanol and Diesel and focused on analysis of emissions. Ullman et al. [13] conducted experiments on three heavy-duty engines: a Volvo TD-100C Diesel; a Volvo TD-100A alcohol-Diesel engine and a MAN D2566 FMUH spark-ignited direct-injected methanol-fueled engine. The Volvo TD-100A alcohol-Diesel engine featured two injectors for direct injection of methanol and Diesel. Emissions from all three engines were evaluated under steady-state and transient FTP conditions. The results showed unburned HC from Volvo TD-100A alcohol-Diesel engine were significantly higher than for Diesel engine Volvo TD-100C due to substantial emissions of unburned methanol. Another study using direct injection of gasoline instead of methanol together with Diesel was investigated by Wissink et al. [14]. The results indicated that direct injection of two fuels provided performance at least as good as port-injected gasoline reactivity controlled compression ignition (RCCI) combustion, but with significantly less NO_x and similar HC and CO.

The main objective of the present work is to examine the possibility to improve the emissions of unburned HC and CO from port-injected methanol RCCI combustion by using direct injection of both methanol and Diesel. The effect of the Diesel SOI timing and PI2/PI1 duration ratio were examined for all three configurations. In addition, the performance and emissions of two methanol injection configurations (port and DI_L) were investigated under various load conditions.

2. Experimental setup and methods

2.1. Test engine and fuels

The experiments were conducted using a single cylinder, four-stroke, compression ignition research engine designed to mimic the characteristics of Volvo's heavy-duty D13 engine. The engine was controlled using an AVL PUMA OPEN control system; its layout is depicted in Fig. 1. Table 1 shows the specifications of the engine and port injectors. The specifications of the common rail injectors are given in Table 2. Three Delphi common rail injectors were used – two for methanol and one for reference Diesel injections. One of the methanol injectors was used to perform direct injection (DI) on the intake stroke, and is designated DI_E; the other was used to perform DI on the compression stroke and is designated DI_L. The reason to have two different methanol DI configurations was to investigate the effect of methanol wall wetting on the methanol-Diesel RCCI combustion. The DI_E configuration didn't involve in wall wetting, but DI_L configuration did. A

Table 1
Specifications of the single cylinder engine and port injectors.

Engine Geometry	
Engine type	Single-cylinder AVL 501
Bore [mm]	131
Stroke [mm]	158
Connecting rod [mm]	267.5
Compression ratio [–]	16.6
Port Fuel Injector	
Model	Bosch 0280158123
Number of injectors	4
Spray angle	25
Injection pressure [bar]	7.8