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An experimental investigation of incomplete combustion of gaseous fuels of a heavy-duty diesel engine supplemented with hydrogen and natural gas

Timothy Gatts, Shiyu Liu, Chetmun Liew, Bradley Ralston, Clay Bell, Hailin Li*

Department of Mechanical and Aerospace Engineering, West Virginia University, Morgantown, WV 20506, USA

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ABSTRACT

This paper investigates the emissions of the unburned gaseous fuels of a heavy-duty diesel engine converted to operate under natural gas (NG)-diesel and hydrogen (H_2)-diesel dual fuel combustion mode. The detailed effects of the addition of H_2, NG, engine load, and engine speed on the exhaust emissions of the unburned H_2, methane (CH_4), and carbon monoxide (CO) were experimentally investigated. The combustion efficiencies of CH_4 and H_2 supplemented were also examined and compared.

The emissions of the unburned gaseous fuels and their combustion efficiency were affected by the engine load, the amount of gaseous fuel added, and the engine speed. Among these, the engine load was recognized as the main factor dominating the emissions and combustion efficiency of the gaseous fuels especially when added at a small amount. The maximum emissions of H_2 or CH_4 were observed when the volumetric concentration of H_2 or NG in the intake mixture reached 4% or 3%, respectively. Increasing the addition of H_2 or NG over 4% or 3% started to dramatically improve the combustion efficiency of gaseous fuels with the maximum combustion efficiency of H_2 and CH_4 observed with the maximum addition of gaseous fuels. Although having significantly different combustion characteristics, the combustion efficiencies of H_2 and CH_4 of H_2-diesel and NG-diesel dual fuel engines were comparable especially at high load operation. When added at a small amount, the combustion efficiency of CH_4 was comparable but always slightly lower than that of H_2. This was due to the increased CO emissions of the NG-diesel dual fuel engine. The CO emissions originating from diesel fuel also contributed to this difference.

1. Introduction

The application of alternative fuels has been recognized as an effective approach to reduce our dependence on imported oil and to enhance national energy security. The traditional alternative gaseous fuels explored include the natural gas (NG) [1,2], liquefied petroleum gas (LPG) [3], synthesis gas produced through gas reforming of solid fuels such as coal and bio-mass [1,4,5], and the most promising on-site carbon-free energy carrier noted as hydrogen (H_2) [6]. There is increasing recent interest to effectively utilize opportunity gaseous fuels that have been either used in inefficient processes or disposed as industry byproducts. For example, Booz/Allen/Hamilton identified a number of opportunity fuels, which can be

* *Corresponding author*. Tel.: +1 304 2933187.
E-mail address: hailin.li@mail.wvu.edu (H. Li).

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classified into two categories: (1) H_2 and carbon monoxide (CO) containing gaseous fuels such as industrial gases and gasified fuels from bio-mass and coal; (2) methane (CH_4)-rich gases such as low quality coal bed methane, wellhead gases, landfill and digester gas [7].

The CH_4 containing gaseous fuels can be used in spark ignition (SI) engines [8–10] to utilize the excellent knock resisting properties of CH_4 containing gaseous fuels [11–13]. The application of H_2 containing gaseous fuels in SI engines is attractive due to its fast flame propagation and wide lean operational range [14,15]. However, the burning of gaseous fuels in SI engines is limited by the low thermal efficiency due to the lower compression ratio of SI engines and energy loss associated with the throttling of the intake mixture. The lean burn operation technology has been widely used to improve the thermal efficiency of large bore SI stationary engines operated with gaseous fuels. However, the ever increasingly stringent emission regulations have made it impractical for lean burn SI gaseous fuel engines to meet the NO_x emissions requirements without utilizing after-treatment systems.

Gaseous fuels can also be burned in compression ignition (CI) engines with gaseous fuels supplemented into the intake air noted as dual fuel combustion mode [16–18]. When supplied into the intake air of diesel engines, a homogeneous gaseous fuel-air-diluents mixture is formed during the intake and early compression stroke. At the end of the compression stroke, a pilot of diesel fuel is injected into the hot gaseous fuel-air-diluents mixture and serves as an ignition source. Prior to the injection of pilot diesel fuel, gaseous fuels have been mixed well with air and heated through compression to high temperatures, but not high enough to initiate the auto-ignition process of the gaseous fuels. After being injected into the hot bulk mixture, the pilot diesel fuel is first atomized and then vaporized, mixed with the hot gaseous fuel-air mixture, ignited, and burned through compression ignition. The energy released by diesel fuel combustion serves as an ignition source of the gaseous fuel. Detailed information about the dual fuel engine combustion process can be found in the literature [16–18].

Such a dual fuel combustion mode has been highlighted for the following attractive features: (1) higher thermal efficiency than SI engines; (2) flexible fuel capability with the full capability of operation on diesel fuel when gaseous fuel is not available [16,17,19]; (3) reduced emissions of particulate matter (PM) due to the improved premixed combustion, better mixing of gaseous fuel with air and the relatively low carbon/hydrogen ratio of the gaseous fuel; (4) stable combustion as indicated by less cycle-to-cycle variation under normal operating conditions compared to lean burn SI engines.

Compared to diesel engine operation the performance of the dual fuel engine is far from perfect. When operated at high load, the onset of knock is one of the main factors limiting the maximum portion of gaseous fuel added to the dual fuel engine [20–22]. This is due to the higher compression ratio of CI engines and the quick burning of the gaseous fuels benefiting from the multi-point fuel ignition process of the pilot diesel fuel. When operated at low load, the dual fuel engine suffers from the emissions of unburned gaseous fuels [18,23,24]. A portion of the gaseous fuel added into the intake mixture slips through the engine combustion chamber without participating in the combustion process. For example, Karim examined the emissions of unburned CH_4 and CO of a dual fuel engine with CH_4 supplemented to the intake air [16,23]. The research shows that below a gaseous fuel addition lean limit, the CH_4 emissions increased almost linearly with the increasing addition of NG. This line approaches theoretical CH_4 emissions in the situation where only NG entrained into diesel spray plume burned with diesel fuel. The natural gas presented outside the diesel plume cannot be burned. The research also found that the CH_4 emissions decrease with increased pilot diesel fuel, similar to the findings of other research measuring total unburned hydrocarbon (UHC) emissions. Karim concluded that most of the UHC emissions in a NG-diesel dual fuel engine are only CH_4 emissions with little to no unburned diesel fuel.

Extensive research has been conducted to investigate the effects of H_2 addition on the performance, combustion and exhaust emissions of diesel engines. In the early decades, most of the research was conducted using small, single-cylinder diesel engines [25–27]. For example, Varde and Frame [25] investigated the effects of H_2 addition on the exhaust emissions of a single-cylinder direct injection diesel engine. Tomita et al. [26] investigated the effects of H_2 addition on NO_x and PM emissions using a 0.64 L, single-cylinder diesel engine. Recently, the effect of H_2 addition on the engine performance, combustion and exhaust emissions has been investigated using light duty, multi-cylinder, diesel engines with advanced diesel engine technologies including cooled exhaust gas recirculation (EGR) and common rail fuel injection [28–30]. Most of the past researches to H_2-diesel dual fuel engines focused on the investigation of engine performance, combustion process, and exhaust emissions of NO_x and PM.

There is increasing recent interest to investigate the combustion efficiency of H_2 from H_2-diesel dual fuel engine. For example, Mohammadi et al. [31] investigated the effects of engine load on the exhaust emissions of H_2 and its combustion efficiency. When the concentration of H_2 in the intake mixture was kept constant, the increase in engine load was found to substantially reduce the emissions of H_2 indicating the improved combustion efficiency of H_2. For example, the increases in the engine load from a brake mean effective pressure (bmep) of 0.8 bar–7 bar bmep increased the combustion efficiency of H_2 from 52% to 96%. However, the impact of the amount of H_2 added on the combustion efficiency was not reported. Abu-Jrai et al. [32] examined the emissions of unburned H_2 of a single-cylinder diesel engine supplemented with H_2. With the addition of 7.5% H_2 in the intake mixture, the emissions of H_2 observed were 1.53% and 0.73% (vol.) when operated at indicated mean effective pressure (imep) of 2.8 bar and 4.0 bar, respectively. However, the impact of engine load on the combustion efficiency was not reported. Recently, Gatts et al. [33] explored the effects of H_2 addition and engine load on H_2 emissions and its combustion efficiency of a heavy-duty engine converted to operate under H_2-diesel dual fuel mode. The research found that engine load dominates the H_2 combustion efficiency especially when operated under low load. At high load, H_2 combustion efficiency has little dependence on the amount of H_2 added.

The past research to the burning of NG and H_2 in SI engines demonstrated the significant difference in combustion