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Performance and emissions of a dual-fuel pilot diesel ignition engine operating on various premixed fuels

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ABSTRACT

A multi-dimensional computational fluid dynamics (CFD) model coupled with chemical kinetics mechanisms was applied to investigate the effect of various premixed fuels and equivalence ratios on the combustion, performance, and emissions characteristics of a dual-fuel indirect injection (IDI) pilot diesel ignition engine. The diesel fuel is supplied via indirect injection into the cylinder prior to the end of the compression stroke. Various premixed fuels were inducted into the engine through the intake manifold. The results showed that the dual-fuel case using hydrogen/diesel has a steeper pressure rise rate, higher peak heat release rate (PHRR), more advanced ignition timing, and shorter ignition delay compared to the natural gas/diesel and methanol/diesel dual-fuel cases. For leaner mixtures ($\Phi_P < 0.32$), the hydrogen/diesel case has a higher indicated mean effective pressure (IMEP) and indicated thermal efficiency (ITE); however, the methanol/diesel case has the maximum IMEP and ITE for richer mixtures ($\Phi_P > 0.32$). For instance, with an equivalence ratio of 0.35, the ITE is 56.24% and 60.85% for hydrogen/diesel and methanol/diesel dual-fuel cases, respectively. For an equivalence ratio of 0.15, the natural gas/diesel simulation exhibits partial burn combustion and thus results in a negative IMEP. At equivalence ratios of 0.15, 0.2, and 0.25, the methanol/diesel case experiences misfiring phenomenon which consequently deteriorates the engine performance considerably. As for the engine-out emissions, the hydrogen/diesel results display carbon monoxide (CO) free combustion relative to natural gas/diesel and methanol/diesel engines; however, considerable amount of nitrogen oxides (NO_x) emissions are produced at an equivalence ratio of 0.35 which exceeds the Euro 6 NO_x limit. Due to the larger area exposed to high temperature regions and the higher content of oxygen with increased methanol, soot and CO emissions are significantly reduced for richer premixed methanol mixtures. According to these findings, a dual-fuel engine operating on methanol and diesel performs better at rich conditions, whereas the performance of hydrogen and diesel is superior to that of natural gas/diesel and methanol/diesel mixtures at lean conditions.

1. Introduction

The ever increasing fossil fuel price and stringent emission regulations have led researchers to put more focus on the high efficiency and low emissions combustion concepts as well as alternative fuels for internal combustion (IC) engine applications. Particulate matter (PM) and NO_x are the main detrimental pollutant emissions generated by diesel engines. Several concepts have been investigated to reduce these emissions such as low temperature combustion (LTC), as well as using alternative fuels [1,2]. One of the emerging LTC concepts for the compression ignition (CI) mode is the homogeneous charge compression ignition (HCCI) combustion which enables achieving high thermal efficiency and ultra-low NO_x and soot emissions. However, this technology still suffers from the inability to control auto-ignition which is the major obstacle for the implementation of HCCI combustion in practical engines [3–5]. In order to address this issue, many research efforts and development endeavors have been focused on dual-fuel pilot diesel ignition engine concept, where the premixed fuel is ignited by a small amount of diesel fuel [6,7]. On the other hand, the demand for alternative/renewable fuels is increasing dramatically in the transportation sector as well as other industrial applications in order to meet the stringent emissions regulations and to reduce the dependency on conventional fossil fuels [8].

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Nomenclature

ABDC	after bottom dead center
ATDC	after top dead center
AFR	air fuel ratio
BDC	bottom dead center
BBDC	before bottom dead center
BSFC	break specific fuel consumption
BTE	break thermal efficiency
BTDC	before bottom dead center
CI	compression ignition
CO	carbon monoxide
CO_2	carbon dioxide
CAD	crank angle degree
CA_{10}	crank angle for 10% burnt fuel
CFD	computational fluid dynamic
CN	cetane number
EVC	exhaust valve close
EVO	exhaust valve open
HRR	heat release rate
HCCI	homogeneous charge compression ignition
IC	internal combustion
IDI	indirect injection
IMEP	indicated mean effective pressure
ISFC	indicated specific fuel consumption
ITE	indicated thermal efficiency
IVC	inlet valve close
IVO	inlet valve open
LTC	low temperature combustion
NO_x	nitrogen oxide
PFI	port fuel injected
PHHR	peak heat release rate
PM	particulate matter
rpm	revolution per minute
SI	spark ignition
SOI	start of injection
SOC	start of combustion
TDC	top dead center
THC	total hydrocarbon
UHC	unburned hydrocarbon

Therefore, a considerable amount of research is directed toward the optimization of diesel engines with the incorporation of alternative fuels. Among alternative fuels, natural gas [9,10], methanol [11,12], and hydrogen [13] are the most investigated for dual-fuel pilot diesel ignition engines.

Natural gas is the lowest-cost transportation fuel available today and has been widely used with diesel fuel in CI engines. The use of natural gas offers a lot of environmental benefits because it produces fewer emissions than conventional fossil fuels. Low carbon content and clean burn features, especially low soot/smoke, have helped the proliferation of natural gas as an alternative fuel with introduction of ever more severe emissions standards. Increased natural gas energy substitution has been found to be very effective in reducing NO_x and PM emissions while maintaining acceptable engine performance [14,15].

Methanol is an advantageous choice for diesel vehicles due to its efficient combustion, environmental benefits, low cost compared to other fuels, and its availability worldwide [16]. Emissions of unburned hydrocarbons (UHC) and CO are much lower when consuming methanol. Furthermore, methanol has a much higher latent heat of vaporization which decreases temperature considerably and consequently restricts NO_x formation. Methanol has no carbon–carbon bonds which inhibits soot formation [17,18].

Hydrogen has long been recognized as a carbon-free fuel and has several advantages when used to fuel IC engines due to its none-toxic and renewability nature, high calorific value, and environmental benefits [19]. A hydrogen-operated engine produces water vapor as its main combustion products. Moreover, hydrogen has a wide flammability range in comparison with all other fuels. As a result, hydrogen can be combusted in an IC engine over a wide range of fuel–air mixtures especially very lean mixtures where lower combustion temperature and hence NO_x emissions can be achieved [21]. However, hydrogen is not ignitable via compression in modern diesel engines as it requires an ignition source. Therefore, the auto-ignition of the diesel spray can act as a pilot to ignite the premixed mixture of hydrogen/air [21].

1.1. Literature review

Compared to diesel fuel, natural gas, methanol, and hydrogen are considered alternative fuels due to their renewable nature and abundant sources. The properties of these fuels are given in Table 1 [20,21]. Despite the various advantages of these alternative fuels, the auto-ignition is still their weakest property due to their very low cetane number (CN) in comparison with diesel fuel, especially at cold starts and light load conditions. In order to address this issue a dual-fuel pilot diesel ignition engine can be used where the main fuel fumigated into the intake air steam is ignited by a small amount of diesel fuel. Lounici et al. [22] examined the effect of dual-fuel operation on the combustion characteristics, engine performance, and emissions of a diesel engine using natural gas as the premixed fuel ignited by diesel as a pilot fuel. Their results showed that at low engine loads, the total break specific fuel consumption (BSFC) for dual-fuel mode was higher than that of the conventional diesel. However, at high and moderate loads, the total BSFC was found lower for all the examined engine speeds. Moreover, the use of natural gas for dual-fuel mode showed a reduction of soot and NO_x over a wide engine operating conditions.

Table 1
Properties of natural gas, methanol, hydrogen and diesel fuels [20,21].

	Natural gas (methane)	Methanol	Hydrogen	Diesel
Formula	CH_4	CH_3OH	H_2	$C_{12}H_{26}$–$C_{14}H_{30}$
Molecular weight (g/mol)	16	32	2	170–198
Density (g/cm^3 at 20 °C)	0.65	790	8.37E−2	820–860
Boiling temperature (°C)	−161.5	64.7	−252.9	190–280
Flash point (°C)	–	11	–	52
Auto-ignition temperature (°C)	540	470	585	300–340
Stoichiometric fuel–air ratio	0.058	0.154	0.029	0.069
Cetane number	–	3–5	–	40–55
Lower heating value (MJ/kg)	50.02	20.27	119.93	42.74