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Full Length Article

Exploring the potential of reformed-exhaust gas recirculation (R-EGR) for increased efficiency of methanol fueled SI engines

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ABSTRACT

Methanol is a promising fuel for spark ignition engines because of its high octane number, high octane sensitivity, high heat of vaporization and high laminar flame speed. To further boost the efficiency of methanol engines, the use of waste heat for driving fuel reforming was considered. This study explores the possibility of the reformed-exhaust gas recirculation (R-EGR) concept for increased efficiency of methanol engines. A simple Otto cycle calculation and a more detailed gas dynamic engine simulation are used to evaluate that potential. Both methodologies point to an enhancement in engine efficiency with fuel reforming compared to conventional EGR but not as much as the increase in lower heating value of the reforming product would suggest. A gas dynamic engine simulation shows a shortening of the flame development period and the combustion duration in line with the expected behavior with the hydrogen-rich reformer product gas. However, the heat loss increases with the presence of hydrogen in the reactants. The improvement of brake thermal efficiency is mainly attributed to the reduction of pumping work. The R-EGR concept is also evaluated for ethanol and iso-octane. As the reforming fraction increases, the efficiency of ethanol and iso-octane fueled engines rises faster than for the methanol engines due to a higher enhancement of exergy in their reforming products. At high reforming fractions, the efficiency of the ethanol engine becomes higher than with methanol. However, if the impact of optimal compression ratio for different fuels are considered, the methanol engine is able to produce a higher efficiency than the ethanol engine.

1. Introduction

Increasing brake thermal efficiency (BTE) of spark ignition (SI) engines currently is a strict requirement for engine manufacturers to meet the future CO_2 emission legislation. Several technologies have been investigated and applied to increase the engine efficiency such as cylinder deactivation, variable compression ratio, exhaust gas recirculation (EGR), Miller/Atkinson cycle, water injection, etc. [1]. Together with the development of engine technologies, fuel properties play an important role for the potential engine efficiency [2,3]. Due to the limitation of fossil fuels and the requirement of a sustainable mobility, fuels synthesized using renewable energy sources (or electrofuels, e-fuels) could play a key role [4]. The e-fuel properties can be optimized to increase engine efficiency and reduce raw emissions [5]. The fuel should have a high research octane number (RON), high octane sensitivity, high heat of vaporization (HoV), and high laminar burning velocity (LBV) [6]. Methanol (CH_3OH) is the simplest type of liquid synthetic fuel [7], and therefore has production advantages compared to more complex fuels. There is no C–C bond in the chemical formula enabling an almost soot-free combustion. Compared to other soot-free e-fuel candidates such as dimethyl carbonate (DMC) and methyl formate (MF) [8], methanol has a higher energy density, higher HoV and faster LBV [9,10]. The RON of methanol is comparable to DMC, and lower than MF (RON of 115), however, the octane sensitivity of methanol is the highest (20 for methanol versus 7 for DMC, and 0.2 for MF). Based on these considerations, methanol seems to be a very promising synthetic fuel for future SI engines in term of production, energy density as well as combustion.

The potential of methanol for increased efficiency and reduced exhaust emissions has been reported in previous researches [11–13]. A higher compression ratio (CR) engine can be used to fully utilize the anti-knock properties of the fuel, and the engine can be further downsized compared to gasoline engines [14]. In order to further boost the fuel economy, a waste heat recovery system can be used. The engine exhaust heat can be employed to reform methanol at low temperature using a cheap catalyst [15]. Methanol can dissociate to a H_2/CO blend (methanol thermal decomposition, reaction R1) or react with H_2O to produce a H_2/CO_2 mixture (methanol steam reforming, reaction R2). As

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Nomenclature

Abbreviations

aBDC	after bottom dead center
Al_2O_3	aluminum oxide
aTDC	after non-firing top dead center
$aTDC_f$	after firing top dead center
bBDC	before bottom dead center
BMEP	brake mean effective pressure
bTDC	before non-firing top dead center
$bTDC_f$	before firing top dead center
BTE	brake thermal efficiency
CA	crank angle
CAD	crank angle degree
CH_3OH	methanol
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
COV	coefficient of variance
CR	compression ratio
Cu	copper
D-EGR	dedicated-exhaust gas recirculation
DEM	dilution effect multiplier
DISI	direct-injection spark-ignition
DMC	dimethyl carbonate
EGR	exhaust gas recirculation
EtOH	ethanol
EVO	exhaust valve opening
FMEP	friction mean effective pressure
H_2	hydrogen
HCOOH	formic acid
HoV	heat of vaporization
HP	high pressure
IMEP	indicated mean effective pressure
ITE	indicated thermal efficiency
IVC	intake valve closure
LBV	laminar burning velocity
LHV	lower heating value
MBT	maximum brake torque
MEP	mean effective pressure
MER	molar-expansion ratio
MF	methyl formate
Mn	manganese
N_2	nitrogen
O_2	oxygen
PMEP	pumping mean effective pressure
R-EGR	reformed-exhaust gas recirculation
Rh	rhodium
RON	research octane number
SI	spark ignition

Symbols

Δh	enthalpy of formation
γ	specific heat ratio
λ	excess air fuel ratio
u'	turbulent intensity

both are endothermic reactions, the lower heating value (LHV) of decomposed methanol (in R1) and methanol steam reforming product (in R2) increases by 20% and 13% against methanol, respectively.

$$CH_3OH \xrightarrow{\text{catalyst}} CO + 2H_2 \qquad \Delta\ h = +91(kJ/mol) \tag{R1}$$

$$CH_3OH + H_2\ O \xrightarrow{\text{catalyst}} CO_2 + 3H_2 \qquad \Delta\ h = +49(kJ/mol) \tag{R2}$$

During the 1980s, several tests with dissociated/decomposed methanol on SI engines were performed and a large relative improvement in engine efficiency versus gasoline was found [16–18]. However, the enhancement was small (3–7%) if it was compared to the efficiency that could be obtained with an engine operated on pure methanol, which itself is smaller than the change in LHV of dissociated methanol [19]. Work was also done on decomposed methanol at lean conditions, and showed a significant improvement in efficiency compared to neat methanol [20,21].

Recently, Poran et al. have built the first prototype of a direct-injection SI engine with a high-pressure thermal recuperation [22]. Methanol is converted to syngas at high pressure through steam reforming. The product is injected directly in the combustion chamber, allowing the volumetric efficiency of the engine to be maintained. The occurrence of back-fire and pre-ignition can also easily be solved then. The experiments with methanol reformate from the reformer [22] and from the compressed gas bottles [23–25] both showed a significant improvement in efficiency (18–39%) and lower emissions (up to 94% in NO_x, 96% in CO, 97% in HC, and 25% in CO_2) compared to gasoline.

These above mentioned studies employed methanol reformate as the fuel for SI engines, i.e. 100% fuel was reformed. A part of the fuel also can be reformed to support the combustion of liquid fuels. The fuel can be reformed through in-cylinder reforming or through catalytic reforming. In the former case, the cylinder works as a reactor for partial oxidation to produce syngas [26,27]. The dedicated-exhaust gas recirculation (D-EGR) engine concept has been built [28] based on that principle. One (of four) cylinder operates with a rich mixture, the exhaust gas of that cylinder returns back to the intake to mix with the intake air. The EGR ratio is almost fixed at 25%, and the engine can be operated at a higher CR. Because of the rich combustion in the dedicated cylinder, the combustion produces H_2 and CO. The amount of H_2 and CO strongly depends on the enrichment in the dedicated cylinder. Richer combustion generates a higher concentration of H_2 and CO, which supports the combustion in the other cylinders. Shorter combustion duration was observed, leading to a reduction in fuel consumption. The rich limit of methanol combustion is higher than gasoline, causing the dedicated cylinder to be able to operate at an equivalence ratio of 2.67 (versus 1.6 for gasoline) [29], so more hydrogen can be produced. The brake thermal efficiency of the D-EGR engine with methanol improves by 1–3% compared to gasoline.

For the catalytic reforming, the catalyst is heated up by contacting directly with the hot gas or through a heat exchanger. The direct contact is preferred because it provides a better heat transfer and the combustion products can be used as an additional reactant. The hot gas is the EGR mixture (reformed-EGR concept) [30], or is the exhaust of one cylinder [31,32]. In the first one, the fuel is injected into the EGR loop, upstream the catalyst and reacted with water vapor and/or CO_2 in the exhaust over the catalyst to produce syngas (see Fig. 1). The reforming products and the inert gases then recirculate back to the intake

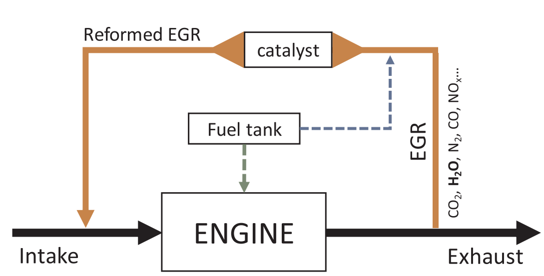

Fig. 1. The reformed-exhaust gas recirculation (R-EGR) concept.