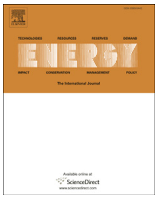
Energy 124 (2017) 214–226

Contents lists available at ScienceDirect

Energy

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



Performance and emissions of a direct injection internal combustion engine devised for joint operation with a high-pressure thermochemical recuperation system

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ARTICLE INFO

Article history:
Received 11 September 2016
Received in revised form
7 December 2016
Accepted 13 February 2017

Keywords:
Thermo-chemical recuperation
Steam reforming of methanol
Ethanol decomposition
High-pressure reforming
Reformate direct injection
Combustion of hydrogen-rich reformate

ABSTRACT

This paper presents the results of an experimental study on performance and pollutant emissions of a direct-injection spark-ignition engine devised for joint operation with a high-pressure thermochemical recuperation system based on methanol steam reforming. A comparison with gasoline and ethanol decomposition is performed. Engine feeding with methanol steam reforming products shows an 18%–39% increase in the indicated efficiency and a reduction of 73–94%, 90–96%, 85–97%, and 10–25% in NO_x, CO, HC and CO_2 emissions, respectively, compared to gasoline within a wide power range. Efficiency improvement and emissions reductions are obtained compared to ethanol decomposition products as well. The possibility of an unthrottled engine operating with a substantially lower cycle-to-cycle variation compared to both gasoline and ethanol decomposition is demonstrated. At high loads, the injector flow area was insufficient for a low injection pressure of 40 bar, leading to late injection and reduced engine efficiency for methanol steam reforming products. In the case of ethanol decomposition, the problem was less severe due to the higher energy content of ethanol decomposition products per mole. The concept of a direct-injection internal combustion engine with high-pressure methanol steam reforming shows good potential, while additional research on injection strategies and gaseous reformate combustion is required.

1. Introduction

In recent decades, there has been a continuous effort to reduce global environmental pollution and fossil oil consumption. As the main power source for transportation, internal combustion engines (ICE) are a major source of both environmental pollution and oil consumption. Thus, the reduction of pollutant and greenhouse gas (GHG) emissions generation as well as petroleum depletion can be achieved by increasing the ICEs' efficiency and using alternative low-carbon-intensity fuels. Ethanol and especially methanol are low-carbon-intensity fuels that are considered by many as good alternatives to petroleum because of their availability from various sources such as bio-mass, coal, natural gas and renewable energy-derived hydrogen [1–4]. In this article, we consider using these alcohols as the primary fuel in an ICE-reformer system with waste heat recovery (WHR) through high-pressure thermochemical recuperation (TCR).

It is known that in ICE, approximately 1/3 of the energy introduced with the fuel is wasted along with the hot exhaust gases [5]. Thus, partial utilization of this energy, also known as waste heat recovery, can lead to a significant increase in the overall ICE efficiency [6]. One possible method of WHR is utilizing the energy of hot exhaust gases to sustain endothermic fuel reforming reactions. This method is known as thermochemical recuperation [7]. TCR has two main benefits. First, it increases the fuel's LHV due to the WHR process through endothermic fuel reforming reactions — see Eqs. (1)–(3). Second, the mixture of gaseous reforming products (reformate) usually has a high hydrogen content, resulting in the increased burning velocity, higher octane number and wider flammability limits [8,9]. Thus, TCR allows improvement in the ICE efficiency, not only due to the WHR process but also lean-burn operating possibilities, which approach the theoretical Otto cycle and the possibility of increasing the engine compression ratio.

Aside from their previously mentioned advantages, methanol and ethanol are also excellent primary fuels for reforming since they can be reformed at relatively low temperatures

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http://dx.doi.org/10.1016/j.energy.2017.02.074
0360-5442/

Nomenclature

Symbols

δR	uncertainty of calculated parameter R
δX_i	accuracy of measured value X_i
ΔH	enthalpy of reaction
e_b	burned zone energy
e_s	sensible energy
e_u	unburned zone energy
E_i	emissions of pollutant *i*
h_a	air enthalpy
h_{av}	enthalpy available for reforming
h_f	fuel enthalpy
$h_{f,i}$	injected fuel enthalpy
m	in-cylinder mass
m_a	air mass
$\dot{m}_a$	air flow rate
m_b	burned zone mass
m_f	fuel mass
$\dot{m}_f$	fuel flow rate
$m_{f,i}$	injected fuel mass
m_u	unburned zone mass
$\dot{m}_f$	fuel mass flow rate
M_C	molecular weight of carbon
M_i	molecular weight of pollutant *i*
p	cylinder pressure
Q	heat transfer rate
Q_b	burned zone heat transfer rate
Q_u	unburned zone heat transfer rate
V	cylinder volume
V_b	burned zone volume
V_d	displaced volume
V_u	unburned zone volume
$W_{i,g}$	gross indicated work
$\dot{W}_{i,\,g}$	gross indicated power
x_i	mass fraction of species *i*
$y_{c,fuel}$	fuel's carbon mass fraction
y_i	molar fraction of pollutant i
y_j	CO/CO_2/$CH_{1.85}$ molar fraction

Greek symbols

η_c	combustion efficiency
η_i	gross indicated efficiency
θ	crank angle (360 firing top dead center)
θ_{50}	anchor angle, the CAD of 50% fuel mass burned
θ_{0-10}	flame development angle, CAD difference ignition and 10% of the fuel mass is burned
θ_{10-75}	CAD difference between 10% and 75% of the fuel mass burned
θ_{10-90}	rapid burning angle – CAD difference between 10% and 90% of the fuel mass burned
λ	excess air ratio
σ_{IMEP}	IMEP standard deviation

Acronyms

BTE	brake thermal efficiency
CAD	crank angle degrees
COV	coefficient of variation in the IMEP
DI	direct injection
ED	ethanol decomposition
HC	hydrocarbons
HRR	heat release rate
ICE	internal combustion engine
IMEP	indicated mean effective pressure (gross)
LHV	lower heating value
MD	methanol decomposition
MSR	methanol steam reforming
PN	particle number concentration
SI	spark ignition
TCR	thermochemical recuperation
TDC	top dead center
WHR	waste heat recovery
WOT	wide-open throttle

(approximately 250–300 °C [3,10]) to produce hydrogen-rich reformate. Commonly investigated reforming reactions for ICE applications are methanol decomposition — MD (Eq. (1)), methanol steam reforming — MSR (Eq. (2)), and low-temperature ethanol decomposition — ED (Eq. (3)) [11–13].

$$CH_3OH_{(g)} \rightarrow CO + 2H_2 \quad \Delta H = 90\ \text{kJ/mol} \tag{1}$$

$$CH_3OH_{(g)} + H_2O_{(g)} \rightarrow CO_2 + 3H_2 \quad \Delta H = 50\ \text{kJ/mol} \tag{2}$$

$$C_2H_5OH_{(g)} \rightarrow CH_4 + CO + H_2 \quad \Delta H = 50\ \text{kJ/mol} \tag{3}$$

In this work, we focused mainly on MSR and ED due to the problems of catalyst stability and deactivation that are frequently observed in the MD process [14,15]. It is possible that newly developed catalysts will make MD a beneficial option in the future [16].

Methanol reforming schemes investigated in the past showed up to 40% brake thermal efficiency (BTE) improvement compared to their gasoline counterparts but have also exhibited serious problems [17]. The main problems reported include uncontrolled combustion, catalyst deactivation, cold start and engine maximal power loss due to reduced volumetric efficiency. The latter is a result of supplying gaseous reformate into the intake system that reduces the partial pressure of the air in the intake manifold, and the absence of an evaporative cooling effect compared to the case of a liquid fuel port injection.

More recent studies have reported on a high-efficiency, low-emission hydrogen-fueled ICE, for which the problems of reduced power and uncontrolled combustion were solved by the direct injection (DI) of hydrogen [18]. Hagos et al. [19,20] studied the combustion of syngas (H_2 + CO) derived from biomass gasification in a DI SI engine and reported on the possibility of CO and HC emissions reduction together with NO_x emissions increases at higher loads. Li et al. [21] and Shimada & Ishikawa [22] studied the onboard reforming of hydrous ethanol with a reformate supply to the intake manifold. Both reformate gas and unreformed ethanol were burned for power production. They reported on engine efficiency improvement up to 18%, together with a substantial decrease in NO_x, CO and THC emissions. Yoon [23] studied reformer design limitations for the steam reforming of methanol. He [24] proved that H_2 and CO participation in the combustion process of ICE results in the increase of O, H and OH radicals' concentration and hence improves the flame propagation and combustion process. Recent studies propose solving the cold start problem by integrating the reforming system in an electric-hybrid vehicle and