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Full Length Article

Performance optimization of in-cylinder thermochemical fuel reforming (TFR) with compression ratio in an SI natural gas engine

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HIGHLIGHTS

- In-cylinder TFR could generate H_2 and CO.
- Increasing compression ratio could improve in-cylinder TFR process.
- Elevated compression ratio extends the scope for high efficiency in-cylinder TFR.

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ABSTRACT

The potential for in-cylinder thermochemical fuel reforming (TFR) to improve engine performance has been well studied. Meanwhile, achievable TFR gas can ensure that an engine coupled with in-cylinder TFR can run at a comparatively high compression ratio (CR), which might facilitate the in-cylinder TFR reforming process and then improve engine performance. This study focuses on performance optimization of in-cylinder TFR with compression ratio. Two compression ratios, of 11 and 13 were selected in the experiment. With the original compression ratio of 11, the brake thermal efficiency rose while the brake specific fuel consumption declined rapidly with increases in the equivalence ratio of the TFR cylinder (Φ_{TFR}). Thermal efficiency reached a maximum while consumption fell to a minimum when the Φ_{TFR} reached 1.25, at which point large amounts of H_2 and CO were generated in the reformed gas. In the case of 11 compression ratio, the in-cylinder TFR slightly worsened engine stability if the Φ_{TFR} exceeded 1.25. When the compression ratio was up to 13, the reformed gas had a higher proportion of CO, with a comparable proportion of H_2 compared with lower compression ratio. Meanwhile, thermal efficiency was elevated while fuel consumption was reduced and the engine achieved better stability, with less discrepancy between the cylinders. Moreover, the engine combustion and emissions characteristics were improved. Results also demonstrated that increased compression ratio could extend the scope for high efficiency in-cylinder TFR. Thus, combined with higher compression ratio, TFR has potential to further reduce emissions and to improve brake specific fuel consumption in an SI natural gas engine simultaneously.

1. Introduction

Natural gas is considered as one of the most promising alternative fuels for vehicles, due to its reduced CO_2 emission with a high H/C ratio, and its good anti-knocking properties with high octane numbers (120–130) [1,2]. Moreover, natural gas engines can achieve extremely low PM emission [3,4], as natural gas is mainly composed of methane, which has a simple chemical structure. In addition, globally abundant shale gas resources and advanced development techniques such as horizontal drilling and hydraulic fracture techniques ensure vast sources and competitive costs of natural gas for a long time to come [5]. This availability of the fuel suggests that natural gas engines may be adopted far more widely in the future.

Natural gas has been extensively used in spark-ignition (SI) and compression-ignition (CI) engines. However, natural-gas fueled SI engines produce relatively less power than gasoline-fueled engines, due to their lower volumetric efficiencies and more advanced spark timing. Still, these limitations can be overcome by increasing the compression ratio. When combined with turbocharging or supercharging and intercooling systems, these engines can achieve increased levels of power and thermal efficiency. Compared with gasoline engines, natural-gas fueled SI engines running at higher

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Nomenclature

BMEP	brake mean effective pressure
BSCO	brake specific CO
BSFC	brake specific fuel consumption
BSHC	brake specific HC
BSNOx	brake specific NOx
BTDC	before top dead center
CAD	crank angle degree
CI	compression ignition
CNG	compressed natural gas
CoVIMEP	coefficient of variance of IMEP
CR	compression ratio
EGR	exhaust gas recirculation
HCCI	homogenous charge compression ignition
HRR	heat release rate
IMEP	indicated mean effective pressure
$IMEP_2$	IMEP of cylinders 1–3
IMEPTFR	IMEP of TFR cylinder
n	engine speed
OC	oxidation catalyst
p	cylinder pressure
REGR	reformed exhaust gas recirculation
rpm	revolutions per minute
SCR	selective catalytic reduction
SI	spark ignition
ST	spark timing
TDC	top dead center
TFR	thermochemical fuel reforming
TWC	three-way catalyst
Φ	equivalence ratio
ΦTFR	equivalence ratio of the TFR cylinder
Ω	coefficient of uniformity
η	brake thermal efficiency

compression ratios yield reduced CO_2, HC and CO emissions, but increased NOx emissions [6]. Natural gas can also be applied in CI engines via a dual-fuel mode, in which a small amount of high-cetane fuel is injected directly into the cylinder to provide an ignition source for the premixed natural gas-air mixture. Compared with normal diesel-fueled CI engines, natural-gas fueled CI engines produce comparative thermal efficiency and significantly reduced smoke levels. At the same time, natural-gas fueled CI engines have lower NOx and CO_2 emissions, and higher HC and CO emissions (at low and intermediate loads) than normal CI engines [7]. Therefore, both the SI and CI types of natural gas engines require further refinement and optimization.

For natural gas SI engines, two combustion modes have gained pervasive application, namely the lean burn and stoichiometric modes. The lean burn mode can simultaneously realize higher thermal efficiency and lower emissions levels without exhaust gas after-treatment, because this mode allows less heat transfer loss, less pumping work and relatively high compression ratios [8,9]. However, with the implementation of increasingly stringent emission legislations such as the Euro VI emission regulations (which require extremely low NOx emissions of under 0.46 g/kWh, WHTC), a much leaner mixture has to be used to suppress NOx emissions [10]. When natural gas engines run on an extremely lean mixture, even beyond the lean burn limit, it causes several problems. These problems include engine instability with high cyclic variation, an increase in HC and CO emissions, and a decrease in engine thermal efficiency [6,10]. Hence, it seems to be inevitable that lean-burn natural gas engines must apply deNOx systems, such as selective catalytic reduction (SCR) devices, to meet the NOx emissions regulations. These systems in turn involve increased cost and complexity for the engines [11,12]. In addition, an oxidation catalyst (OC) becomes necessary to reduce HC and CO emissions.

Another strategy to meet the Euro VI emission regulations is a stoichiometric operation with three-way catalyst (TWC) technology. This approach is now attracting considerable attention, as it can reduce NOx, HC and CO emissions with lower cost and less complexity than the lean burn operation with SCR and OC [13]. However, stoichiometric operation results in higher in-cylinder temperatures, and consequently increased thermal stress, more heat transfer loss and a greater knocking tendency. To solve these problems, exhaust gas recirculation (EGR) can be applied as an effective method for reducing the combustion temperature in stoichiometric natural gas engines. The introduction of EGR increases the specific heat capacity and reduces oxygen partial pressure in the inlet mixture, which leads to lower in-cylinder temperatures and reduced NOx emissions [12,14]. Thus, a stoichiometric operation, in combination with EGR and TWC, offers an effective strategy that can achieve much lower engine emissions and meet the stringent emission limits [6]. These gains, however, come at a slight cost to brake thermal efficiency, because stoichiometric operations cause a higher flame temperature and greater heat loss than lean burn operations [15]. Therefore, there is much work to do in developing innovative strategies that can achieve a stoichiometric, high thermal-efficiency natural gas engine.

H_2 is another competitive candidate fuel for internal combustion engines, because of its favorable physical properties and combustion characteristics. These characteristics include a high diffusion coefficient and laminar flame speed, a small quenching distance and wide flammability limits [16]. However, the lower volumetric energy density of H_2 means that internal combustion engines fueled with pure H_2 have less power output than natural gas-powered engines [17]. Therefore, it is beneficial for H_2 to be only partially substituted for natural gas in internal combustion engines [18]. The addition of H_2 fuel in natural gas engines can help to improve the lean burn limit or the EGR tolerance, which can lead to improvements in engine efficiency and emissions reduction [19,20]. Nevertheless, the difficulties involved in the storage and movement of H_2 still present barriers to the commercialized use of H_2 as a partial or a principle fuel for internal combustion engines [21]. Therefore, researchers are forced to seek some valid means for solving this problem.

Onboard catalytic fuel reforming is regarded as a feasible strategy for producing H_2. In this approach, HC fuels are reformed to H_2, CO_2, CO and some of the lowest HCs, usually through reaction with water and/or oxygen over a solid phase catalyst at a suitable temperature [22]. Ethanol is usually used as the reforming feedstock, due to its comparatively low temperature requirement for the reforming process, and the results from using ethanol show that the reformed gas has a positive effect on engine performance [23,24]. As a potential means of onboard H_2 production, exhaust gas fuel reforming has been extensively investigated at the University of Birmingham [25]. This process makes use of residual oxygen, steam and the high temperature of engine exhaust gas to enable a reaction with HC fuels in a reformer. The product is hydrogen-rich gas, which can then be recycled to the engine