Energy 89 (2015) 236–243

Contents lists available at ScienceDirect

Energy

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

Critical firing and misfiring boundary in a spark ignition methanol engine during cold start based on single cycle fuel injection

Zhaohui Li [a, b], Changming Gong [c, *], Xiang Qu [a, b], Fenghua Liu [c], Jingzhen Sun [a], Kang Wang [a], Yufeng Li [a, d]

[a] *State Key Laboratory of Automotive Simulation and Control, Jilin University, Changchun 130022, China*
[b] *School of Vehicle Engineering, Chongqing University of Technology, Chongqing 400054, China*
[c] *College of Electromechanical Engineering, Dalian Nationalities University, Dalian 116600, China*
[d] *China North Engine Research Institute, Tianjin 300400, China*

ARTICLE INFO

Article history:
Received 9 January 2015
Received in revised form
26 June 2015
Accepted 17 July 2015
Available online 6 August 2015

Keywords:
Spark ignition
Methanol engine
Critical firing and misfiring boundary
Cold start
Single cycle fuel injection

ABSTRACT

The influence of the mass of methanol injected per cycle, ambient temperature, injection and ignition timing, preheating methods, and supplying additional liquefied petroleum gas (LPG) injection into the intake manifold on the critical firing and misfiring boundary of an electronically injection controlled spark ignition (SI) methanol engine during cold start were investigated experimentally based on a single cycle fuel injection with cycle-by-cycle control strategy. The critical firing and misfiring boundary was restricted by all parameters. For ambient temperatures below 16 °C, methanol engines must use auxiliary start-aids during cold start. Optimal control of the methanol injection and ignition timing can realize ideal next cycle firing combustion after injection. Resistance wire and glow plug preheating can provide critical firing down to ambient temperatures of 5 °C and 0 °C, respectively. Using an additional LPG injection into the intake manifold can provide critical firing down to an ambient temperature of −13 °C during cold start. As the ambient temperature decreases, the optimal angle difference between methanol injection timing and LPG injection timing for critical firing of a methanol engine increases rapidly during cold start.

1. Introduction

To match the ultra-low emissions vehicle standard, 80–90% of tailpipe hydrocarbon (HC) emissions are emitted during the first test cycle of the federal test procedure [1]. The first few cycles are very important to the process of engine cold start. Successful ignition and combustion of the first few cycles not only reduces HC emissions, but also improves the firing and combustion behavior for the following cycles [2]. Conversely, a misfire in the first cycle can result in an excess of unburned HC emissions and impact the stability of the following cycles [3]. Mixture preparation for the first few cycles during cold start is especially difficult. Fuel evaporation is unfavorable because ambient, intake port, and combustion chamber temperatures are low. Santoso et al. [4] found that only 10–20% of the fuel vaporizes during the first few cycles of cold start and therefore 8 to 15 times the stoichiometric amount of gasoline is injected during the first several cycles of the cold start and warm-up transient [5]. Fuel vaporization at the inlet port injection location deteriorates at low ambient temperatures. The lower the ambient temperature, the richer the air fuel mixture that is required for a startup [6]. However, higher injected mass results in thicker port and valve films, and consequently thicker in-cylinder films, which evaporate more slowly [7]. Fuel vaporization and mixture preparation in a port fuel injected spark ignition (SI) engine during a cold start depend critically on both ambient temperature and engine coolant temperature. In particular, the temperature of the intake valve is important for triggering vaporization during the first engine cycle. After the first successful fired cycle, backflow of hot residual gases into the intake port aids in vaporizing the fuel in subsequent cycles [8,9].

The boiling point of methanol (65 °C) is higher than the initial boiling point of gasoline (approximately 40 °C), and relatively low

---

Abbreviations: LPG, liquefied petroleum gas; SI, spark ignition; HC, hydrocarbon; M100, 100% methanol; M85, 85% methanol and 15% gasoline; DME, dimethyl ether; ECU, electronic control unit; BTDC, before top dead center; CA, crank angle; TDC, top dead center; ATDC, after top dead center; CABTDC, crank angle before top dead center; IVO, intake valve opening; IVC, intake valve closing.

* Corresponding author. Tel.: +86 411 87188945; fax: +86 411 87656133.
E-mail address: gongcm@dlnu.edu.cn (C. Gong).

http://dx.doi.org/10.1016/j.energy.2015.07.071
0360-5442/© 2015 Elsevier Ltd. All rights reserved.

vapor pressure and high latent heat of vaporization of methanol may cause cold start difficulties for an SI methanol engine compared to a gasoline engine [10,11]. Dhaliwai et al. [12] found that 100% methanol (M100) is particularly difficult for cold starts at temperatures below approximately 15 °C. A mixture of 85% methanol and 15% gasoline (M85) is often used to partially alleviate the cold start problems of M100. There has been much research undertaken to address the problem of cold start of alcohol (methanol or ethanol) engines and expand their firing boundary [13–18]. Kabasin et al. [16] reported the use of heated injectors for ethanol cold starts. They found these offered a practical means to increase the temperature of injected ethanol. Engines equipped with heated injector systems have exhibited robust and fast E100 (100% ethanol) cold starts down to ambient temperatures of −5 °C without gasoline assistance. Liang et al. [19] investigated the combustion and emissions performance of dimethyl ether (DME) enriched methanol at idle conditions to widen the operational range and improve the performance of SI methanol engines. They found that since DME vaporizes and ignites at lower temperatures, it could provide almost instantaneous vaporization in air when injected into the intake ports and realize low temperature combustion.

Previous research has concentrated on SI engines fueled with gasoline, LPG, DME, gasoline/methanol, or gasoline/ethanol blends during cold start [20–25], with little work on methanol alone [26,27]. Almost no research has focused on the critical firing boundary of an SI methanol engine during cold start. Therefore, this work concentrates on investigating the critical firing and misfiring boundary of SI methanol engines during cold start based on a single cycle fuel injection strategy. The main aim of this study is to provide an effective method to extend the critical firing boundary of SI methanol engines during cold start. The results will be helpful to understand and expand the cold start critical firing and misfiring behaviors and boundaries, and improve HC emissions of SI methanol engines.

2. Experiment system and procedure

The test engine was a single-cylinder, four-stroke, electronically controlled SI methanol engine with intake manifold fuel injection, with technical specifications listed in Table 1, and the schematic of the engine layout shown in Fig. 1.

An air heater was fixed onto the front of the intake manifold, and a methanol heater was fixed on the outer surface of the methanol tank. A resistance wire heater was fixed on the outer surface of the intake manifold, and a glow plug heater was fixed in the intake manifold plenum. The effect of the glow plug surface on injected methanol was very small. To prevent injected methanol combustion on the glow plug, the glow plug surface was covered with a copper sleeve, ensuring the surface temperature of the glow plug remained below the methanol auto-ignition temperature. In-cylinder pressure was measured using a Kistler-6125B piezoelectric transducer (0–25 MPa range, 150 pc/MPa accuracy) coupled to a WDF-3 charge amplifier. Instantaneous engine speed was determined by an optical shaft encoder. The temperatures of air, methanol, intake manifold, and glow plug surface were measured with a K type thermocouple. The injection pulse width of methanol and LPG, ignition timing, and injection timing of methanol and LPG were controlled by an electronic control unit (ECU) developed in-house. The mass of methanol and LPG injected per cycle was calculated from the injection pulse width and nozzle flow characteristics of the methanol and LPG injectors. In-cylinder pressure and instantaneous engine speed were recorded synchronously by a multichannel data acquisition card (PLC-8018HG). The uncertainties of some measured and calculated parameters are shown in Table 2.

Methanol used in the test was industrial grade with purity above 99.9%. The LPG was composed of 49% propane, 15% butane, 21% isobutene, 8% dimethyl-propylene, 5% butadiene, and other components (mass percentages). The main fuel properties of methanol and LPG are shown in Table 3. The methanol and additional LPG were injected at constant fuel pressures of 0.3 MPa and 0.14 MPa, respectively.

For ambient temperatures below 16 °C, the following auxiliary start-aids were assessed:

(1) Air preheating to 26 °C.
(2) Methanol preheating to 50 °C.
(3) Resistance wire preheating, heating the intake manifold surface to 45 °C.
(4) Glow plug preheating, heating the surface of the glow plug to approximately 400 °C.
(5) Additional LPG injected into the intake manifold.

The ECU also controlled the electric motor to crank the SI methanol engine. The engine was always started from piston position of approximately 300° crank angle before top dead center (CABTDC) of the compression stroke. The cycle where to engine started rotation was defined as the first cycle, and methanol (and additional LPG during that trial) were injected in the first cycle based on a single cycle fuel injection strategy. The 0° crank angle (CA) for ignition, methanol injection, and LPG injection timing corresponded to top dead center (TDC) of the first cycle in the compression stroke.

The combined in-cylinder pressure and instantaneous engine speed was used to determine the critical firing or misfiring boundary of during cold starting. Using in-cylinder pressure or instantaneous engine speed alone cannot accurately determine this boundary. Figs. 2 and 3 show the in-cylinder pressures and instantaneous engine speed histories for critical firing and misfiring during cold start.

A single cycle fuel injection strategy was employed during the cold start experiments. Due to differences in the characteristics of methanol and LPG evaporation, when additional LPG injection

Table 1
Engine specifications.

Bore (mm)	52.4
Stroke (mm)	57.8
Displacement (cm^3)	125
Compression ratio	10.55:1
Maximum power/speed (kW/rpm)	6.5/7500
Maximum torque/speed (Nm/rpm)	9/6000
Cooling system	Air cooled
Intake valve opening (IVO) (°CABTDC)	15
Intake valve closing (IVC) (°CAABDC)	35
Exhaust valve opening (EVO) (°CABBDC)	35
Exhaust valve closing (EVC) (°CAATDC)	15