Applied Energy 170 (2016) 403–414

Contents lists available at ScienceDirect

Applied Energy

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

Using variable piston trajectory to reduce engine-out emissions

Chen Zhang, Zongxuan Sun *

Department of Mechanical Engineering, University of Minnesota, Twin Cities Campus, 111 Church Street SE, Minneapolis, MN 55455, United States

HIGHLIGHTS

- This paper presents the ability of trajectory-based combustion control on reducing engine-out emissions.
- Asymmetric piston trajectories are designed aimed at reducing both CO and NOx emissions significantly.
- The trajectory-based combustion control not only reduces emissions but also increases thermal efficiency simultaneously.

ARTICLE INFO

Article history:
Received 28 November 2015
Received in revised form 18 February 2016
Accepted 19 February 2016
Available online 12 March 2016

Keywords:
Emissions control
Dynamic modeling
Free piston engine
Trajectory-based combustion control

ABSTRACT

Previously, the authors have proposed the concept of piston trajectory-based combustion control enabled by free piston engines (FPEs). With this novel method, the FPE realizes in-cycle adjustment of combustion phase and real-time control of in-cylinder temperature and pressure through variable piston trajectories. As a result, higher indicated thermal efficiency, compared to conventional internal combustion engines (ICEs), is achieved. In this paper, the effects of this new combustion control on engine-out emissions are investigated. First, a comprehensive model is developed that includes different piston trajectories in the FPE, a convective heat loss model and a reduced *n*-heptane reaction mechanism with major emissions species. Afterwards, the chemical kinetics of CO and NOx emissions are described in details that reveal the feasibility of reducing engine-out emissions by employing novel piston trajectories. At last, analyses of the corresponding simulation results and comparisons of emissions and thermal efficiencies between the FPE and conventional ICEs are presented, which further shows the advantages of the trajectory-based combustion control.

1. Introduction

Investigations of cleaner and more efficient ways for transportation energy usage have attracted more and more public attentions to date due to the increasing concerns on the environmental issues and the future energy supply. Currently, vehicle propulsion systems are still dominated by conventional internal combustion engines (ICEs), a technology invented more than a century ago. Although significant progresses have been made, the overall efficiency of the ICE is still under the requirement while the room for further improvement is limited. Furthermore, such limitation is exacerbated if taking the engine emissions performance into account.

Typically, the term "engine emissions" refers to several components in the engine exhaust, including carbon monoxide (CO), various oxides of nitrogen (NOx), unburnt hydrocarbons (HC), and particulate matter (PM). It is widely-known that unlimited release of these pollutants would cause formidable damages to both human health and environment [1,2]. As a result, more and more countries and regions have provided or followed increasingly stringent emissions regulations [3,4].

Technologies to reduce emissions are mainly separated into two categories. One is aimed to optimize the combustion processes inside the ICE and reduces so-called "engine-out" emissions directly. Extensive researches have been conducted on this approach and several technologies, including retarding the ignition time [5–7], exhaust gas recirculation (EGR) [8–11] and advanced fuel injection strategy [12–15], have been widely adopted in real world applications. However, the reductions of emissions achieved by these methods are limited, especially if higher engine efficiency and fuel economy are required. For instance, it was reported that between 5% and 10% EGR in the spark–ignition (SI) engine could reduce almost half NOx emission in specific working conditions [16]. Nonetheless, this NOx reduction is achieved by adding large amounts of inert gases into the intake air–fuel mixture and therefore reducing the combustion rate and peak temperature. As a result, the EGR method decreases the maximal achievable power

* Corresponding author. Tel.: +1 612 625 2107.
E-mail address: zsun@umn.edu (Z. Sun).

http://dx.doi.org/10.1016/j.apenergy.2016.02.104
0306-2619/

in high load, increases the fuel consumption in elevated load and causes unstable combustion or even misfire in low load or idle condition.

The other approach is to reduce the engine emissions through advanced aftertreatment systems. Such method receives great success in vehicles powered by SI engines since its air–fuel mixture remains at stoichiometric ratio for the majority of loading conditions [17]. This feature ensures the effectiveness of the three-way catalyst converter which decreases the tail-out production of CO, HC and NOx simultaneously. Unfortunately, this system possess a severe cold-start problem [18–20] and also fails to regulate the emissions performance while engine is in transient (e.g. acceleration) conditions [21,22]. On the other hand, comprehensive aftertreatment system for compression-ignition (CI) engine is still an open question which asks for further research. The existing three-way catalyst converter cannot be adopted in diesel engines directly due to the following two reasons: first, diesel engines usually operate in fuel-lean condition; second, the exhaust from the diesel engine contains large amounts of PM and other organic compounds which poison the catalyst easily. Other methods, such as diesel oxidation catalyst [23,24], diesel particulate filter [25,26] and selective catalytic reduction [27] are also proposed, but those systems are quite complicated due to their strong temperature dependence while the corresponding manufacture costs also increase significantly.

Hence, existing emission controls in conventional ICE may not be able to optimize the combustion processes and reduce the pollutants under the entire engine operation domain. As a consequence, revolutionary technical innovation is required to transform the conventional ICE into a much cleaner and more flexible energy conversion device.

Free piston engine (FPE), with a totally different architecture, is considered as one of the most promising alternatives of conventional ICEs [28–37]. Without the constraints caused by the mechanical crankshaft, the FPE enables the ultimate freedom of piston motion and be able to generate variable piston trajectories. As a result, the FPE is able to utilize this variable trajectory as an additional control means to enhance the engine performance. The main technical barrier for the mass production of this technology is the lack of precise and robust piston motion control since the piston movement is determined by the combustion force and the load dynamics in real-time [34,35,38–42]. Previously, an active control, named as "virtual crankshaft", has been developed by the authors and implemented on a prototype hydraulic FPE (Fig. 1). The "virtual crankshaft" mechanism is achieved by controlling the opening of the servo valve and therefore manipulating the hydraulic forces acting on the pistons. Consequently, the piston motion can be controlled to precisely track the desired reference trajectories [34,35].

With the capability of generating various piston trajectories, the FPE is expected to tailor the combustion processes in real-time and optimize the combustion outputs by implementing the optimal piston trajectory, which forms the basic concept of trajectory-based combustion control. This expectation is rational since the combustion process is determined by the interactions between the gas dynamics and the fuel chemical kinetics through a feedback manner (Fig. 2). The optimal piston trajectory can be designed and generates the most appropriate volume profile to affect the aforementioned interactions. Previously, the authors have investigated the effects of various trajectories on the engine performance and showed that the trajectory-based combustion control enabled by FPE is able to adjust combustion phasing, reduce the heat loss and therefore increase the indicated thermal efficiency [43]. However, few results have been shown previously to reveal the benefit of the advanced combustion control on emissions reduction.

In this paper, the effects of the trajectory-based combustion control on engine emissions are investigated and a new approach, reducing the engine-out emissions by employing asymmetric piston trajectories, is proposed. A system model, including a physical-based model representing the FPE operation and a reduced *n*-heptane reaction mechanism [44], is developed which demonstrates the feasibility of this new approach. The corresponding simulation results show the trajectory's positive influences on the engine-out emissions, indicating the advantages of the trajectory-based combustion control.

2. Modeling approach

The model is developed by assuming the combustion chamber of the FPE as a homogeneous variable-volume reactor. Additionally, the scavenging process is neglected and air–fuel mixture is presumed to be well-stirred initially in the reactor. The detailed modeling approach is presented as follow: First, a method aimed to generate various piston trajectories in the FPE is presented. Secondly, a physics-based model is constructed using the first law of thermodynamics and convective heat transfer process. Afterwards, a reduced *n*-heptane mechanism [44] is employed to reproduce the combustion process and emissions production. Finally, the modeling tools used to integrate the above subsystems into a completed model and simulate the engine performance are introduced.

2.1. Variable piston trajectories

Due to the elimination of the mechanical crankshaft, the piston movement in the FPE completely relies on the combination of all the forces acting on the piston, including the in-cylinder gas force and the variable loading force. As a result, arbitrary piston

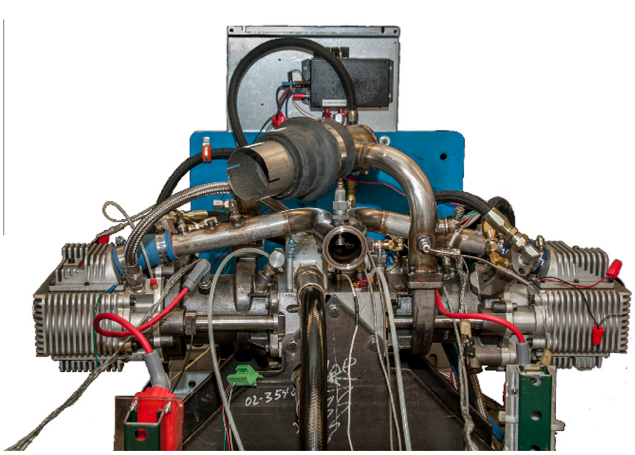

Fig. 1. Picture of the Free Piston Engine at University of Minnesota.

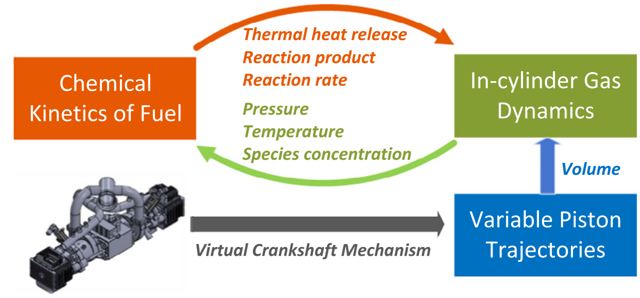

Fig. 2. Interaction between chemical kinetics and gas dynamics.