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An evaluation of a 2/4-stroke switchable secondary expansion internal combustion engine

Yong Lu [a], Pucheng Pei [a,*], Yongfeng Liu [b]

[a] State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, China
[b] School of Mechanical-electronic and Automobile Engineering, Beijing University of Civil Engineering and Architecture, Beijing 100044, China

HIGHLIGHTS

- A 2/4-stroke switchable secondary expansion IC engine concept is proposed in this article.
- The engine can switch its working mode just by varying the valve timing of expansion cylinders.
- The engine works on 2-stroke secondary expansion mode in high load condition and 4-stroke working mode in low load condition.
- This innovative engine saves fuel up to 10%–18% in all frequently-used working conditions of a general vehicle IC engine.

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ABSTRACT

To develop an internal combustion (IC) engine with high energy conversion efficiency, simple structure, and high reliability, a 2/4-stroke switchable secondary expansion IC engine concept is proposed in this paper. The secondary expansion means the burned gas, after working in a traditional 4-stroke combustion cylinder, is transferred into another cylinder to expand again. The 2/4-stroke switchable secondary expansion IC engine is a 4-cylinder engine with two combustion cylinders and two expansion cylinders. The expansion cylinder could switch its working mode between 2-stroke and 4-stroke to perform different secondary expansion modes just by varying the valve timing. The 2-stroke secondary expansion mode has great advantages in high load condition on both fuel efficiency and power output, but it is not suitable in low load condition, so the 4-stroke secondary expansion is applied to maintain the high energy conversion efficiency in the low load condition. A traditional 4-cylinder gasoline IC engine was transformed into a secondary expansion IC engine, however, without the valve time switching device, its expansion cylinder could only work on the 4-stroke working mode. A GT-Power simulation model was established as the supplement of the experiment to evaluate the 2/4-stroke switchable secondary expansion IC engine. The experiment results showed that the fuel consumption of the engine working on the 4-stroke secondary expansion mode was lower than that of the original engine. According to the simulation results, compared with the original engine, the fuel saving rate map of the 2/4-stroke switchable secondary expansion IC engine was made by combining the high fuel saving rate conditions of the 2-stroke and 4-stroke working modes. This innovative engine could save fuel up to 10%–18% in all frequently-used working conditions of a general vehicle IC engine.

1. Introduction

According to the report of BP world energy review, the total proved oil reserve of the world was 235.8 million tonnes at the end of 2012. In addition, the length of time for oil remaining to produce was only 52.9 years based on the current oil production rate [1]. Thus, the energy crisis is becoming serious. The vehicle internal combustion (IC) engine is one of the main oil consumption products, and the electric powertrains as the substitute products of IC engine are still facing many technological challenges in relation to their major components [2], therefore it is still necessary to develop and optimize IC engine working process for continuously improving the total energy conversion efficiency to ease the oil crisis.

* Corresponding author. Room 401, Automotive Building, Tsinghua University, Beijing 100084, China. Tel.: +86 18611075515.
E-mail addresses: luy05@mails.tsinghua.eud.cn, luyongcar53@gmail.com (Y. Lu).

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For the potential of the substantial amount of energy that can be recovered from the exhaust waste heat, the exhaust energy recovery in IC engine has attracted many researchers' interests. Studies have shown that an increase of 20% of fuel efficiency can be easily achieved by converting about 10% of the waste heat into electricity [3]. For the high energy conversion efficiency [4–6], the heat recovery system based on the organic Rankine cycles (ORC) is a hot research area in recent years [7]. However, the ORC system cannot avoid the complex mechanical parts, such as pump, evaporator, condenser, and expander, which sometimes makes the size of the recovery device even larger than that of the IC engine [6]. The thermoelectric generator (TEG), for its silent operation, high reliability, and no moving and complex mechanical parts [8], is supposed to be a promising technology to recover waste heat from IC engine, but the low thermal efficiency, normally smaller than 4% [9], is a big challenge for TEG to be applied in the automotive industry. Therefore, there is barely an exhaust energy recovery technology in IC engine with simple structure, high reliability, and high energy conversion efficiency.

Secondary expansion IC engine is another technology of exhaust energy recovery. The burned gas, after working in one combustion cylinder, is transferred into another cylinder to expand again to recover the exhaust energy. By varying the volumes of the combustion and expansion cylinders, the Miller cycle [10], having higher expansion ratio than compression ratio, can be easily realized to increase the fuel efficiency. Ilmor proposed a 3-cylinder 5-stroke secondary expansion engine, whose two traditional 4-stroke cylinders take turns to exhaust their burned gas into a 2-stroke expansion cylinder [11]. The volume of the expansion cylinder is larger than that of the two power cylinders, so the burned gas could be fully expanded to realize the Miller cycle, which could improve the fuel efficiency by 5%–20% [12]. GM also proposed a 3-cylinder secondary expansion engine, which divided the working cycle into three 2-stroke cylinders performing compression, power, and secondary expansion separately [13]. The volume of the secondary expansion cylinder is the largest one to carry out the Miller cycle.

The expansion cylinders of both engines mentioned above work on the 2-stroke operation, but such expansion cylinder may waste energy in low load condition, because the exhaust pressure of low load condition is so low that it cannot make the expansion cylinder perform a positive work, especially for the gasoline engine. To solve this problem, a 4-stroke secondary expansion mode is proposed in this paper, which has an advantage on fuel consumption in the low load condition. The 2/4-stroke switchable expansion IC engine is an engine whose expansion cylinder could switch its operation between 2-stroke and 4-stroke to achieve high fuel efficiency in both high and low load conditions. With the development of camless valve-train system, such as electro-mechanical valve [14–16] and electro-hydraulic valve [17–20], the valve time can be controlled flexibly, so the 2/4-stroke switchable engine has already been proposed in previous work. Ricardo proposed a 2/4 SIGHT engine concept [21,22], and Y. Zhang also developed a 2/4-stroke switchable GDI engine [23].

In this paper, a 2/4-stroke switchable secondary expansion gasoline IC engine with two combustion cylinders and two expansion cylinders is proposed. The combustion cylinders work on the traditional 4-stroke working cycle, and the expansion cylinders work without combustion, whose operation could be switched between 2-stroke and 4-stroke just by varying the valve timing to perform different secondary expansion modes. For the 2/4-stroke switching has already been realized in the previous studies [21–23], this paper will not discuss the stroke switching method.

2. Principle

2.1. The 2-stroke secondary expansion mode

The 2-stroke secondary expansion mode means that the burned gas, exhausted from the combustion cylinder, is transferred into a 2-stroke secondary expansion cylinder to expand again. The combustion cylinder works on the traditional 4-stroke working cycle, while the expansion cylinder only concludes two strokes, which are intake and exhaust. To solve the problem of the stroke number difference, one expansion cylinder needs to cooperate with two combustion cylinders to form a whole working cycle, as shown in Fig. 1. The exhaust valves of the combustion cylinders and the intake valve of the expansion cylinder are connected by a chamber. The exhaust strokes of the two combustion cylinders are separated by 360°crank angle (CA), and the expansion cylinder breathes once within every 360°CA, so the burned gas of the combustion cylinders could take turns to be exhausted into the expansion cylinders.

2.2. The 4-stroke secondary expansion mode

For the 4-stroke secondary expansion mode, the situation is simpler compared with the 2-stroke working mode mentioned above. The burned gas, after working in a traditional 4-stroke combustion cylinder, is transferred into an expansion cylinder, in which the burned gas goes through four strokes without combustion, namely "intake-compress–expansion-exhaust". Because the combustion cylinder and expansion cylinder both include four strokes, one combustion cylinder and one expansion cylinder could form a whole working cycle, as shown in Fig. 2. The exhaust valve of the combustion cylinder is connected with the intake valve of the expansion cylinder by a connecting pipe directly. When the combustion cylinder is in the exhaust stroke, the expansion cylinder is right in the intake stroke, so the burned gas can be exhaust into the expansion cylinder smoothly.

2.3. The 4-cylinder 2/4-stroke switchable secondary expansion IC engine

As previously discussed, there are at least two cylinders to form a working unit for the 4-stroke secondary expansion IC engine, but the 2-stroke secondary expansion IC engine needs at least three cylinders to form a whole working unit. To apply these two secondary expansion modes on one engine, a 4-cylinder engine working process is proposed as shown in Fig. 3 to solve the problem of cylinder number difference. There are two combustion cylinders and two expansion cylinders for the 2/4-stroke switchable secondary expansion engine. Both combustion cylinders work on the traditional 4-stroke cycle, and both expansion cylinders can switch its operation between 2-stroke and 4-stroke by just varying the valve timing. The exhaust valves of both combustion cylinders and the intake valves of both expansion cylinders are connected by a chamber to regulate the pressure during the burned gas transferring process.

The exhaust strokes of the combustion cylinders are separated by 360°CA. If the expansion cylinders work as the 2-stroke working mode, the valves of these two cylinders open and close simultaneously. So the burned gas can be exhausted into these two expansion cylinders at the same time, as shown in Fig. 3(a) and Fig. 4(a). In this way, two expansion cylinders work as one cylinder to realize the 2-stroke secondary expansion mode. If the expansion cylinders work on the 4-stroke working mode, the intake strokes would be also separated by 360°CA. When the cylinder #1 exhausts, cylinder #2 is right on the intake stroke, and when the cylinder #4 exhausts, cylinder #3 is right on the intake stroke, as