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A new six stroke single cylinder diesel engine referring Rankine cycle☆

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ABSTRACT

Six stroke engine presented by Conklin and Szybist is an effective way to recover energy of exhaust gas by adding a partial exhaust stroke and steam expansion stroke. Characteristics of the engine are analyzed and its disadvantages are pointed out. A new six stroke diesel engine is presented here. It refers rankine cycle inside cylinder. Total exhaust gas is recompressed and at a relatively low back pressure in the fourth stroke water is injected to which maintains liquid phase until the piston moves to the TDC. At c′ 720 °CA (crank angle) the water becomes saturated. An ideal thermodynamics model of exhaust gas compression, water injection and expansion is constructed to investigate this modification. Properties at characteristic points are calculated to determine the increased indicated work. Results show that the work increases with the advance of water injection timing and the quality of water. The cycle is more efficient and the new engine has potential for saving energy. Moreover, it is forecasted that HC and PM emissions may reform with steam in reality and H_2 is produced which will react with NO_X.

1. Introduction

Nowadays, energy crisis and environmental pollution have become two primary problems which are concerned by the countries all over the world [1]. Non-renewable fossil fuels are still in the predominant position in energy consumption such as oil, coal and natural gas. With the social development and progress, hazards of air pollution and global warming derived from fossil fuels have been gradually recognized. Oil, widely used on engines, is the most indispensable energy in transport sector. In recent years the scientific and public awareness on energy saving and emission reduction issues has brought in great interests to advanced technologies particularly in highly efficient internal combustion engines.

Traditional Otto or Diesel cycles include four sequential thermodynamic processes called strokes: intake, compression, combustion or expansion, and exhaust. Efficiency of the four stroke engines can hardly been improved due to the technological limits. In internal combustion engines a huge amount of energy lost through the exhaust gas in the form of heat. Conklin and Szybist [2] investigated the percentage of fuel energy under FTP-75 cycle. The energy converted to useful work is 10.4%. A much larger portion of fuel energy, 27.7%, exits the vehicle in the form of thermal energy in the exhaust, while the remaining 61.9% of the energy balance consists of energy losses to friction, coolant, and other. Utilization of thermal energy in the exhaust is an effective way to improve efficiency and promote technological progress.

Exhaust turbo-charging, which uses IC engine exhaust gas energy to drive the compressor through exhaust turbocharger, is a kind of means for exhaust gas energy recovery. Compared with mechanical supercharging engine, exhaust turbo-charging engine has more advantages, e.g., higher thermal efficiency, for the compressor power comes from exhaust gas energy rather than IC engine effective work [3]. However, compared with energy lost, recovery proportion is relatively low.

Thermoelectric generator is another technology for directly converting thermal energy of exhaust gas into electrical energy [4]. It has no moving parts, is compact, quiet, highly reliable and environmentally friendly [5]. Much attention has been paid on this noticeable technology [4,5]. However, the quantity of heat recycled is quite limited, generally less than 5%. This is somewhat limited by thermoelectric materials [5].

☆ Research activities: combustion and emission of engine; renewable and alternative fuels of road transport.

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The high temperature of exhaust gases has also led the study of bottoming power cycles as an efficient way to reuse the energy, as Tian et al. [6] that used the exhaust gases from a diesel ICE to produce electricity through an organic Rankine cycle (ORC). Organic Rankine cycle (ORC) is an effective one because of its flexibility, economy and good thermal performance [7]. Gequn Shu et al. studied alkanes as working fluids for high-temperature exhaust heat recovery of diesel engine using organic Rankine cycle [8]. Hui Xie and Can Yang obtained dynamic behavior of Rankine cycle system for waste heat recovery of heavy duty diesel engines under driving cycle [9]. Sipeng Zhu et al. analyzed energy and exergy characteristics of a bottoming Rankine cycle for engine exhaust heat recovery [10]. Alberto Boretti recovered the exhaust and coolant heat with R245fa organic Rankine cycles in a hybrid passenger car with a naturally aspirated gasoline engine [11]. Guopeng Yu et al. studied simulation and thermodynamic analysis of a bottoming ORC of diesel engine [12]. Based on experimental results and theoretical calculation, Kai Yang et al. discussed the effects of eight kinds of zeotropic mixtures on the performance of ORC system for exhaust energy recovery under various operating conditions [13].

Therefore, to effectively recycle the exhaust energy, a new six stroke single cylinder diesel engine with reference to Rankine cycle is presented. Working principle, ideal cycle and efficiency potential are studied in this paper.

2. Analysis for present six stroke engines

Some patents utilize a complete exhaust stroke during 540–720 °CA (crank angle), and water is injected on the combustion chamber surfaces [14,15]. However, the primary sources of heat to vaporize the water in these engine cycles are the combustion chamber surfaces rather than the exhaust gases. To recover the exhaust energy, Conklin and Szybist put forward a working principle of six stroke gasoline engine based on partial exhaust and recompression and its ideal in-cylinder pressure is shown in Fig. 1 [2]. The operation process includes intake (0–180 °CA), compression (180–360 °CA), combustion and expansion (360–540 °CA), partial exhaust and recompression (540–720 °CA), steam expansion (720–900 °CA) and exhaust (900–1080 °CA). The first three strokes are similar with conventional engines during 0–540 °CA. Then during 540–720 °CA the exhaust gas is partially discharged

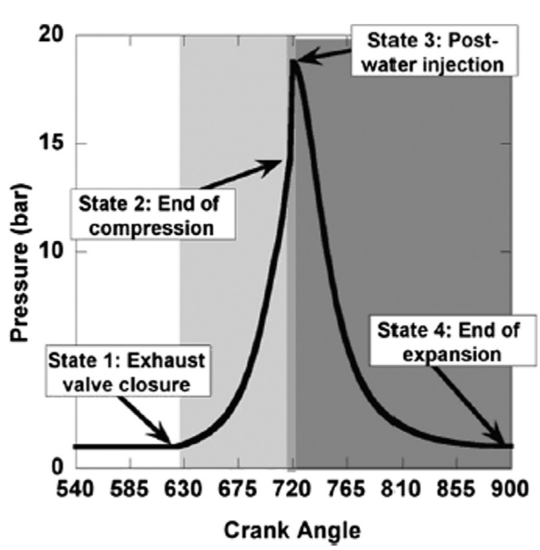

Fig. 1. Ideal in-cylinder pressure of present six stroke engine.

and the rest is recompressed when exhaust valve is closed. The following is steam expansion stroke from 720 to 900 °CA, during which water is injected to absorb heat from the exhaust gas directly. As a result, mixture of rest gas and steam is discharged in exhaust stroke from 900 to 1080 °CA. Conklin and Szybist also made initial conditions, assumptions and constraints to calculate state properties, that 1) water injection duration, water vaporization, and mixing of water steam and air are instantaneous at 720 °CA (top dead center), shown in Figs. 1 and 2) no heat transfer to cylinder walls; 3) gas is composed of complete stoichiometric products of iso-octane; 4) pressure and temperature at 900 °CA respectively are no less than 1 bar and the dew point; 5) water injection temperature is 100 °C.

Theoretically, the above design can improve the engine efficiency. However, several problems exist as following: 1) requirement for water temperature is strict, so that the water can vaporize as soon as possible. In the above research, the water injection temperature was chosen to be 100 °C because the water can be heated by installing a liquid-to-liquid heat exchanger in the engine coolant circuit; 2) certain proportion of energy lost in process of partial exhaust; 3) water injection at 720 °CA means relatively high back pressure, 15 bar more or less for gasoline engines. Consequently diesel engines are not suitable to be adapted through this method, because high compression ratios will contribute to considerably higher back pressure, which correspondingly increases the water injection pressure; 4) in reality water injection starts at 720 °CA and lasts a period in the fifth stroke. Aiming at solving these problems, this paper makes an entirely new design for six stroke diesel engine with steam stroke based on inside Rankine cycle.

3. A new six stroke diesel engine

3.1. Operation principle

During 0–540 °CA, intake, compression and combustion are still the same with traditional engines. In the fourth stroke (540–720 °CA), partial exhaust is cancelled which means that no exhaust gas runs out of cylinder and the whole exhaust gas is directly recompressed. At certain crank angle corresponding to low pressure, indicated as “A1”, about 10 bars, water is injected. On the one hand, the exhaust gas is compressed and the pressure increase, on the other hand, the thermal energy of gas is absorbed by water and the temperature reduces which will decrease the pressure of exhaust gas in the cylinder. As a result, isobaric volume reduction process of exhaust gas is expected after A1. Before 720 °CA, water maintains unsaturated state and is isobarically heated from A1 to 720 °CA. At 720 °CA the water becomes saturated. In the fifth stroke it turns into steam in its phase transition and then the steam blends with exhaust gas forming mixture.

3.2. Features of the new engine

Compared with six stroke engine designed by Conklin and Szybist, this engine solve the above problems, 1) there is no special requirement for water temperature; 2) no exhaust gas discharges and all the energy can be used for recovery which may improve the engine efficiency more obviously; 3) water injection is in the fourth stroke and accordingly the injection timing is adjustable to obtain a suitable and low back pressure which is preferable for diesel engines.

Beside these, this kind of six stroke engine has other two significant advantages. Firstly mechanical design of valve train is simple. As for partial exhaust (Conklin and Szybist), the valve must be redesigned. For example, ZH1105W is chosen for adapted to six