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Technical feasibility study of scroll-type rotary gasoline engine: A compact and efficient small-scale Humphrey cycle engine☆

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HIGHLIGHTS

- A novel scroll-type rotary engine using Humphrey cycle was proposed and studied.
- Evaluation of energy and exergy efficiency were conducted.
- Performance and fuel consumption of a small scale system were investigated.

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ABSTRACT

This paper reports the study of a conceptual gasoline Internal Combustion Engine (ICE) using scroll type rotary device rather than conventional piston as the main engine component. The proposed innovation engine adopts Humphrey Cycle to maximise the power performance of ICE. A performance comparison of the Humphrey Cycle, Otto cycle and Brayton cycle has been conducted and studied. The effects of using different designed compression ratio under variable expansion ratio have been investigated, which identify the optimal operational conditions under different compression/expansion ratio of the engine. Optimal performance can be achieved under the compression/expansion ratio at 2:1/4.8:1, 4:1/7.4:1, 6:1/9.9:1, 8:1/11.8:1 and 10:1/14.1:1, when the energy efficiency of the system can be respectively achieved at 42.22%, 49.13%, 52.82%, 55.08% and 56.96%. A case study has been conducted to study the performance of small-scale scroll-type rotary ICE. Results pointed out under designed compression ratio from 2:1 to 10:1 the effective power from the system ranges from 3.343 to 19.01 kW. The analysis of fuel efficiency pointed out the Brake Specific Fuel Efficiency (BSFC) of the scroll-type rotary engine burning gasoline ranges from 130.5 to 148.5 g/kWh, which improve the fuel efficiency by 28.02% and 65.89% compared to that of the conventional gasoline engine.

1. Introduction

1.1. Demand for high efficient combustion cycles

For over 100 years the conventional Internal Combustion Engine (ICE) has only 33% efficient and it is extremely difficult to improve the overall energy efficiency of the ICE because all aspects of ICE are almost operated under the best conditions [1]. The two most well-known ICE technologies are gasoline engine and diesel engine, which respectively adopts Otto cycle and Diesel cycle. The increasing concerns on the environmental problems caused by burning fossil fuels promote the technology development of more efficient, more compact and more cost-effective ICE, which can potentially improve the overall energy efficiency, reduce the emissions compared with the conventional engine and generate more effective engine shaft power by burning fossil fuels.

1.1.1. Constant volume combustion cycles-Otto and Miller

The compression stroke of the Otto cycle equals to the expansion stroke, which means the in-cylinder pressure at the end of the expansion is much higher than the atmospheric pressure. There is still considerable energy to make useful work at the end of the expansion process. The study of Miller cycle was proposed by Miller [2] with the purpose of improving engine efficiency. The Miller cycle adopts over-expansion, which has an expansion ratio higher than its compression ratio [3]. A real Miller cycle generally left the intake valve open longer than it would be in an Otto cycle engine [4]. Wang et al. [5] concluded

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Nomenclature

$\dot{E}$	exergy flow per unit time (kW)
h	specific enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
M	molecular mass (g/mol)
N	rotational speed (rpm)
P	pressure (kPa)
$\dot{Q}$	rate of heat flow (kW)
s	specific entropy (kJ/kg·K)
T	temperature (°C)
v	specific volume (m^3/kg)
$\dot{W}$	power (kW)

Greek letters

$\eta_{I\,scroll\,ICE}$	first law efficiency
$\eta_{II\,scroll\,ICE}$	second law efficiency
θ	crank angle between the fixed scroll and orbiting scroll
γ_{com}	built-in compression volume ratio of the scroll-type engine
γ_{exp}	built-in expansion volume ratio of the scroll-type engine
x	mass fraction

Subscripts

com	compression process
combustion	combustion process
d	geometric designed point
exp	expansion process
ise	isentropic
iso	isochoric

Acronyms

BSFC	brake specific fuel consumption (g/kWh)
ICE	Internal Combustion Engine

the application of Miller cycle on petrol engine can reduce the engine exhaust gas emissions and significant NO_x reduction could be achieved with a penalty in engine fuel consumption. Mikalson et al. [3] investigated the potential of using Miller cycle natural gas engine as a domestic combined heat and power system. They concluded the Miller cycle engine has a potential for improved fuel efficiency but at the cost of a reduced power to weight ratio [3].

1.1.2. Constant pressure combustion cycles-Diesel and Brayton

The main difference between Diesel and Otto cycles is the combustion process, where Diesel cycle adopts constant pressure combustion and Otto cycle utilises constant volume combustion [6]. Under the same designed compression ratio, the efficiency of Otto cycle is higher than that of Diesel cycle. And high compression ratio is always desirable, because the higher of the engine compression ratio, the higher the overall efficiency of the ICE can be achieved. However, the typical compression ratio of gasoline engine ranges from 7:1 to 10:1, which is much lower than that of the typical diesel engine. The reason is that in the Otto cycle engine an air-fuel mixture is compressed and detonation becomes a serious problem if too high a compression ratio is used [6]. Diesel engine does not have this problem because only air is compressed during the compression process. Gas turbine engine adopting Brayton cycle is playing a pivotal role in power generation and transportation technology during the past seventy years [7,8]. Under the same operational conditions, the gas turbine engine using the same combustion process as the diesel engine can perform full expansion process, which can produce much higher power than diesel engine [9–11]. The industrial gas turbine can be particularly efficient if the waste heat from the turbine can be recovered by a heat recovery system to form a combined cycle [12]. The majority use of gas turbine technology is for large-scale application due to the limited manufactures and other technical issues. Small-scale gas turbine systems have many promising advantages over reciprocating engines (Otto or Diesel engines), such as higher power-to-weight ratio, relatively low emissions and very compact with only one moving part [13].

1.1.3. Full expansion cycle- Atkinson (piston) or Humphrey (gas turbine)

Fig. 1 shows the P-V diagram of the full expansion cycle. Under the same compression ratio, the work for full expansion cycle can be higher than that of Brayton and Otto cycles as illustrated in Fig. 1. The application of full expansion cycle was first proposed in the piston-type engine to further improve the engine efficiency and potentially reduce the emissions. However, the reality of using full expansion cycle by the piston-type engine cannot be achieved. Similar as the concept of Miller cycle, which recovers the energy from the in-cylinder high pressure of Otto cycle, the full expansion cycle generally means all of the in-cylinder pressure is recovered through full expansion to the atmospheric pressure. The British engineer James Atkinson invented a piston-type engine with the potential to achieve full expansion [14]. The Atkinson cycle was realized with a complex linkage mechanism through a long expansion stroke and short intake and compression stroke [4]. The piston-type Atkinson cycle has the advantage of high thermal efficiency with the penalty of reduced power density and increased complexity [4]. However, the realistic Atkinson cycle cannot operate as full expansion process because the low in-cylinder pressure at the end of expansion stroke will lead to large exhaust pumping loss [15,16]. Therefore the thermodynamic cycle of the real Atkinson engine is closer to Miller cycle engine rather than the original proposed full expansion cycle engine.

The concept of full expansion cycle also exists in gas turbine engines The definition of Humphrey cycle engine is mainly used for aviation application [17,18]. The Humphrey cycle is a thermodynamic cycle modified from Brayton cycle and similar to pulse detonation engine [19]. The only difference between the Humphrey and Brayton cycle is the heat supply (combustion) process, in which Humphrey cycle adopts the heat through constant volume combustion rather than constant pressure combustion in Brayton cycle. Heiser and Pratt reported the

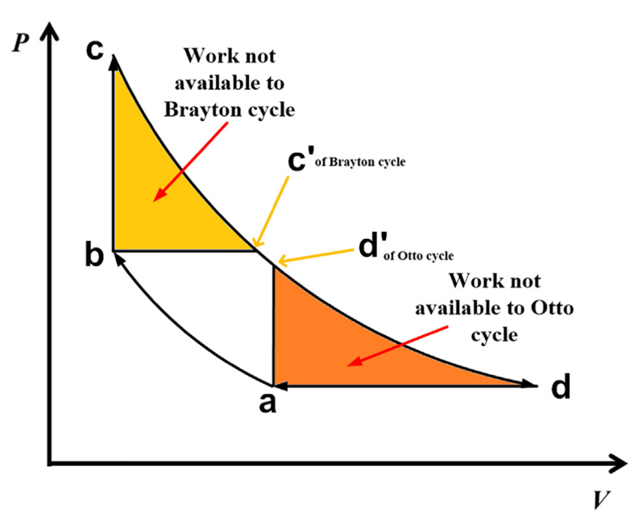

Fig. 1. P-V diagram of (1) a-b-c-d Humphrey cycle; (2) a-b-c′-d Brayton cycle; (3) a-b-c-d′ Otto cycle.