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Research and application of over-expansion cycle (Atkinson and Miller) engines – A review

Jinxing Zhao

School of Mechanical Engineering, University of Shanghai for Science and Technology, Shanghai, China

HIGHLIGHTS

- A review of study and application of over-expansion cycle engine is provided.
- Mechanical realizations and real applications of over-expansion cycle are studied.
- Some novel strategies for applying "Atkinson cycle effect" are provided.
- Challenges and prospective solutions for using Atkinson cycle engine are discussed.
- Primary problems and suggestions for future R&D in potential fields are given.

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ABSTRACT

Vehicle electrification has to be addressed to reduce dependence on fossil fuels and meet future emission regulations. Pure electric vehicles still have many limitations, but hybrid vehicles are the optimum transference scheme. An over-expansion cycle (Atkinson or Miller) engine is the most suitable for hybrid vehicles. Compared with a conventional Otto cycle engine, an over-expansion cycle engine can realize a larger expansion ratio and thus, a higher thermal efficiency while maintaining a normal effective compression ratio to avoid the knock.

Basics for the Atkinson and Miller cycles are introduced first. An in-depth survey on mechanical realizations for the over-expansion cycle is conducted. Challenges and general recommendations for real applications of these mechanical realizations are presented. After a comprehensive review of the advantages and applications of the "Atkinson cycle effect" in load control, reducing NOx formation and suppressing the knock, primary problems are discussed and some novel strategies are provided. Prospective technical solutions that handle the reduced effective compression ratio and power density for over-expansion cycle engines are studied and discussed. Finally, in the potential application fields of range-extended electric vehicles and cogeneration plants, a significant problem is presented; the efficiency optimum working points for the engine and generator do not match. A multi-disciplinary design and optimization methodology is provided to resolve the problem.

The main objective of this paper is to explore the critical problems, challenges and prospective solutions that push forward broader applications for over-expansion cycle engines. This paper can be used as a critical review of the current state-of-the-art research for over-expansion cycle engines and also as guidance towards future research directions in this domain.

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E-mail address: jinxing831018@163.com

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Nomenclature

ICE	internal combustion engine	GHG	greenhouse gases
TWC	three-way catalyst converter	CR	compression ratio
EGR	exhaust gas recirculation	HCCI	homogeneous charge compression ignition
PM	particulate matters	NO	nitrogen oxide
EV	electric vehicle	BEV	battery electric vehicle
REEV	range extended electric vehicle	PHEV	plug-in hybrid electric vehicle
GCR	geometrical compression ratio	ECR	effective compression ratio
WOT	widely open throttle	LIVC	late intake valve closure
VVT	variable valve timing	EIVC	early intake valve closure
BDC	bottom dead centre	IMEP	indicated mean effective pressure
VCR	variable compression ratio	MBT	minimum spark angle for best torque
PMEP	pumping mean effective pressure	T_{soi}	in-cylinder air temperature at the start of fuel injection
IVC	intake valve closure	CR_{eff}	effective compression ratio
k	specific heat ratio	CA	crank angle
T_{IVC}	in-cylinder temperature at the IVC timing	BSFC	brake specific fuel consumption
OA	Otto-Atkinson	TDC	top dead centre
GDI	gasoline direct injection	SOC	state of charge
ACE	Atkinson cycle engine	MCE	Miller cycle engine
PFI	port fuel injection	ETC	electric throttling control
AFR	air-to-fuel ratio	CI	compression ignition

1. Introduction

In 1882, an English engineer named James Atkinson invented the first ACE [1]. The original ACE, with a long expansion stroke and short intake and compression strokes, was realized with a complex linkage mechanism. High thermal efficiency of the original ACE was achieved at the expense of reduced power density and increased complexity. Minimal attention from the automotive industry was focused on the ACE for several years. In recent years, ACEs realized via VVT technology have been widely applied in hybrid vehicles. Increasing studies involving ACEs have been published.

1.1. Background and significance

A shortage of energy sources and climate warming have attracted global attention and become a severe problem that impacts the sustainable development of humans [2]. GHGs are a main factor leading to global climate warming [3,4]. Reducing the GHGs and harmful emissions (NOx, HC, etc.) from the transport sector, especially from vehicles, is a key factor that eliminates the climate change risk. In Europe, approximately 22% of CO_2 emissions are caused by transportation systems [5] while in China, almost 85% of transportation system emissions are caused by vehicles [6]. Vehicle emissions are also the main contributor leading to haze and photochemical smog.

Fossil fuels are the main energy source, but these have finite reserves. The U.S. Energy administration estimates that approximately 2/3 of the total petroleum demand is from the transportation sector [3,7]. Assuming daily production remains steady at 63.5 million barrels, the total global petroleum reserves will be consumed in ~50 years [7]. It is particularly crucial to decrease the degree of vehicle dependence on fossil fuels. Developing new energy resources and significantly enhancing the energy efficiency of the conventional ICE are both effective paths and are also necessary to control GHGs and harmful emissions.