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The effects of the engine design and operation parameters on the performance of an Atkinson engine considering heat-transfer, friction, combustion efficiency and variable specific-heat

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ABSTRACT

Atkinson cycle engines have become particularly popular because of high energy efficiency. A novel model considering heat-transfer, friction, and variable specific-heat has been established for an Atkinson cycle engine based on the finite-time thermodynamics. Different from the ones in previous investigations, the heat-transfer and friction losses are computed considering the effects of the cycle conditions, and the design and operation parameters. In this way, the study can have practical physical meanings and is closer to real conditions. The effects of mean piston speed, friction coefficient, cylinder bore, stroke length, stroke-to-bore ratio, equivalence ratio, and compression ratio on the energy losses and cycle performance have been investigated. The results show that there are the optimum values of compression and equivalence ratios making the cycle performance the best; the energy losses from friction, heat-transfer and exhaust process monotonously increase or decrease with respect to increasing the compression ratio. Increasing the friction loss, cylinder bore and stroke length has negative effects on the cycle performance. Increasing the mean piston speed has positive effect on the power output and the power density but less effect on the energy efficiency. The study results could provide significant guidance for designing a real Atkinson cycle engine and optimizing the performance.

1. Introduction

In 1882, an English engineer named James Atkinson invented the first ACE (Atkinson cycle engine, ACE) [1,2]. 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 Atkinson cycle engine for many years. In recent years, Atkinson cycle engines realized via VVT (Variable valve timing, VVT) technology have been widely applied in hybrid vehicles.

An ICE (Internal combustion engine, ICE) in a hybrid vehicle is so crucial that it considerably determines the vehicle fuel consumption and emissions [3,4]. When the hybrid vehicle such as the Toyota Prius adopts an over-expansion Atkinson cycle SI engine as one of primary power sources, significant reduction in fuel consumption can be achieved [5,6]. In a hybrid vehicle, the ACE can achieve a lower BSFC value than its baseline Otto cycle engine; and the ACE can be controlled to work cross over the low fuel consumption region for reducing the vehicle fuel consumption. When running under a high load or with high speed, if the required power exceeds the engine efficient power or the maximum value, the driven motor can provide the leaving power. The reduced power density for the ACE can be compensated by a driven motor. Therefore, the ACE is the most suitable for hybrid vehicles. Yoshiharu Yamamoto stated that, *"If we hit the 45% efficiency mark, the ICE will long remain a worthy being."* One possible way to increase the efficiency of ICEs is the usage of the Atkinson cycle [7,8].

Many investigations have been published to confirm the thermodynamic merits of Atkinson cycles and study the effects of important engine parameters on the cycle performance. Cycle models describing general characteristics in the real process of ICEs can be established by using the FTT (Finite-time thermodynamics, FTT) [9]. A series of study achievements [10–41] for Atkinson and other thermodynamic cycles have been published since the FTT was used to analyze and optimize the performance of real ICEs [10,11]. In Ref. [9], Ge et al introduced the origin and development of the FTT, and reviewed the applications of the FTT in ICE cycles such as Otto, Miller, Atkinson and so on. Chen et al. [12] investigated the efficiency of an Atkinson engine at MPD (Maximum power density, MPD) basing on the FTT. Ge et al. [13] analyzed the influences of heat-transfer and friction on the cycle

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Nomenclature

FTT	finite time thermodynamics
MP	maximum dimensionless power
MPD	maximum dimensionless power density
MEF	maximum energy efficiency
TDC	top dead center
R	ratio of energy loss (–)
ICE	internal combustion engine
r_c	compression ratio (–)
T	temperature (K)
P_d	power density (kW/L)
C_v	constant volume specific heat (kJ/kg·K)
N	engine rotating speed (r/s)
Q_{LHV}	low heat value of fuel (kJ/kg)
$\dot{Q}$	rate of heat added (kJ/s)
A_{cc}	surface area of combustion chamber (m^2)
p	instantaneous cylinder pressure (bar)
a, b, C	constants (–)

Greek letters

η	effective efficiency (–)

Subscripts

d	displacement
T	total
c	charges
in	input
tr	transfer
r	reference
m	mean
ACE	Atkinson cycle engine
VVT	variable valve timing
BSFC	brake specific fuel consumption
FMEP	friction mean effective pressure
B	cylinder bore (m)
P	effective power (kW)
$\dot{m}_c$	mass rate of intake charges (kg/s)
L	stroke length (m)
V	volume (m^3)
C_p	constant pressure specific heat (kJ/kg·K)
$\bar{S}_P$	mean piston speed (m/s)
R_g	gas constant (kJ/kg·K)
P_f	friction lost power (kW)
h_c	convective heat-transfer coefficient (kJ m^2·K·s)
P	cylinder pressure (bar)
A_{peff}	effective area of piston skirt (m^2)
w	average in-cylinder charge velocity (m/s)
ϕ	equivalence ratio (–)
max	maximum
f	fuel
a	air
out	output
m	motored
com	combustion
w	wall

performance of an air-standard Miller cycle. Moreover, the performance for the lower limits and the upper limits of the Miller cycle, which are the Otto and Atkinson cycle respectively, are also presented. Ge et al. [14] analyzed the performance of an irreversible dual cycle based on a FTT model. Furthermore, the performance for the Diesel and Otto cycles, as the maximum and minimum envelope lines of the Dual cycle, were also demonstrated. Chen et al. [15] investigated the effects of heat-transfer and a friction-like term loss on the performance of an irreversible dual cycle. Lin et al. [16] analyzed the performance of an irreversible air-standard Miller cycle in a four-stroke free piston engine using the FTT.

Zhu et al. [17] proposed turbocharged Dual and Miller cycle models considering all the irreversible losses of a real cycle. Their results prove that the Miller cycle always needs a high efficiency turbocharger and an efficient charge air cooling system to realize the low temperature cycle and guarantee the fuel economy at the same time. Dobrucali [18] performed a thermodynamic analysis and investigated the effects of engine design and running parameters on the cycle performance for an irreversible Otto-Miller cycle by taking into account heat transfer, frictions, time-dependent specific-heats, internal irreversibility resulting from compression and expansion processes. Mousapour et al. [19] discussed the effects of various design parameters on the power output and the first and second-laws efficiencies of a Miller cycle with the consideration of the linear specific-heat, the internal irreversibility, the friction and the heat-transfer losses. In Ref. [20], Ust et al. carried out a comparative performance analysis and optimization for an irreversible Dual-Miller Cycle cogeneration system.

Zhao and Chen conducted the performance analysis and presented the parametric optimum criteria for an Atkinson cycle heat-engine [21], a Miller cycle heat-engine [22] and a Dual cycle including two special conditions of Diesel and Otto cycle heat-engines [23], respectively. Especially, the power output and the efficiency in Refs. [21–23] were derived as function of pressure ratio, and the compression and expansion efficiency that indicate the adiabatic process irreversibility.

Hou [24] compared the performance of an Atkinson and an Otto cycle with heat-transfer consideration. Wang and Hou [42] conducted the performance analysis and comparison based on the MP (Maximum power, MP) and MPD conditions for an Atkinson cycle using classic thermodynamic analysis methodology. Lin and Hou [25–27] analyzed the effects of heat loss, friction and variable specific heats on the performance of an air standard Otto cycle, an Atkinson cycle and a Miller cycle respectively. They characterized the heat loss as a percentage of fuel's energy like that in Ref. [28].

Gonca et al. [29–34] conducted some significant investigations on performance analyses, optimizations and comparisons for some irreversible thermodynamic cycles such as the irreversible Otto-Miller cycle, Diesel-Miller cycle and Dual-Miller cycle [29], and Dual–Atkinson cycle [33]. In these investigations, those irreversible losses in a real cycle were all considered, such as the irreversibility due to irreversible-adiabatic compression and expansion, heat-transfer, friction losses, and incomplete combustion. In Refs. [29–31], the performance analyses, optimizations and comparisons for different kinds of Miller, Diesel and Atkinson cycles were conducted based on the MP output, MPD and MEF (Maximum energy efficiency, MEF) criteria; the engine design and operation parameters at the MP, MPD and MEF conditions were investigated and optimized. The results demonstrate that the best results are obtained for MP, MPD and MEF with Atkinson, Diesel and Miller cycles, respectively. In Ref. [33], Gonca investigated the effects of the engine design and operating parameters on the performance parameters and energy losses of the irreversible Dual–Atkinson cycle. The results demonstrate that the effective power, power density and effective efficiency increase up to a determined value and then start to decrease with increasing mean piston speed, equivalence ratio and compression ratio; and the losses depend on incomplete combustion are constant, while heat-transfer losses increase, exhaust output losses and friction losses decrease with increasing