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Finite-time thermodynamic modeling and analysis of an irreversible Miller cycle working on a four-stroke engine ☆

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ABSTRACT

The performance of an irreversible air standard Miller cycle in a four-stroke free-piston engine is analyzed using finite-time thermodynamic. In the model, the relation between the internal irreversibility described by using the compression and expansion efficiencies, the specific heat of the working substance depending on its temperature, the heat transfer loss as a percentage of fuel's energy and the friction loss computed according to the mean velocity of the piston is considered. Moreover, the influences of the excess air coefficient, initial temperature, compression ratio and another compression ratio corresponding to expansion level on the Miller cycle are analyzed by detailed numerical examples. The results show that the efficiency increases with the decrease of specific heat of working substance. The heat transfer loss and friction loss have negative effects on the performance. Comparison of the Miller and Otto cycles shows that the Miller cycle has a higher efficiency through extra expansion work. The conclusions of this investigation are of importance to provide guidelines for the performance evaluation and improvement of practical Miller engines.

1. Introduction

Concerns about energy saving and emission of pollutants have resulted in modifications in the internal combustion engine's structure. One method to address this issue is via the free-piston engine [1–4]. The free-piston engine is advantageous because it's mechanically simpler and allows for a great deal of freedom in defining a piston motion profile, enabling the use of novel combustion cycle. In the 1940's, Miller proposed a different Otto cycle with an unequal compression and expansion stroke called the Miller cycle [5]. Since the piston is unconstrained in a four-stroke free-piston engine, the Miller cycle is suitable to use in this device.

The Miller cycle has been given attention recently [6–11] and several authors have applied finite-time thermodynamic methods to the analysis of the Miller cycle [12–18]. Sasaki et al. [19] reported an efficient Miller cycle with a high performance capacitor system for hybrid busses. Al-Sarkhi et al. [20] studied the optimal power density characteristics for the Miller cycle without any loss. With consideration of supercharge pressure and intake valve late (or early) closing, Wu et al. [21] performed a performance analysis and optimization of a supercharged Miller cycle Otto engine. Besides, some effort has been paid to analyze the effects of heat transfer loss and friction loss on the performance of real internal combustion engines. Ge et al. derived the performance characteristics of the Miller cycle with heat transfer loss and friction loss [22]. The work mentioned above was done without considering the variable specific heats of the working substance. However, in the real engine cycle, the specific heat is not constant and should be considered in practice cycle analysis. Lin and Hou [23] examined the effects of heat transfer loss characterized by a percentage of fuel's energy, friction and variable specific heats on the performance of an air-standard Miller cycle under the restriction of maximum cycle temperature. Chen et al. [24] and Al-Sarkhi et al. [25] presented theoretical investigations into the Miller cycle engine's performance, studying the influence of the main engine design variables and system irreversibilities.

Otherwise, there are some other articles concerning the finite time thermodynamics [26–37] and they are meaningful to our research. In the present study, we aim at examining these effects on the power output and the thermal efficiency of a four-stroke free-piston engine which works as an air standard Miller cycle. Heat leakage between the working substance and the environment is considered and characterized by a percentage of fuel's energy; friction loss is also taken into account. Moreover, we consider the variable specific heats of working substance and a finite-time thermodynamic model of the Miller engine affected by irreversibilities is established. The main parameters affecting the cycle performance are analyzed and some performance characteristic curves are presented through numerical calculation. The results obtained will lay a foundation for the further investigation of the four-stroke free-piston Miller engine.

2. Cycle model and analysis

A functional schematic of the four-stroke free-piston engine system is shown in Fig. 1. It is clear from this figure that the main parts of the

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Nomenclature

a_p	constant, defined in Eq. (5)
b_V	constant, defined in Eq. (6)
C_p	specific heat at constant pressure
C_V	specific heat at constant volume
f	friction force
H_μ	low heating value of the fuel
k	specific heat ratio, $k = C_p/C_V$
k_1	constant, defined in Eqs. (5) and (6)
L	the total distance the piston travels per cycle
m_a	mass of air per cycle
m_f	mass of fuel per cycle
N	cycles per second
P	net actual power output of the cycle
P_f	lost power due to friction
Q_{fuel}	total energy of the fuel combustion
Q_{leak}	heat leakage per second
Q_{in}	heat input
Q_{out}	heat reject
R	gas constant of working substance
T	temperature
$T_1, T_2, T_{2s}, T_3, T_4, T_{4s}, T_5$	temperatures at state points 1, 2, 2s, 3, 4, 4s, and 5
V	volume
v	piston's mean velocity
x	piston's displacement
x_1	piston's position corresponding to the volume V_1 of the trapped gases
x_2	piston's position corresponding to the volume V_2 of the trapped gases
x_4	piston's position corresponding to the volume V_4 of the trapped gases

Greek symbols

α	heat leak percentage
γ	another compression ratio, $\gamma = V_5/V_1$
γ_c	compression ratio, $\gamma_c = V_1/V_2$
η	efficiency of the cycle
η_c	compression efficiency
η_e	expansion efficiency
λ	excess air coefficient
μ	coefficient of friction

system are a gasoline engine and a linear electric generator. The system combines the single piston with the mover of the linear electric generator into one compact component to directly output electric power. The piston will move freely between its two end points and its motion is exclusively the result of an imbalance of forces acting on it. It is noteworthy that a Miller cycle is more efficient than a conventional four-stroke Otto cycle engine from a lot of articles [6,7]. A general Miller cycle is characterized by low compression ratio and high expansion ratio through advance (or retarding) intake valve's closing time. In order to optimize the system performance, an improved Miller thermodynamic cycle has been proposed in this free-piston engine only by controlling the piston's motion. Then the intake and compression strokes are shorter than the expansion and exhaust strokes through controlling the piston, consequently enhancing the system operating frequency and increasing the power density.

The pressure–volume (p–V) and temperature–entropy (T–S) diagrams of an irreversible four-stroke free-piston Miller engine are shown in Fig. 2: thermodynamic cycle 1–2s–3′–4′–5–1 denotes the ideal reversible Miller cycle without heat leakage, thermodynamic cycle 1–2s–3–4s–5–1 denotes the reversible Miller cycle with heat leakage, while cycle 1–2–3–4–5–1 designates the irreversible Miller cycle with heat leakage. The internal irreversibility comes from the adiabatic compression and expansion processes. Process 1–2s is an isentropic (reversible adiabatic) compression, while process 1–2 is an irreversible adiabatic process that takes into account the internal irreversibility in the real compression process. The heat addition takes place in process 2–3, which is isochoric. The isentropic expansion process, 3–4s, is a reversible adiabatic stroke, while process 3–4 takes into account the irreversibility that occurs in the real expansion process. The cycle is completed by an isochoric 4–5 and an isobaric 5–1 heat rejection processes. In this study, considering heat leakage during the combustion, the temperature at the completion of constant-volume combustion (T_3) depends on the heat input due to combustion and heat leakage through the cylinder wall. The amount of heat leakage is considered to be a percentage of the delivered fuel's energy [38]. If any heat leakage occurs, the maximum cycle temperature T_3 remains less than that of no-heat leakage case.

Assuming that an ideal gas is used as the working substance and the free-piston engine is operated at the rate of N cycles per second, the heat added to and rejected by the working substance per second can be given by

$$Q_{in} = Q_{2\to3} = Nm_a\int_{T_2}^{T_3} C_V dT \tag{1}$$

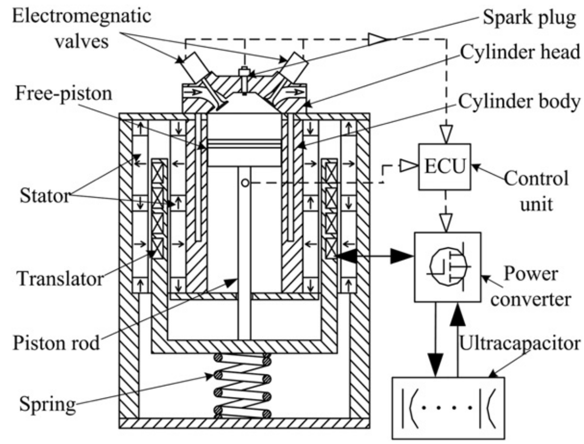

Fig. 1. Functional schematic of the four-stroke free-piston engine system.

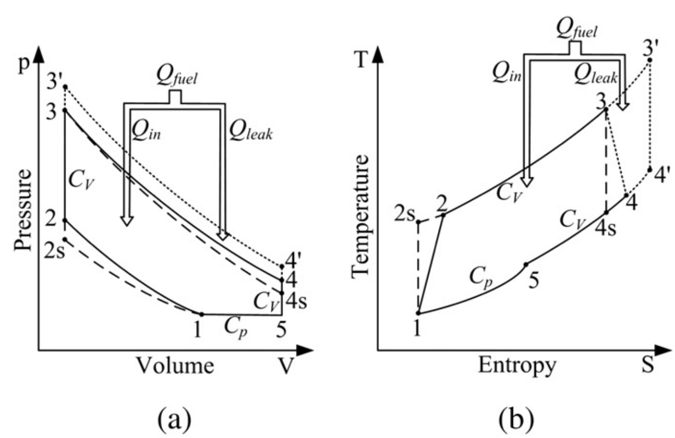

Fig. 2. (a) p–V diagram; (b) T–S diagram for the air standard Miller cycle.