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Engine performance improved by controlling piston motion: Linear phenomenological law system Diesel cycle

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ABSTRACT

A Diesel cycle engine with internal and external irreversibilities of finite combustion rate of the fuel, friction and heat leakage is investigated in this paper. The heat transfer between the working fluid and the environment obeys the linear phenomenological heat transfer law $[q \propto \Delta(T^{-1})]$. Under the conditions of the fixed total cycle time and fuel consumed per cycle, the optimal piston motion trajectories for maximizing the work output per cycle of the cases with unconstrained and constrained piston accelerations are derived on each stroke by applying optimal control theory. The optimal distribution of the total cycle time among the strokes is also obtained. The piston motion along the optimal power stroke with constrained acceleration consists of three segments including the initial motion delay, the middle motion and the final maximum deceleration segments. Numerical example for the case with constrained acceleration is given, and the obtained results are also compared with those obtained with Newtonian heat transfer law. The results show that optimizing the piston motion can improve both the net work output per cycle and the net efficiency of the standard engine by more than 12%, which is mainly due to increase the average temperature of the working fluid during the initial segment of the power stroke.

1. Introduction

The researches on improving heat engine performance by optimizing the piston motion trajectory have always been one of the most active works in finite time thermodynamics [1–11]. It belongs to a class of dynamic optimization problems, which should be solved by applying optimal control theory. There are only analytical solutions for a few optimal control problems, while for most of others, one has to refer to numerical calculation methods. It includes two aspects at least. The first is to study the maximum work that could be extracted from the optimal expansion of an ideal gas inside a cylinder with a moveable piston. Band et al. [12–14], Salamon et al. [15] and Aizenbud et al. [16,17] investigated the problem of maximizing the work obtained from an ideal gas inside a cylinder with a moveable piston. The gas was coupled to an external heat bath at constant temperature, and the heat transfer between the gas and bath obeyed Newtonian heat transfer law $[q \propto \Delta(T)]$. Huleihil and Andresen [18] considered optimal piston motion derived for adiabatic process in the presence of different types of friction, and found that in the externally dissipative mode maximizing power or minimizing frictional loss are equivalent, while in the internally dissipative mode the optimal motions are different for the two optimization objectives. The second is to establish more detailed, realistic models, and improve the engine performance by optimizing the piston motion trajectory on each stroke and the distribution of the total cycle time among each stroke. Mozurkewich and Berry [19,20] investigated an Otto cycle engine with losses of piston friction and heat leakage, in which the heat transfer between the working fluid and the cylinder wall obeys Newtonian heat transfer law. The optimal piston trajectory for maximizing the work output per cycle was derived, and it turned out that optimizing the piston motion can improve engine power and efficiency by more than 10%. Hoffmann et al. [21] and Blaudeck and Hoffmann [22] further considered the effect of the finite combustion rate of the fuel on the performance of engines, and studied the optimal piston motion for a Diesel cycle engine with losses of piston friction and heat leakage, in which the heat transfer between the working fluid and the cylinder wall also obeys Newtonian heat transfer law. It turned out that optimizing the piston motion can improve engine net work output per cycle and net efficiency by 10%. Teh and Edwards [23–25] and Teh et al. [26] investigated the optimal piston motions of adiabatic internal combustion engines for the maximum work output [23], the minimum entropy generation [24,25], and the maximum efficiency [26]. Watowich et al. [27,28] investigated a class of light-driven engines with Newtonian heat transfer law, and determined the

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Nomenclature

a	acceleration (m/s^2)
b	cylinder diameter
C	constant-volume heat capacity per mole (J/(mol K))
F	explosion fraction
f	friction force
H	Hamilton function
h	heating function (J)
L_{ex1}	loss due to dissipating hot exhaust gases into the environment (J)
L_{ex2}	loss due to incomplete combustion (J)
l	length of connecting rod (cm)
N	mole number (mol)
n	rotating speed (r/min)
Q	heat leakage (J)
Q_c	heat of combustion per molar fuel-air mixture charge (J)
R	universal gas constant (J/(mol K))
Rn	combustion function
r	crank radius (cm)
T	temperature of working fluid (K)
T_0	universal environment temperature (K)
T_w	environment temperature outside the cylinder (K)
t	time (ms)
t'	initial time for the maximum deceleration segment
t_1	total time spent on the exhaust or compression stroke (ms)
t_2	total time spent on the intake stroke (ms)
V	cylinder volume (cm^3)
v	piston velocity (m/s)
W	work output (J)
W_f	work loss due to friction (J)
W_τ	work output per cycle (J)
X	piston position (cm)
X_0	initial piston position (cm)
y	intermediate parameter

Greek symbols

α	heat transfer coefficient
η_1	net efficiency
η_2	thermal efficiency
λ_1, λ_2, λ_3	adjoint variable
μ	friction coefficient (N s/m)
θ	rotating angle of crankshaft
τ	cycle period (ms)

Subscripts

b	burning process
c	compression stroke
com	compression
d	motion delay
exp	expansion
f	final state
i	initial state
m	maximum
np	non-power stroke
p	power stroke
R	reversible

optimal piston motion trajectories for maximizing work output and minimizing entropy generation, respectively.

In general, heat transfer is not necessarily Newtonian and also obeys other laws. Newtonian heat transfer law is valid for the common heat conduction and convective heat transfer processes, while the driving force of the heat flux q is the difference of reciprocal temperatures $\Delta(T^{-1})$ in irreversible thermodynamics [29–34], i.e. the heat transfer process always obeys the linear phenomenological heat transfer law $[q \propto \Delta(T^{-1})]$. Heat transfer laws not only have significant influences on the performances of the given thermodynamic process [35–40], but also have influences on the optimal configurations of thermodynamic process for the given optimization objectives [41–47]. Chen et al. [48–50] and Song et al. [51,52] determined the optimal configurations of expansion process of a heated working fluid in the piston cylinder with linear phenomenological $[q \propto \Delta(T^{-1})]$ [48,49,51], generalized radiative $[q \propto \Delta(T^n)]$ [52] and convective–radiative $[q \propto \Delta(T) + \Delta(T^4)]$ [50] heat transfer laws. Chen et al. [53] further investigated the optimal expansion of a heated working fluid for maximum work output with time-dependent heat conductance and generalized radiative heat transfer law. Burzler and Hoffmann [54] and Burzler [55] considered the effect of non-ideal working fluid, and derived the optimal piston motion for maximizing power output during the compression and power strokes of a Diesel engine with the convective–radiative heat transfer law. Xia et al. [56] investigated the optimal piston motion of the Otto cycle engine with the linear phenomenological heat transfer law for the maximum work output. Ge et al. [57] investigated the optimal piston motion of the Otto cycle engine with Newtonian and linear phenomenological heat transfer laws for the minimum entropy generation. Ma et al. [58] further studied the optimal piston motion of the light-driven dissipative engine with the linear phenomenological heat transfer law.

Based on Refs. [19–22,54–56], this paper will further study the four stroke Diesel cycle engine with internal and external irreversibilities of finite combustion rate of the fuel, friction and heat leakage, and consider that the heat transfer between the working fluid and the environment outside the cylinder obeys the linear phenomenological heat transfer law in the linear irreversible thermodynamics [36–39,41–45,48,49,51,56–58]. The optimal piston motion trajectory over the total cycle for the maximum work output will be obtained by applying optimal control theory, and the obtained results will also be compared with those obtained for Newtonian heat transfer law [21,22]. The research on the optimal configurations of the engines from Newtonian [21,22] to the linear phenomenological heat transfer laws enriches the finite time thermodynamic theory. The results presented herein can provide some guidelines for optimal design and operation of real internal combustion engines.

2. Diesel cycle engine model

A four stroke Diesel cycle engine model is studied in this paper. Cycle period, fuel intake per cycle, fuel–air mixture composition, and compression ratio are taken as constant. Besides, according to Refs. [19–22,54,59,60], the finite combustion rate of the fuel, the major losses in real internal combustion engines and the piston motion of the conventional engine are simplified and described, qualitatively and quantitatively, as follows.

2.1. Finite combustion rate [21,22]

In the Diesel engine, fuel is injected towards the end of the compression stroke. Following injection there is commonly a delay before sufficient fuel evaporates and burns to initiate a noticeable rise in temperature and pressure. Part of the injected fuel is burned rapidly and early during the power stroke. The remaining fuel burns relatively slowly as it evaporates and diffuses into oxygen-rich regions where combustion can be sustained. In moderately and heavily loaded engines, this burning continues for most of the