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Effect of specific heat variations on irreversible Otto cycle performance

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ABSTRACT

Considering internal irreversibility loss, friction loss and heat transfer loss, an irreversible Otto cycle model is built up by using finite-time thermodynamics with air standard assumption. Using the various irreversible losses in the cycle to compute the entropy generation rate, the optimal ecological function performance of the cycle is studied when the specific heats of working fluid are nonlinear relation with its temperature. Some important expressions, including ecological function, entropy generation rate, efficiency and power output, are obtained. The cycle ecological function performances with constant specific heats, specific heats changed with linear and nonlinear relations of its temperature are compared. Moreover, the impacts of internal irreversibility loss, friction loss and heat transfer loss on ecological function performance are analyzed. The results show that optimization of the exergy-based ecological function not only represents a compromise between the power output and the rate of entropy generation but also represents a compromise between the power output and the thermal efficiency, the specific heat models have no qualitative effect and only have quantitative effect on the performance characteristics of ecological function versus power output and ecological function versus efficiency, and the ecological function, power output and efficiency decrease with the increase of heat transfer, friction and internal irreversibility losses.

1. Introduction

Otto cycle heat engine is widely used in industry, agriculture, communication and transport, as well as national defense construction. It is the main power source of automobile, tractor, agricultural machinery, engineering machinery, shipping, locomotive, military vehicle, moving and emergency electric station and so on. For the amounts and distributions of Otto cycle heat engine are numerous and extensive, the Otto cycle heat engine has significant influences on energy and environment. From the point of view of saving energy and protecting the environment against pollution, more and more strict requirements have been imposed on the Otto cycle heat engine, such as large power output, little specific fuel consumption, low pollution and even zero emission.

Using thermodynamics to analyze the performance of Otto cycle is not only the base of improving and exploiting new technologies of Otto cycle heat engine but also the main method of perfecting and developing Otto cycle. Using classical thermodynamics to perform the first law analysis for Otto cycle can study the quantitative relation between the efficiency and different losses [1–5]. Using the second law of thermodynamics to analyze performance of Otto cycle can study the work capacity loss due to various irreversible losses during the energy transformation process [5–8]. Using simulation study which is based on the first law and irreversible thermodynamics to analyze performance of Otto cycle can obtain the law of state parameters varied with space-time of cycle process [9,10].

As a new branch of modern thermodynamic theory, finite-time thermodynamics (FTT) has made great progress in recent years [11–19]. FTT can be used to optimize various processes and cycles, such as gas turbine cycle [20], absorption thermodynamic cycles [21], two-heat-reservoir thermodynamic cycle [22], microscopic energy conversion system [23], thermoelectric device [24] and internal combustion engine cycle (ICE) [25] and so on. The research on the optimal performance (OP) of ICE cycles focus on the following five aspects: the influences of optimization objectives on cycle

Abbreviations: AS, air standard; EF, ecological function; EGR, entropy generation rate; FL, friction loss; FTT, finite time thermodynamics; HTL, heat transfer loss; ICE, Internal combustion engine; IIL, internal irreversibility loss; IOC, irreversible Otto cycle; OP, optimal performance; SH, specific heat; WF, working fluid.

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Nomenclature

B	constant of heat transfer $kJ/(K \cdot s)$
C	specific heat $kJ/(kg \cdot K)$
E	ecological function kW
K	coefficient of specific heat varying with temperature $kJ/(kg \cdot K^2)$
L	stroke length m
M	mass flow rate kg/s
n	the number of cycle happened per second rpm
P	power output kW
Q	heat rate kW
R	gas constant $kJ/(kg \cdot K)$
T	Temperature K
Greek symbol	
γ	compression ratio
η	efficiency
η_c	compression efficiency
η_e	expansion efficiency
μ	friction coefficient
σ	entropy generation rate kW/K
Subscripts	
in	heat addition
leak	heat transfer
ot	Otto cycle
out	heat rejection
p	isobaric process
pq	exhaust stroke
q	influence of heat transfer loss
v	isochoric process
μ	influence of friction loss
0	environment
1, 2, 2*S*, 3, 4, 4*S*	state points

OP, the influences of specific heat (SH) models of working fluid (WF) on cycle OP, the influences of loss models on cycle OP, the influences of WF characteristics on cycle OP, and the OPs of universal cycle [25]. According to the different losses existed in the cycle, Otto cycle can be classified as reversible Otto cycle, endoreversible Otto cycle and irreversible Otto cycle. The main losses existed in Otto cycle include heat transfer loss (HTL), friction loss (FL), internal irreversible loss (IIL) and mechanical loss. The cycle with no any loss is a reversible Otto cycle. The cycle with only HTL is an endoreversible Otto cycle, while the cycle with other losses is an irreversible Otto cycle (IOC).

In the early studies, the specific heats (SH) of WF were usually assumed to be constant. But for practical cycle, the property and composition of the WF will change with the happening of combustion reaction. So the SH of WF will also change with the happening of combustion reaction and this change will has great influence on cycle performance. For Otto cycle, many scholars studied the power output [26–35], thermal efficiency [26–35], efficient power [36] and ecological function (EF) [27,37–40] performance characteristics of air standard (AS) Otto cycle models with constant [26–30,36–39] or variable SH (including SH varied with the component [31], varied with linear [32,33,40] and nonlinear [34] relations of temperature) and variable specific heat ratio (specific heat ratio varied with temperature with linear relation [35]) when the WF was conventional and different loss items were considered (including IIL, FL and HTL, and the different loss combinations). The progresses can be seen in the review paper [25] in detail. From above analysis, one can see that the optimal EF performance of an open Otto cycle with SH varied with temperature with nonlinear function and IIL, FL and HTL has not been studied. In this paper, based on the AS IOC model with IIL, FL and HTL established in Ref. [34], computing the entropy generation rate (EGR) by using various irreversible losses in the cycle, the optimal EF performance of the cycle will be studied with SH changed with temperature with nonlinear function, and will be compared with those with constant SH, SH changed with linear relation of temperature.

Ecological criterion for heat engine was first proposed by Angulo-Brown [37] as $E' = P - T_c\sigma$, where P is the power output, T_c is the temperature of the cold reservoir and σ is the entropy generation rate. Yan [41] showed that it might be more reasonable to use $E'' = P - T_0\sigma$ if the cold reservoir temperature T_c is not equal to the environment temperature T_0, because in the definition of E', two different quantities, exergy out P and non-exergy $T_c\sigma$ were compared together. Further, Chen et al. [42] provided a unified ecological optimization objective for all thermodynamic cycles $E = A/\tau - T_0\Delta S/\tau = A/\tau - T_0\sigma$, where A is the exergy output, ΔS is the entropy generation and τ is the cycle period. It means the exergy output minus the exergy loss. For heat engine cycles, the exergy output rate is the power output P, and the ecological function is $E = P - T_0\sigma$. Ecological function not only reflects the best compromise between entropy generation rate and power output, but also reflects an optimal compromise between efficiency and power output. This criterion has a long-range goal in the sense that it is compatible with ecological objectives. It is more reasonable to be chosen as optimization objective than exergy output rate, because it considers both the exergy output rate and the exergy loss rate. It has been applied to the performance optimizations not only for heat engines [27,43–57] but also for refrigeration [42,58–62] and heat pump [42,63–67] cycles.

2. FTT analysis of the Otto cycle

Fig. 1 is the sketch of AS IOC model. Process $1 \rightarrow 2S$ is a reversible adiabatic compression, while process $1 \rightarrow 2$ is an irreversible adiabatic process that takes into account the internal irreversibility in the real compression process. The heat addition is an isochoric process $2 \rightarrow 3$. Process $3 \rightarrow 4S$ is a reversible adiabatic expansion, while $3 \rightarrow 4$ is an irreversible adiabatic process that takes into

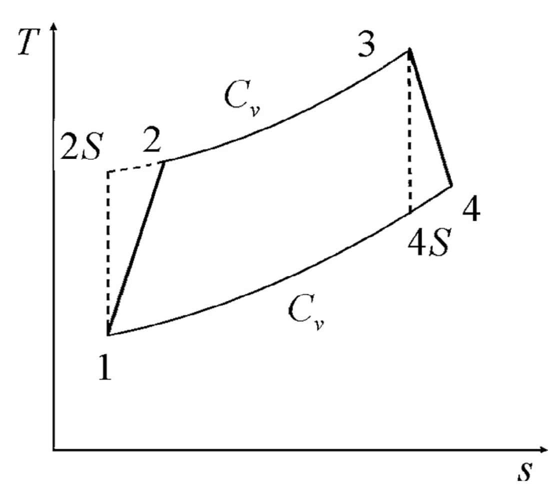

Fig. 1. The *T-s* diagram for an IOC model.