International Journal of Heat and Mass Transfer 124 (2018) 46–57

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Thermodynamic optimization for an air-standard irreversible Dual-Miller cycle with linearly variable specific heat ratio of working fluid

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ARTICLE INFO

Article history:
Received 3 October 2017
Received in revised form 27 January 2018
Accepted 15 March 2018

Keywords:
Finite-time thermodynamics
Dual-Miller cycle
Linearly variable specific heat ratio
Power output
Efficiency
Ecological function

ABSTRACT

This paper establishes an air-standard irreversible Dual-Miller cycle (DMC) model with the specific heat ratio (SHR) of working fluid (WF) linearly varying with its temperature. Because the specific heat (SH) of WF varies with combustion reaction in actual internal combustion engine (ICE), the SHR of WF should be a function of temperature but not a constant. In order to accurately reflect the practical characteristics of DMC engine, performance of DMC with linearly variable SHR, and with heat transfer (HT) loss, friction loss (FL) and other internal irreversible losses (IILs) is analyzed and optimized by applying finite-time thermodynamics. Analytical formulae of the power output (P), efficiency (η), entropy generation rate (EGR) and ecological function (E) are derived. Relationships among P, η, E and compression ratio are obtained via numerical calculations. Effects of the design parameters, cycle temperatures and linearly variable SHR of WF on P, η and E are investigated. Performance differences among the DMC and its simplified cycles, including Otto cycle (OC), Dual cycle (DDC) and Miller cycle (OMC) are compared. Performance characteristics of the DMC with different optimization objective functions (OOFs) are analyzed. The results indicate that the maximum power output (*MP*), maximum efficiency (*MEF*) and maximum ecological function (*ME*) of the DMC are superior to those of OC, DDC and OMC, and optimizing E is the best compromise between optimizing P and optimizing η. The presented results may be helpful to optimize the performance of practical DMC engines.

1. Introduction

Thermodynamic study of internal combustion engine (ICE) cycles can determine theoretical boundaries of the power output (P) and efficiency (η), find out the ways of improving P and η, and compare the performance characteristics of different ICE cycles. Some scholars have applied finite-time thermodynamics (FTT) [1–24] to study the performance of ICE cycles, and a lot of works have been performed, seeing the review article by Ge et al. [25]. The researches involve the performance limits [26–29] and optimal paths [30–40] for various ICE cycles. The common ICE cycles include Otto cycle (OC), Dual cycle (DDC), Miller cycle (OMC), Dual-Miller cycle (DMC), etc. Because P and η represent the dynamic performance and economic performance of ICE, respectively, there are lots of studies on P and η characteristics of ICE cycles.

For performance analysis and optimization of OC, Klein [41] investigated the work output (W) characteristic of an endoreversible OC with heat transfer (HT) loss. Wu and Blank [42] examined the influence of combustion on W for an endoreversible OC. Chen et al. [43] analyzed the effects of HT coefficient and cycle initial temperature on W and η of an endoreversible OC. Angulo-Brown et al. [44] established a friction loss (FL) model, optimized P and η of an irreversible OC. Chen et al. [45] optimized P and η of an irreversible OC with HT loss and FL. Chen et al. [46] defined the internal irreversibility factor of cycle, studied P and η of an irreversible OC with HT loss and internal irreversible losses (IILs). Zhao and Chen [47] optimized P and η of an irreversible OC with HT loss, FL and other IILs. For performance analysis and optimization of DDC, Blank and Wu [48] investigated the effect of combustion on W for an endoreversible DDC. Lin et al. [49] and Hou [50] analyzed the effects of HT loss and cycle initial temperature on W and η of

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.03.049
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Nomenclature

AC	Atkinson cycle
a	constant (K^{-1})
B	constant related to heat transfer (W/K)
CP	constant pressure
C_p	specific heat at constant pressure (J/(mol K))
CV	constant volume
C_v	specific heat at constant volume (J/(mol K))
DAC	Dual-Atkinson cycle
DC	Diesel cycle
DDC	Dual cycle
DMC	Dual-Miller cycle
E	ecological function (W)
EGR	entropy generation rate
FL	friction loss
FTT	finite-time thermodynamics
f_μ	friction force (N)
HAR	heat addition rate
HRR	heat rejection rate
HT	heat transfer
ICE	internal combustion engine
IIL	internal irreversible loss
k	specific heat ratio
k_0	constant
L	stroke length (m)
ME	maximum ecological function
MEF	maximum efficiency
MP	maximum power output
m	mole of working fluid (mol)
n	cycle index per second (s^{-1})
OC	Otto cycle
OMC	Miller cycle
OOF	optimization objective function
P	power output (W)
p	pressure (Pa)
Q	quantity of heat transfer (J)
R	gas constant (J/(mol K))
r_M	Miller cycle ratio
S	entropy generation (J/K)
SH	specific heat
SHR	specific heat ratio
T	temperature (K)
t	time (s)
u	piston speed (m/s)
v	volume (m^3)
W	work (J)
WF	working fluid
X	displacement of piston (m)
x	$x = \varepsilon^{k_0-1}$
y	$y = [\rho/(\varepsilon r_M)]^{k_0-1}$

Greek letters

α	$\alpha = k_0 - aT_1 - 1$
β	$\beta = k_0 - aT_4 - 1$
ε	compression ratio
η	efficiency
η_c	isentropic compression efficiency
η_e	isentropic expansion efficiency
μ	friction coefficient (kg/s)
ρ	cut-off ratio
σ	entropy generation rate (W/K)
τ	cycle temperature ratio $\tau = T_4/T_1$

Subscripts

in	input
leak	leakage
max	maximum value
min	minimum value
opt	optimal value
out	output
pq	effect of working fluid exhausting to environment
q	effect of heat transfer
s	reversible
sum	sum
μ	effect of friction
1, 2, 3, 4, 5, 6	cycle state points

Superscripts

•	rate
–	mean value

an endoreversible DDC. Wang et al. [51] derived the analytical formulae of P and η of an irreversible DDC with FL. Chen et al. [52] and Zheng et al. [53] optimized P and η for an irreversible DDC with HT loss and FL. Ust et al. [54] analyzed the maximum power output (*MP*), maximum effective power and maximum efficiency (*MEF*) of an irreversible DDC with HT loss and IILs. Parlak [55] compared η characteristic between irreversible DDC and DC under *MP* condition. Ge [56] optimized P and η for an irreversible DDC with HT loss, FL and other IILs. For performance analysis and optimization of OMC, Fukuzawa et al. [57] indicated that OMC has the advantages of high efficiency and low emissions. Ebrahimi [58] performed an analysis for an air-standard OMC according to thermodynamic second law. Gonca et al. [59] theoretically and experimentally investigated the emissions parameters and performance characteristics of an OMC. Wu et al. [60] compared W and η characteristics between OMC and OC. Zhao and Chen [61] studied the effects of HT loss and IILs on P and η for an irreversible OMC. Ge et al. [62] optimized P and η of an irreversible OMC with HT loss and FL.

From the above researches, one can know that DDC has an advantage of high P, OMC has an advantage of low NO_x emissions. There is a cycle, called DMC, has the advantages of high P and low NO_x emissions simultaneously, it is because the heat addition processes of DMC are similar to those of DDC, and the heat rejection processes of DMC are similar to those of OMC. Before DMC applying to the heat engine, there should be more complete theory and more mature technology because of its complex structures. Thus, scholars have carried out some studies on it. Gonca et al. [63–65] established an irreversible DMC with HT loss and IILs, investigated P, η, *MP* and *MEF* characteristics, and compared the performance differences among DMC, OMC and DiMC (Diesel-Miller cycle). Wu et al. [66] optimized P and η for an irreversible DMC with HT loss, FL and other IILs. You et al. [67] investigated P and η for a DMC with polytropic processes. Ust et al. [68] optimized total exergy output and exergetic performance coefficient for an irreversible DMC.

η will be low when optimizing P, on the contrary, P will be low when optimizing η. In order to make thermodynamic and economic performances of the heat engines reach ideal values simultaneously, Angulo-Brown [69] firstly proposed the ecological function $E' = P - T_L\sigma$ for heat engine cycle, where T_L is cold-side temperature, σ is entropy generation rate (EGR) of the heat engine cycle, and $T_L\sigma$ reflects power dissipation of the heat engine. But the definition ignored the difference between energy and exergy, Yan