Energy Conversion and Management 142 (2017) 188–199

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Design condition and operating strategy analysis of CO_2 transcritical waste heat recovery system for engine with variable operating conditions

Gequn Shu, Xiaoya Li, Hua Tian *, Lingfeng Shi, Xuan Wang, Guopeng Yu

State Key Laboratory of Engines, Tianjin University, 92 Weijin Road, Nankai District, Tianjin 300072, China

ARTICLE INFO

Article history:
Received 29 December 2016
Received in revised form 21 February 2017
Accepted 23 February 2017

Keywords:
Design condition analysis
CO_2 transcritical power cycle
Variable heat source
Waste heat recovery
Gasoline engine

ABSTRACT

Waste heat recovery by means of a CO_2 transcritical power cycle (CTPC) is suitable for dealing with high-temperature heat sources and achieving miniaturization. Considering the variable operating conditions of engines, the object of current work is to reveal the influence of design condition selection on CTPC systems. Two different engine operating conditions are chosen for system design. System performance has been predicted by a dynamic model and compared by net power output at off-design conditions. Constraints on temperatures, pressures and pump rotational speed have been taken into account. The results show that system designed under a partial load condition possesses a broad range of operation which will be beneficial to operate continuously when engine condition varies. The operating condition determined by driving cycles is recommended for system design of waste heat recovery for gasoline engines. Optimal performance can be obtained by adopting the mass flow rate guided operation strategy. Moreover, the average fuel consumption reduction during the Highway Fuel Economy Test Cycle over the original is 2.84% if system is designed under a partial condition. These preliminary results give reference to system design and optimization for waste heat recovery of engines based on thermodynamic cycles.

1. Introduction

Driven by escalating fuel prices and future carbon dioxide emission legislations, the automotive industry is strongly focusing on improving the thermal efficiency of internal combustion engines (ICEs). However, only about one third of the fuel energy is transformed into useful power at crankshaft. The most part of the fuel energy is lost by coolant and exhaust gas. The potentially available energy to be converted into usable power in exhaust gas and coolant is quite significant. Therefore, waste heat recovery (WHR) technology has recently attracted a lot of interest beyond the limit of in-cylinder techniques. A wide range of research work has shown that organic Rankine cycle (ORC) has been accepted as a viable technology to convert waste heat into electrical or mechanical energy [1]. Research mainly includes system configurations design [2–4], working fluids selection [5,6], thermodynamic parameters optimization [7] and performance evaluation [8,9]. These investigations have made excellent contributions to improving cycle performance and developing the potential for application. Yet before an ORC system being applied to commercial vehicles, several specific challenges of its integration have to be faced.

The first challenge deals with the high temperature of engine exhaust gas as well as system miniaturization requirement. In view of the relatively low thermal decomposition temperature of organic working fluids, a traditional solution is to add a thermal-oil circuit between exhaust gas and ORCs [10] or use a dual-loop ORC [2]. However, a thermal-oil circuit not only leads to extra energy and exergy losses but also forms a bulky system. A dual-loop ORC also makes a complicated and costly system. It is difficult to integrate these schematics with vehicles due to space limitation.

To overcome this challenge, CO_2 transcritical power cycle (CTPC) has been put into perspective for engine WHR [11–15]. The decomposition temperature of CO_2 reaches as high as 2000 K which shows a high thermal stability. Carstens [16] investigated a supercritical CO_2 (sCO_2) power conversion system and showed that CO_2 could be heated up to 650 °C. It means CO_2 could be directly heated by the high temperature of engine exhaust gas, eliminating the cost and complexity of an intermediate heat transfer loop typically used in ORC applications. Besides, sCO_2 enables extremely compact turbomachinery designs for high fluid density and permits the use of compact and microchannel-based heat exchanger technology for single-phase heat transfer process [11].

* Corresponding author.
E-mail address: thtju@tju.edu.cn (H. Tian).

http://dx.doi.org/10.1016/j.enconman.2017.02.067
0196-8904/

Nomenclature

A	area [m^2]
a_0, a_1, a_2, a_3	parameters of pump
B	fuel consumption [kg/h]
b_0, b_1, b_2, b_3, c_0, c_1, c_2, c_3	parameters of expander
c_p	specific heat capacity [J/(kg K)]
C_v	coefficient of expander [m^2]
C_{sv}/C_{st}	leakage coefficients
D	diameter [m]
f	friction factor
G	mass flux [kg/(m^2 s)]
h	specific enthalpy [J/kg]
H_u	low heating value [J/kg]
k	thermal conductivity [W/(m K)]
L	length [m]
m	mass flow rate [kg/s]
Nu	Nusselt number
p	pressure [Pa]
Pr	Prandtl number
Q	volume flow rate [m^3/s]
Re	Reynolds number
S	slip ratio
T	temperature [K]
u	specific internal energy [J/kg]
U	heat transfer coefficient [W/(m^2 K)]
V	volume [m^3]
W	power [W]
x	vapor quality
z	direction along tube length

Greek letters

α	heat transfer coefficient [W/(m^2 K)]
ρ	density [kg/m^3]
ω	rotational speed [rpm/s]
η	efficiency
μ	viscosity [Pa·s]
γ	void fraction

Subscripts

1,2	first, second region
12	intermediate of the first and second region
amb	ambient
c	condenser
cs	cross section
exp, v	expander
f	saturated liquid
g	saturated vapor, exhaust gas
i, in	inlet
o, out	outlet
p	pump
r	working fluid
rec	receiver
s	isentropic
sv, st	laminar/turbulent leakage
total	total length
w	tube wall
water	cooling water

Abbreviations

CTPC	CO_2 transcritical power cycle
EIT	expander inlet temperature
FV	finite volume
HWY	Highway Fuel Economy Test Cycle
ICE	internal combustion engine
MB	moving boundary
ORC	organic Rankine cycle
PDE	partial differential equation
sCO_2	supercritical CO_2
WHR	waste heat recovery

Gas-like viscosity and diffusion coefficient of sCO_2 allow good flow ability and transmission characteristics. Echogen Power Systems Company [13] compared a 10 MW CO_2 turbine with a 10 MW steam turbine, showing an extremely compact and highly efficient CO_2 turbine design with simpler and single stage. Also, their comparison between a shell-tube and a highly compact heat exchanger of comparable overall heat duty indicated that microchannel heat exchangers had a smaller dimension and 87.4% weight reduction. Shu et al. [15] compared CTPC with R123-based ORC and proposed that the total heat exchange area of basic CTPC is smaller than that of basic transcritical ORC due to a larger heat transfer coefficient. Also, the turbine size of CO_2 system (0.010–0.020 m) is rather smaller than that of R123 system (0.055–0.070 m). Therefore, CTPC ought to outperform ORCs because it has an outstanding potential in miniaturizing.

The second challenge is the transient and variable behavior of the heat source depending on engine operating conditions. Exhaust energy under mapping characteristics changes dramatically [17], which may cause safety and operation problems to CTPC systems. Xie and Yang [18] analyzed an ORC system under actual driving cycle and concluded that energy fluctuation caused on-road thermal inefficiency (3.63%) of Rankine cycle which was less than half of the design point (7.77%). The experimental investigation on thermal oil storage/ORC conducted by Shu et al. [19] demonstrated that even with a significant inertia of thermal oil, the superheat degree of R245fa after evaporation easily went below zero which would cause safety issues to the expander. Therefore, variable engine operating conditions greatly influence the performance of WHR systems.

Moreover, engine operating condition selection is a prerequisite for CTPC system design. Systems designed under different engine operating conditions will have differences in size, volume, weight and performance at off-design conditions. CTPC systems are easily forced to operate at their partial load conditions for any change in engine operating conditions. Operating beyond or below the design points will lead to degradation of the isentropic efficiencies of pumps [20] and expanders [21] as well as variations in the effectiveness of heat exchangers [22]. Usman [23] presented the impact of ORC system installation on vehicles and recommended that the heat exchanger should not be designed for maximum heat recovery due to its unsuitable at partial load operation. However, many waste heat recovery systems were designed under the maximum condition to get a considerable energy saving potential, little research concerns on comparing design condition selection. For vehicle engines, it is meaningful to combine the mapping characteristics with driving cycles when designing a CTPC system.

Based on the analysis above, CTPC is adopted for extracting the energy of exhaust gas from a gasoline engine. This current work is focused on providing an insight into the effects of design condition selection on CTPC systems. Two different engine operating conditions are selected for system design, one is the rated condition and the other is chosen based on driving cycles. For safe operation, constraints on temperatures, pressures and pump rotational speed are considered and the performance of CTPC systems is predicted