Energy Conversion and Management 171 (2018) 1487–1501

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Comparative study on different water/steam injection layouts for fuel reduction in a turbocompound diesel engine

Rongchao Zhao[a,b,*], Zhongbo Zhang[a], Weilin Zhuge[b,**], Yangjun Zhang[b], Yong Yin[c]

[a] School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou 510641, China
[b] State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, China
[c] Dongfeng Commercial Vehicle Technical Center, Dongfeng Motor Co., Ltd, Wuhan 430056, China

ARTICLE INFO

Keywords:
Turbocompound engine
Waste heat recovery
Water injection
Steam injection
Thermodynamics analysis

ABSTRACT

Waste heat recovery is considered to be promising way to reduce fuel consumption of the internal combustion engines. Turbocompounding and water/steam injections are two kinds of methods to recover waste heat from the exhaust. This paper focuses on the impacts of different water/steam injection layouts on the fuel saving potentials of a turbocompound engine. Firstly, the simulation model for an 11-L diesel turbocompound engine is established and validated against experimental data. It is shown that the model obtains high accuracy on predicting the engine BSFC, power, in-cylinder peak pressure, exhaust temperature, etc. Based on the simulation model, the impacts of intake port water injection, in-cylinder water/steam injection and turbocharger turbine (CT) inlet steam injection on the engine BSFC are investigated. The influences of injection parameters including injection mass ratio, temperature and timing on the engine performance are studied in detail. The influence mechanisms of the water/steam injection on the thermodynamic cycle performance are also discussed thoroughly. The results show that merely liquid water injection at intake port or in cylinder cannot obtain fuel reduction. It is mainly due to the fact that water evaporating lowers the in-cylinder temperature, resulting in larger ignition delay and lower in-cylinder pressure. Steam injections in cylinder or at CT inlet can both achieve significant fuel reductions. At engine 1300 rpm condition, the steam injection in cylinder or at CT inlet can reduce the BSFC by 10% and 3.5%, respectively.

1. Introduction

Waste heat recovery has drawn increasingly more attentions from transportation area. Various methods have been proposed to recover the waste heat from the engine exhaust, EGR, charged air and cooling water, which still contain a large amount of energy. Currently, the main technologies for waste heat recovery include organic Rankine cycle (ORC), thermoelectric generation, turbocompounding and water/steam injection [1].

ORC has the potential to recover low and medium temperature heat in several applications: internal combustion engines, geothermal plants, solar thermal systems, biomass plants and industrial processes. Vehicle applications are more challenging due to their transient and highly variable operating profiles, leading to the need of implementing accurate control strategies to achieve performance, reliability and durability targets [2]. ORC system is relatively complicated and contains several important components including evaporator, condenser, expander and pump. Currently, the main attention is focused on long-haul trucks engines waste heat recovery.

Thermoelectric modules are solid-state devices that directly convert thermal energy into electrical energy. However, the conversion efficiency of thermoelectric generation is low and the cost of thermoelectric modules is high. The system can only become cost effective and more competitive when big progress is made [3].

In a typical turbocompound engine, a power turbine is fitted in series with the conventional turbocharger turbine. The power turbine recovers the surplus energy and converts it into mechanical or electrical energy. It can achieve better fuel economy, higher EGR driving capability and improved transient response with relative low cost, volume, and complexity. It is considered to be a promising technology for reducing fuel consumption in both light- and heavy-duty engines [4]. To further exploit the fuel saving potential of the turbocompound engine, a lot of investigations have been carried out. Katsanos et al. [5] studied the impacts of power turbine speed on the fuel consumption of electric turbocompound engine. It was pointed out that the optimum power turbine speed decreased as the engine load decreased. The maximum BSFC reduction achieved was 4.1% at full load and the lowest was 2%

* Corresponding author at: School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou 510641, China.
** Corresponding author at: State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, China.
E-mail addresses: merczhao@scut.edu.cn (R. Zhao), zhugewl@tsinghua.edu.cn (W. Zhuge).

https://doi.org/10.1016/j.enconman.2018.06.084
Received 9 February 2018; Received in revised form 22 June 2018; Accepted 23 June 2018

Nomenclature

Latin symbols

A	area (m^2)
a	sound velocity (m/s)
C_m	mean velocity (m/s)
c_p	specific heat ratio at constant pressure (J/kg K)
c_v	specific heat ratio at constant volume (J/kg K)
D	diameter of cylinder (m)
h	enthalpy (J/kg)
i	number of cylinder
l	length of connecting rod (m)
M	molar mass (kg/mol)
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
n	engine speed
p	pressure (Pa)
P	power (kW)
Q	heat quantity (J)
R_g	gas constant (J/kg K)
r	radius of crank (m)
S	entropy (J/K)
s	shape factor
T	temperature (K)
t	time represented by crankshaft angle ()
U	internal energy (J)
V	cylinder volume (m^3)
v	specific volume (m^3/kg) or velocity (m/s)
x	element dimension (m)

Greek symbols

α	coefficient
γ	adiabatic exponent
Δ	difference
ε	compression ratio
λ	mass ratio of steam to air
φ	crankshaft angle

Acronyms

ATDC	after top dead center
BSFC	brake specific fuel consumption
CA	crankshaft angle
CT	turbocharger turbine
DPF	diesel particulate filter
EGR	exhaust gas recirculation
ORC	organic Rankine cycle
PT	power turbine
TDC	top dead center

Subscripts and superscripts

1–8	locations in the engine systems
a	air
b	burn
e	exhaust
max	maximum
min	minimum
mix	mixture
w	water or wall

at 50% load. Briggs et al. [6] studied the impacts of power turbine rated power on the fuel consumption of a 2.4-L turbcompound engine, which was adopted in a hybrid bus. The optimum size of turbogenerator was a device with a rated power of 7.0 kW at full engine load, accounting for 6.8% of the engine's rated power output. Fuel reduction of 2.4% was observed under the Route 159 London bus drive-cycle. Mamat et al. [78] designed a low pressure power turbine to reduce the engine back pressure, which was applied in a 1.0 L three-cylinder gasoline engine. Experimental results showed that a maximum BSFC reduction of 2.6% was achieved at an engine speed of 2500 rpm during part load operation. Pasini et al. [9] evaluated the engine performance equipped with electric turbo compound system by numerical approval. In Pasini's study, a motor/generator was connected to the turbocharger. The sole turbine acted as the roles of turbocharger turbine and power turbine. The motor/generator could help to accelerate the turbocharger or recover the waste heat from the exhaust, depending on the engine operation condition. It was shown that electric turbocompound could extent the boost range in the lowest engine rotational speed region and reduce turbo lag. Zhao et al. [10] carried out a parametric study of the power turbine for turbocompound engine, which helped to design an appropriated power turbine for turbocompound engine. Zhao et al. [11] also found that the demand expansion ratios of turbocharger turbine and power turbine varied as the operation condition changed. Therefore, variable geometry turbine was proposed to improve the turbocompound engine performance at off-design conditions. He et al. [12] proposed a controllable mechanical turbo-compounding system including continuously variable transmission and power turbine bypass valve to recover waste heat from engine exhaust. Fuel savings of 2% and 3.4% were obtained under highway fuel economy test (HWFET) and Tianjin 503 (TJ503) driving cycle, respectively. The HWFET driving cycle is standard driving cycle and TJ503 is the actual driving condition of a bus in Tianjin city involving both suburb and urban condition. The transient response was also improved with the assist of power turbine bypass valve. The fuel savings obtained by different layouts of turbocompound engine was summarized in [13]. Although a lot of efforts have been made to improve the fuel economic of the turbocompound engine, the fuel savings were still limited, when compared with ORC. This is mainly caused by the increased back pressure. The trade-off relationship between the recovery power and increased pumping loss was also disclosed in [13].

Water/steam injection is also considered as one of technologies in waste heat recovery, although it serves as a method to control emission in some occasions. The water/steam injection locations include intake port, cylinder, turbine inlet and diesel particulate filter (DPF) inlet. Different injection locations affect the thermodynamics cycle efficiency and emissions of the internal combustion significantly.

The main target of water injection at intake port was to control the NOx emission at first. Since the ignition delay is longer and the in-cylinder peak pressure is reduced with water injection, the engine thermal efficiency is slightly reduced [14]. Tesfa et al. [15] studied the effects of water injection on the performance and emission characteristics of a CI engine operating with biodiesel. The NOx emission was reduced by 50% with the water injection in the intake manifold. However, BSFC was increased by a maximum of 4% at low load conditions. However, water injection can reduce the cylinder peak temperature, thus reduce the knock tendency in gasoline engine. Therefore, the gasoline engine compression ratio can be improved to obtain higher thermal efficiency [16]. In addition, the ignition timing can also be advanced in gasoline engine. As a result, the fuel consumption can also be reduced remarkably by intake port water injection with advanced ignition timing [17]. The influence of water injection timing on performance and emission of a hydrogen compression ignition was investigated by Adnan et al. [18]. It was found that injection timing of 20° ATDC and duration of 20° CA obtained higher gross indicated work and