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Numerical study on steam injection in a turbocompound diesel engine for waste heat recovery

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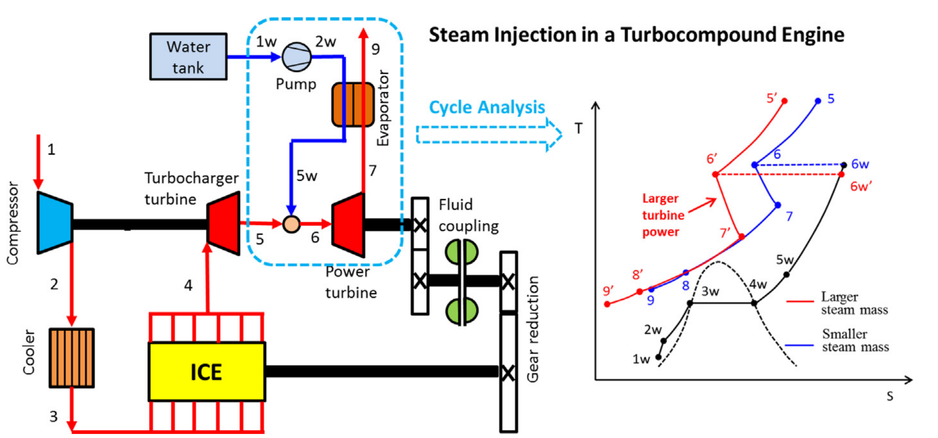
HIGHLIGHTS

- Steam injection was adopted in a turbocompound engine to further recover waste heat.
- Thermodynamics model for the turbocompound engine was established and calibrated.
- Steam injection at CT inlet obtained lower engine BSFC than injection at PT inlet.
- The optimal injected steam mass at different engine speeds was presented.
- Turbocompounding combined with steam injection can reduce the BSFC by 6.0–11.2%.

GRAPHICAL ABSTRACT



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ABSTRACT

Steam injection and turbocompouding are both effective methods for engine waste heat recovery. The fuel saving potential obtained by the combination of the two methods is not clear. Based on a turbocompound engine developed in the previous study, the impacts of pre-turbine steam injection on the fuel saving potentials of the turbocompound engine were investigated in this paper.

Firstly, thermodynamic cycle model for the baseline turbocompound engine is established using commercial software GT-POWER. The cycle model is calibrated with the experiment data of the turbocompound engine and achieves high accuracy. After that, the influences of steam mass flow rate, evaporating pressure and injection location on the engine performance are studied. In addition, the impacts of hot liquid water injection are also investigated.

The results show that steam injection at the turbocharger turbine inlet can reduce the turbocompound engine BSFC at all speed conditions. The largest fuel reduction 6.15% is obtained at 1000 rpm condition. However, steam injection at power turbine inlet can only lower the BSFC at high speed conditions. Besides, it is found that hot liquid water injection in the exhaust cannot improve the engine performance.

When compared with the conventional turbocharged engine, the combination of turbocompounding and steam injection can reduce the BSFC by 6.0–11.2% over different speeds.

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Nomenclature

Latin symbols

A	equivalent turbine flow area (m^2)
C	discharge coefficient
c_p	specific heat ratio at constant pressure (J/kg K)
c_v	specific heat ratio at constant volume (J/kg K)
h	enthalpy (J/kg)
$\dot{m}$	mass flow rate (kg/s)
n	number of cylinder
p	pressure (Pa)
P	power (kW)
R	gas constant (J/kg K)
T	temperature (K)
u	internal energy (J/kg)
V_m	cylinder sweep volume (m^3)
v	specific volume (m^3/kg) or velocity (m/s)

Acronyms

BSFC	brake specific fuel consumption
BTDC	before top dead center
CAD	crank angle degree
CT	turbocharger turbine
ORC	organic Rankine cycle
PT	power turbine
VGT	variable geometry turbine
WHR	waste heat recovery
bmep	brake mean effective pressure
fmep	friction mean effective pressure
imep	indicated mean effective pressure
pmep	pumping mean effective pressure
tmep	turbine mean effective pressure

Greek symbols

γ	adiabatic exponent
η	total-to-static efficiency

Subscripts and superscripts

1–9	locations in the engine systems
e	exhaust
i	indicated
max	maximum
mech	mechanical
min	minimum
mix	mixture
s	isentropic
T	turbine
w	water

1. Introduction

Internal combustion engines are the main powertrains for automobiles at present and in the short to medium term. It is meaningful to improve the engine fuel economic to reduce emission in transportations. In a conventional internal combustion engine, a great deal of thermal energy is dissipated into the environment in the form of exhaust and cooling. Therefore, waste heat recovery (WHR) is proposed to extract the thermal energy from engine exhaust and cooling water, thus increasing the engine thermal efficiency. It is regarded as a highly potential way to reduce fuel consumptions of the conventional engines. Various technologies have been proposed to achieve the target, including Rankine cycle (organic Rankine cycle or steam Rankine cycle), thermoelectric generation, turbocompounding and steam/water injection [1,2].

Among these technologies, Rankine cycle can recover relatively more waste heat from the exhaust. Depending on the working fluid, Rankine cycle can be divided into steam Rankine cycle and organic Rankine cycle. Steam Rankine cycle can generally improve the thermal efficiency by 2.5–7.5%, while organic Rankine cycle can increase it by 5–20%, as summarized in literature [2]. However, Rankine cycle system is relatively complex and costly. It contains at least four components, including evaporator, expander, condenser and pump. The system must be compact and low-cost before it can be widely applied on automobiles.

Thermoelectric generation has the most compact configuration for engine waste heat recovery. However, the conversion efficiency of thermoelectric generation is relatively low and the thermoelectric material is expansive. It can become more competitive only when lower cost and higher conversion efficiency are achieved [3].

Compared with Rankine cycle and thermoelectric generation, turbocompounding [4–9] and water/steam injection are relatively simple and inexpensive. As for the turbocompounding, it has been successfully applied on heavy-duty vehicle engines although its fuel saving potential is smaller than that of Rankine cycle. Turbocompounding also obtains higher exhaust gas recirculation driving capability and improved transient response [4]. Some efforts have been made to further explore the potentials of a turbocompound engine. In the study of Katsanos [5], the turbocompound engine transient performance was improved by adjusting the power turbine rotating speed. The largest fuel reduction is up to 4% with the proposed electrical turbocompounding. Briggs et al. [6] studied the impact of power turbine sizing on the performance of a diesel-electric hybrid bus. It is shown that up to 2.4% reduction in fuel consumption was obtained over the London bus drive-cycle. Mamat et al. [7,8] carried out a study on turbocompounding with low expansion ratio power turbine. The 1-L turbocompound gasoline engine obtained 2.41% fuel savings at low speed conditions. Pasini et al. [9] pointed out that turbocompounding is much more advantageous when it is applied in extra-urban roads or motorways. Although turbocompounding is a relatively mature technology, its fuel saving potentials is relatively limited. It is necessary to further explore its potentials before it can be more widely applied on vehicle engines.

Concerning the steam/water injection on internal combustion engine, a large number of studies have been carried out. The steam/water can be injected at different locations of the engine, including at intake port [10–15], in cylinder [16–21], before turbine [22–25] and before DPF (diesel particulate filter) [26,27].

Ported water injection in a gasoline engine can reduce the chamber temperature, heat losses and knock tendency [10]. Hence the engine compression ratio can be improved and the combustion phasing can be advanced to improve the cylinder peak pressure, resulting in lower fuel consumption. In addition, NO emission is also reduced due to lower in-cylinder temperature and oxygen concentration [11]. The water injection timing and duration have significantly impacts on the power and emission performance, as reported in literature [12]. To recover the waste heat from the exhaust, the water is heated into steam by the exhaust before it is injected at intake port [13–15]. As demonstrated by the experiment in literature [13], ported steam injection can increase the effective power and fuel economic up to 4.65% and 6.44% respectively. The NO and HC emissions are also reduced remarkably.

In-cylinder direct injection of water/steam near the TDC (top dead center) can increase the power output during the power stroke due to more working fluid and higher in-cylinder pressure

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