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A comparative study on various turbocharging approaches based on IC engine exhaust gas energy recovery

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HIGHLIGHTS

- Two novel turbocharging approaches of steam turbocharging and steam-assisted turbocharging were proposed.
- Steam turbocharging has higher energy saving potential than the other two turbocharging approaches.
- Steam turbocharging can achieve the target intake pressure in the entire IC engine speed area.
- Steam-assisted turbocharging can improve IC engine intake pressure at the low-speed operating conditions.

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ABSTRACT

In this paper, two kinds of novel boosting pressure approaches, steam turbocharging and steam-assisted turbocharging, have been proposed. And both are based on the principle of internal combustion (IC) engine exhaust gas energy recovery. In order to demonstrate the advantages of the two types of new turbocharging concepts, a comparative study among exhaust turbocharging, steam turbocharging and steam-assisted turbocharging was conducted on a passenger car gasoline engine, and the effects of various boosting pressure approaches on IC engine performances as well as turbocharging system energy flow were analyzed. The results show that, steam turbocharging can achieve the target intake pressure in the entire IC engine speed range, while steam-assisted turbocharging can improve IC engine intake pressure at the low-speed operating conditions; the energy saving potentials from high to low follow the subsequence of steam turbocharging, steam-assisted turbocharging and exhaust turbocharging; with the increasing of IC engine speed, the exhaust gas energy recovery efficiency of steam turbocharging system decreases and its maximum value is 6.5%, while the exhaust gas energy recovery efficiency of steam-assisted turbocharging and exhaust turbocharging first increases and then decreases.

1. Introduction

Recently, due to the increasingly severe problems of energy and environment, especially the petrol shortage and air pollution, more attention has been paid on the energy saving and environmental protection [1–3]. As the main consumer of fossil oil, the important power source of automobile and also the major source of air pollution, IC engine becomes the primary object for energy conservation and emission reduction in the world [4]. Under the circumstances, higher energy utilization efficiency and lower emissions are the two major development momentums for IC engine.

According to the analysis of IC engine energy balance [5,6], there are several kinds of approaches to improving the IC engine energy utilization efficiency, e.g., boosting pressure, exhaust gas energy recovery. On one hand, since the higher IC engine thermal efficiency appears in the higher load area, boosting pressure becomes one of the effective methods to improve IC engine thermal efficiency. As is well known, the first approach of boosting pressure on IC engine is mechanical supercharging [7]. A lot of research shows that mechanical supercharging could enhance IC engine power and torque under most of operating conditions. However, the improvement to IC engine thermal efficiency is very limited because part of IC engine effective work is consumed to drive the compressor. Another conventional approach of boosting pressure is exhaust turbocharging, which uses IC engine exhaust gas energy to drive the compressor through exhaust turbocharger [7]. In reality, exhaust turbocharging can be classified as a kind of means for exhaust gas energy recovery. Compared with mechanical supercharging engine, exhaust turbocharging engine has more advantages, e.g., higher thermal efficiency, for the compressor power comes from exhaust gas energy rather than IC engine

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Nomenclature

P	power (kW)
$\dot{m}$	mass flow rate (kg/s)
c_P	constant pressure specific heat (kJ/(kg K))
T	temperature (K)
p	pressure (kPa) (MPa)
ρ	density (kg/m^3)
k	adiabatic exponent
η	efficiency
V_s	displacement (l)
n	speed (r/min)
i	cylinder number
τ	stroke number
B	consumption of fuel (kg/s)
H_u	low heating value (kJ/kg)

Subscripts

exh	exhaust gas
com	compressor
int	intake gas
pum	pump
in	inlet
out	outlet
ste	steam
tur	turbine
wme	working medium
ere	exhaust gas energy recovery efficiency
ice	internal combustion engine
me	brake mean effective pressure
imp	improvement of thermal efficiency
tce	turbocharging engine
nae	naturally aspirated engine

Abbreviation

IC	internal combustion
ET	exhaust turbocharging
ST	steam turbocharging
SAT	steam-assisted turbocharging
BMEP	brake mean effective pressure
IMEP	indicated mean effective pressure
PMEP	pumping mean effective pressure
FMEP	friction mean effective pressure

effective work. However, studies indicate that exhaust turbocharging is also not the perfect method to promote the IC engine energy utilization efficiency [8,9], and one of the obvious defects is that it leads to a higher exhaust gas pressure. On the other hand, exhaust gas energy recovery is another approach to improving the total energy utilization efficiency of IC engine, which has been approved by lots of experts [10,11]. At present, an increasing number of scholars have concerned about this aspect. For example, He et al. [12] have proposed a combined thermodynamic cycle used for IC engine waste heat recovery; Dolz et al. [13] have studied the HD diesel engine equipped with a bottoming Rankine cycle as a waste heat recovery system; Liu et al. [14] have analyzed the recovery potentials of IC engine exhaust gas energy through Rankine steam cycle. Although lots of research has been conducted in the field of exhaust gas energy recovery and many concepts have been proposed, up to now, few approaches of exhaust gas energy recovery are used for IC engine boosting pressure except the exhaust turbocharging.

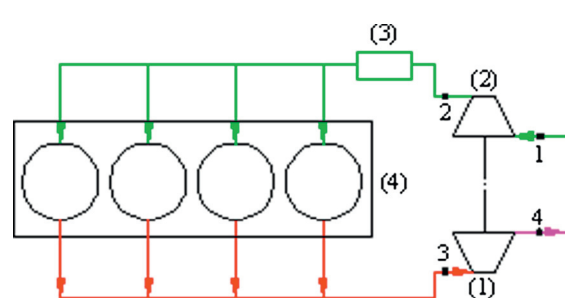
Since most of research on IC engine boosting pressure focused on the exhaust turbocharging, and the research on IC engine exhaust gas energy recovery mainly considered independent bottom cycle, the studies may be more interesting if the two kinds of research are combined together. In the previous study, we have proposed the concepts of steam turbocharging (ST) [15] and steam-assisted turbocharging (SAT), both of which are the new turbocharging approaches based on the principle of IC engine exhaust gas energy recovery. In this paper, a comparative study on various turbocharging approaches is conducted, for the purpose of revealing their energy saving potentials as well as the improvement to the IC engine performances.

2. Turbocharging approaches based on exhaust gas energy recovery

2.1. Exhaust turbocharging

Nowadays, exhaust turbocharging is the most prevalent approach of boosting pressure in the field of IC engine, and it is applied to almost any advanced IC engine [7,16]. Fig. 1 is the schematic diagram of IC engine exhaust turbocharging. As it shows, traditional exhaust turbocharging system consists of turbine, compressor and intercooler, etc. Among them, the turbine and the compressor are connected by a transmission shaft. Because the IC engine exhaust gas has a high temperature and high pressure (compared with ambient pressure), it still contains lots of energy which could be recovered by exhaust turbine. In the exhaust turbocharging system, exhaust gas is used as the working medium of turbine, while turbine acts as the power output device of boosting pressure system. During the exhaust gas expansion process, part of exhaust gas energy is recovered and transformed into useful work. Then, the useful work is used to drive the compressor.

In the light of the theory of IC engine exhaust gas energy recovery [9], exhaust turbocharging is a kind of direct method to reuse exhaust gas energy. Although the power of exhaust turbocharging comes from exhaust gas energy, IC engine exhaust process experiences the throttling loss in turbine and it results in a higher exhaust gas pressure. As a consequence, some of IC engine effective work should be consumed to overcome the additional exhaust gas pressure, and the improvement to the IC engine thermal efficiency by exhaust turbocharging is restrained.



(1) Turbine (2) Compressor (3) Intercooler (4) IC engine

Fig. 1. Schematic diagram of IC engine exhaust turbocharging.