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# An approach for exhaust gas energy recovery of internal combustion engine: Steam-assisted turbocharging

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ABSTRACT

An approach for IC engine exhaust gas energy recovery, named as steam-assisted turbocharging (SAT), is developed to assist the exhaust turbocharger. A steam generating plant is coupled to the exhaust turbocharged engine's exhaust pipe, which uses the high-temperature exhaust gas to generate steam. The steam is injected into turbine inlet and used as the supplementary working medium for turbine. By this means, turbine output power and then boosting pressure can be promoted due to the increase of turbine working medium. To reveal the advantages and energy saving potentials of SAT, this concept was applied to an exhaust turbocharging engine, and a parameter analysis was carried out. Research results show that, SAT can effectively promote the low-speed performances of IC engine, and make the peak torque shift to low-speed area. At 1500 r/min, the intake gas pressure can reach the desired value and the torque can be increased by 25.0% over the exhaust turbocharging engine, while the pumping mean effective pressure (PMEP) and thermal efficiency only have a slight increase. At 1000 r/min, the improvement of IC engine performances is very limited due to the low exhaust gas energy.

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## 1. Introduction

It is well known that exhaust turbocharging can effectively improve the internal combustion (IC) engine working load and downsize the displacement without decreasing its power performances [1,2]. In this way, it can ensure that IC engine often operates in the high efficiency area, and achieve the goals of IC engine energy conservation. For example, the 1.4 L TSI turbocharged engine made by Volkswagen Company, has better performances than the 2.3 L naturally-aspirated (NA) engine in many aspects. Compared with the NA engine, the displacement of TSI turbocharged engine is reduced by 39%, while the fuel consumption and $CO_2$ emission are reduced by 20% [3]. Therefore, exhaust turbocharging becomes a key technology and important approach for energy saving and emission reduction on IC engine [4].

Additionally, waste heat recovery (WHR) is another effective way for IC engine energy saving and $CO_2$ emission reduction [5–7]. So far, various kinds of approaches and technologies were proposed for IC engine WHR, and much attention focuses on this aspect [8]. For instance, Shu et al. [9] have conducted the performance comparison and working fluid analysis of subcritical and transcritical dual-loop organic Rankine cycle (DORC) used in engine WHR. Katsanos et al. [10] have carried on a thermodynamic analysis of a Rankine cycle applied on a diesel truck engine using steam and organic medium. They found that the brake specific fuel consumption improvement ranges from 10.2% (at 25% engine load) to 8.5% (at 100% engine load) for R245ca and from 6.1% (at 25% engine load) to 7.5% (at 100% engine load) for water. In reality, exhaust turbocharging is one of the most common means for IC engine exhaust gas energy recovery (EER) [11,12], since it uses exhaust gas energy to drive the compressor. As the energy source of turbocharging system and also the working medium of turbine, exhaust gas plays a very important role in the working performances of exhaust turbocharging system and IC engine. For example, the mass flow rate, pressure and temperature of exhaust gas determine the output power of turbine, and then influence the IC engine boosting pressure. Since the boosting pressure dominates the fresh charge and even the pumping process work of IC engine, it finally influences the performances of IC engine.

In the traditional exhaust turbocharging system, the mass flow rate of exhaust gas equals to the sum of intake gas and fuel mass flow rate, and it approximately grows in linear with the increase of IC engine speed. As a result, different speed corresponds to

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**Nomenclature**

| | |
|---|---|
| $P$ | power (kW) |
| $\dot{m}$ | mass flow rate (kg/s) |
| $p$ | pressure (kPa) (MPa) |
| $\rho$ | density (kg/m$^3$) |
| $\eta$ | efficiency |
| $c_P$ | constant pressure specific heat (kJ/(kg K)) |
| $T$ | temperature (K) |
| $\gamma$ | specific heat ratio |
| $V_s$ | displacement (l) |
| $n$ | speed (r/min) |
| $i$ | cylinder number |
| $\tau$ | stroke number |
| $B$ | consumption of fuel (kg/h) |
| $H_u$ | low heating value (kJ/kg) |
| $\varepsilon$ | improvement rate |

*Subscripts*

| | |
|---|---|
| pum | pump |
| ste | steam |
| tur | turbine |
| exh | exhaust |
| mix | mixture |
| com | compressor |
| int | intake |
| tra | transmission shaft |
| ice | internal combustion engine |
| me | brake mean effective pressure |
| the | thermal efficiency |
| tor | torque |

*Abbreviation*

| | |
|---|---|
| SAT | steam-assisted turbocharging |
| ET | exhaust turbocharging |
| IC | internal combustion |
| WHR | waste heat recovery |
| DORC | dual-loop organic Rankine cycle |
| EER | exhaust gas energy recovery |
| EAT | electric assisted turbocharging |
| BMEP | brake mean effective pressure |
| PMEP | pump mean effective pressure |
| AFR | air/fuel ratio |
| NA | naturally aspirated |

different exhaust gas mass flow rate, and the change of exhaust gas mass flow rate results in the variation of turbine performances. Generally, under the high-speed operating conditions, since the mass flow rate of IC engine exhaust gas is too large, part of exhaust gas should be bypassed via the waste gate [13]. While under the low-speed operating conditions, the mass flow rate of IC engine exhaust gas is very small. In the meantime, the exhaust gas pressure is also very low, and both of the two aspects lead to a small turbine output power. Under the circumstances, the turbine output power is lower than the required compressor power thus intake gas pressure cannot achieve the desired level. Accordingly, it leads to the consequence that the IC engine torque as well as the power is lower than the expected level. Furthermore, IC engine has bad fuel efficiency and emission performance at the low-speed operating conditions. Consequently, improving the low-speed performances of exhaust turbocharging engine is the goal pursued by many scientists and engineers. To achieve this goal, some approaches were proposed in the past, e.g., two-stage turbocharging [14] and electric assisted turbocharging (EAT). It is true that these approaches can effectively promote the low-speed performances of exhaust turbocharging engine, but IC engine total energy efficiency (or thermal efficiency) is influenced because some additional power is consumed.

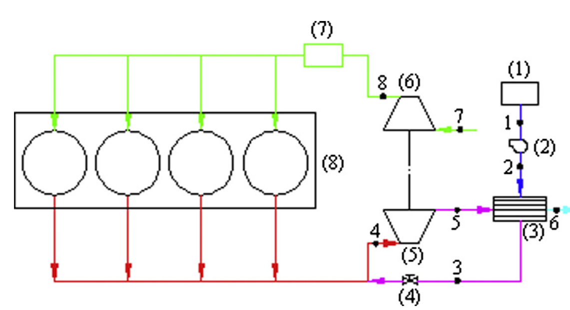
To solve the problems mentioned above, a novel concept of SAT was proposed to improve the performances of traditional IC engine exhaust turbocharging, which is also a kind of novel approach for IC engine exhaust gas energy recovery [15]. In the previous study, the authors only proposed the concept of SAT, and compared the performances of exhaust turbocharging, steam turbocharging and SAT engine [15]. Being different from the previous study, in this research, the detailed working processes of SAT system were analyzed and the calculation method for SAT engine was developed. Also, a numerical calculation and parameter analysis was conducted on the SAT system as well as the SAT engine. On this basis, the performances of SAT engine and exhaust turbocharged engine were compared for the purpose of demonstrating the superiority and feasibility of SAT system. In addition, the overall improvements to torque and thermal efficiency of SAT engine have been compared to previous studies [15].

## 2. Description of steam-assisted turbocharging

### 2.1. Concept of steam-assisted turbocharging

The schematic diagram of proposed SAT system is depicted in Fig. 1. Combining with this schematic diagram, the working principle of SAT is introduced. In the exhaust turbocharging engine, a set of steam generating plant, which includes water tank, pump, heat exchanger, valve, etc., is coupled to the IC engine exhaust pipe to produce steam. In the steam generating plant, the working medium water is heated into superheated steam by the high-temperature exhaust gas of IC engine in heat exchanger. Then, the superheated steam is injected into the turbine inlet and used as the compensatory working medium for the turbine. By this means, the turbine output power can be improved due to the increase of working medium. As a result, the intake gas pressure increases and then the IC engine power performances can also be promoted.

According to what is described above, the SAT system follows the principle of open steam power cycle [16]. Similar to the exhaust turbocharging, it is a kind of approach for IC engine exhaust gas energy recovery. Nevertheless, being different from




(1) Water tank (2) Pump (3) Heat exchanger (4) Valve
(5) Turbine (6) Compressor (7) Intercooler (8) IC engine

**Fig. 1.** Schematic diagram for SAT system.

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