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A Review on Exhaust Gas Energy Recovery Using Steam Turbocharging

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ABSTRACT: A new concept of steam turbocharging was proposed to boost IC engine intake pressure. Both, existing concept of exhaust turbocharging and proposed concept of steam turbocharging are based on principle of exhaust energy recovery. A set of rankine steam cycle system of open type is coupled on IC engine exhaust pipe, which uses IC engine exhaust energy to generate steam and then drive the turbine. Part of steam expansion power is used to drive air compressor and remainder is recovered by motor. To compare both boosting pressure methods, they're applied on same IC engine and the working processes of steam turbocharged engine and exhaust turbocharged engine were simulated by researchers. On this basis, the differences between two kinds of pressure boosting methods have been analyzed. The results show that IC engine power be theoretically improved by 7.2% at most, and thermal efficiencies can be improved by 2 percent points or more except at 1000 r/min by using steam turbocharging. All these can prove this boosting pressure concept is a novel technology with great energy saving potentials.

KEYWORDS: IC engine, steam turbocharging, exhaust energy recovery, turbocharging.

I. INTRODUCTION

So many enthusiasts and prospective tuners are aware that turbocharging is a great way of increasing engine power. Turbocharging is a form of forced induction. The turbocharger forces air into the engine cylinders at a pressure greater than atmospheric pressure. A lot of research indicates that boosting intake pressure is a useful way to improve both the power performance and fuel economy of internal combustion engine (IC engine). From the viewpoint of IC engine energy balance, higher intake pressure results in higher brake mean effective pressure (BMEP), and finally it leads to higher thermal efficiency and power. At the same time, boosting intake pressure can also achieve the goal of downsizing IC engine displacement, thus most of modern advanced IC engines adopt various technologies of boosting pressure. In these boosting pressure technologies on IC engine, such as supercharger, electricity aided turbo (EAT), exhaust turbocharging is used most method for IC engine exhaust energy recovery (EER), since it uses IC engine exhaust pressure energy to drive the turbine.

Advantages of using turbocharging system are: 1) Increase in volumetric efficiency. 2) Increase in power output. 3) Reduce of intake of fuel or air.

However, IC engine exhaust turbocharging is not so good for exhaust energy recovery. The energy recovery efficiency of exhaust turbocharging system is largely determined by the turbocharger efficiency and only a small part of exhaust energy can be recovered. This is because the major form of exhaust energy is thermal energy rather than pressure energy. At the same time, exhaust turbocharging inevitably brings additional exhaust back pressure to IC engine, and it results in the consequence that IC engine has to consume more effective work during the exhaust process. As a result, most of the exhaust energy recovered by turbocharger is used to overcome the additional pumping loss. Sometimes, if the exhaust turbine does not match the compressor well, the recovered exhaust energy will even be less than the additional pumping loss. Moreover, the boosting pressure often cannot reach the desired value under IC engine low-speed. Consequently, exhaust turbocharging is neither the best way to recover exhaust energy nor the best way to boost intake pressure for IC engine. A novel concept has been proposed by researchers which uses IC engine exhaust thermal energy to boost intake pressure. As this concept is based on the principle of steam power cycle, it is named as steam turbocharging, which is different from IC engine exhaust turbocharging. Meanwhile, the steam turbocharging, exhaust

turbocharging and steam assisted turbocharging are applied on the same IC engine, and the performances of IC engine with the two kinds of turbocharging means are compared, for the purpose of demonstrating the advantages and feasibility of steam turbocharging.

II. BACKGROUND

A. EXHAUST TURBOCHARGING

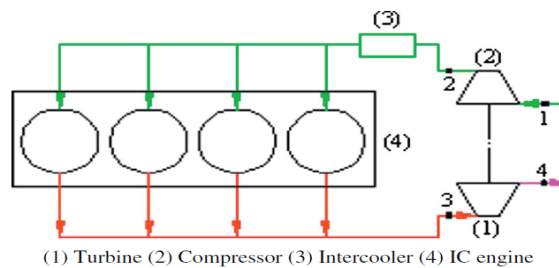


Fig. 1 Schematic diagram of exhaust turbocharging

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. Fig. 1^[3] 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, 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.

A.1 ANALYSIS ON THE PUMPING LOSS OF EXHAUST TURBOCHARGED ENGINE:

As mentioned previously, one of the biggest defects of exhaust turbocharging is that IC engine with exhaust turbocharging system has higher pumping loss, which directly affects the power performance and fuel economy of IC engine. For this reason, how to reduce or even completely remove the additional pumping loss becomes a key issue of exhaust turbocharging. In order to better analyze the relationship between pumping loss and IC engine performance, the following equation is given,

$$BMEP = IMEP + PMEP - FMEP \quad (1)$$

where, BMEP is the brake mean effective pressure, which is one of the most important parameters of IC engine power performance; IMEP is the indicated mean effective pressure; PMEP is the pumping mean effective pressure; FMEP is the friction mean effective pressure.

Relationship among intake pressure, exhaust pressure and PMEP is given as

$$PMEP = P_2 - P_3 - P_{cyl_port_loss} \quad (2)$$

where, P_3 is the mean exhaust pressure of IC engine; P_2 is the mean boosting pressure (compressor outlet pressure); $p_{cyl_port_loss}$ is the mean pressure loss in the intake ports and cylinder. Through analyzing on Equation (2), the following conclusions can be drawn. If IC engine intake pressure is higher than exhaust back pressure, PMEP will be

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positive. Under the circumstances, gas exchange processes do positive work to the IC engine. Conversely, PMEP will be negative, and IC engine has to consume some effective work in the gas exchange processes.

The pumping loss consumes a part of cycle work. During the intake process, because intake pressure of turbocharged engine is higher than ambient pressure, intake process does positive work to the piston. However, during the exhaust process, because exhaust pressure is greater than ambient pressure, exhaust process does negative work to the piston. As is well-known, the pumping loss of exhaust turbocharged engine equals intake process work minus exhaust process work. In the exhaust process, exhaust back pressure directly acts on the IC engine piston. Therefore, any means for exhaust energy recovery at the expense of improving IC engine exhaust back pressure, if the output work of turbine is lower than the additional pumping work due to additional exhaust back pressure, the loss will outweigh the gain. Because the exhaust turbocharging is directly related to exhaust pressure, and exhaust pressure directly affects the IC engine pumping loss, there are many constraints for exhaust turbocharging.

B. STEAM TURBOCHARGING

B.1 PRINCIPLES OF STEAM TURBOCHARGING SYSTEM:

In order to solve the problems of exhaust turbocharging, the new approach of steam turbocharging is proposed, which is based on the principle of Rankine steam cycle. According to the previous analysis, steam turbocharging is a kind of indirect method for exhaust energy recovery. That is, it recovers IC engine exhaust thermal energy by the means of heat transfer, and makes the recovered exhaust energy convert into the effective output work of turbine. Finally, the turbine output work is used to drive air compressor. The schematic diagram of steam turbocharging system is given in Fig. 2^[3] below.

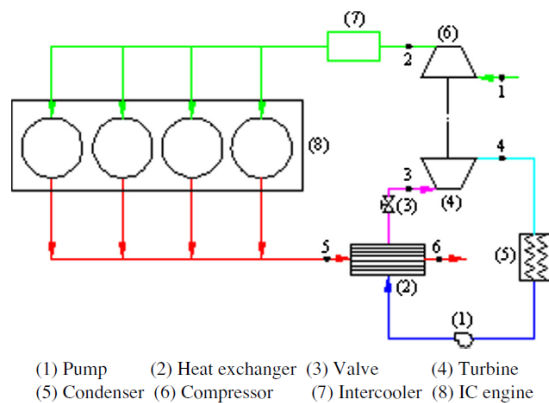


Fig. 2 Schematic diagram of IC engine steam turbocharging^[3]

In these components, valve is used to adjust the flow rate of working medium water, while pump is used to control the cycle pressure. A motor is coupled on the transmission shaft for the purpose of managing bottom cycle energy flow. The operating modes of motor are described as follows. (1) Driving the air compressor: when IC engine starts, the steam turbine does not work immediately and air compressor is driven by the motor to obtain an expected compression pressure; when IC engine works at low-speed and low-load operating conditions, air compressor is driven by both the steam turbine and motor, since exhaust energy is very low. (2) Generating electric energy: when IC engine works at high-load operating conditions, steam turbine output power may be larger than the power required by air compressor. In this situation, both the air compressor and motor are driven by the steam turbine. As a result, extra output power of steam turbine can be stored in the form of electric energy by motor.

The steam turbocharging system shown in Fig. 2 is a kind of open steam power cycle. Actually, it can be designed into both open steam power cycle and closed steam power cycle. Correspondingly, the two kinds of bottom cycle have different applications. Usually, the open steam power cycle is much simpler than the closed steam power cycle, since there is no condenser and condensation process in the former. And the system costs of the former are also much lower than the latter. The steam turbocharging system based on open steam power cycle is suitable for stationary applications,

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e.g. genset, steam plant. Under the circumstances, this should not be an issue for the working medium water. However, the steam turbocharging system based on closed steam power cycle has more widely applications since the working medium water can be recycled. Generally, it can be used in both the stationary applications and the mobile power sources, such as automobile engine and marine engine. The working principles of open steam power cycle and closed steam power cycle are almost the same. In this paper, we have only analyzed the open steam power cycle.

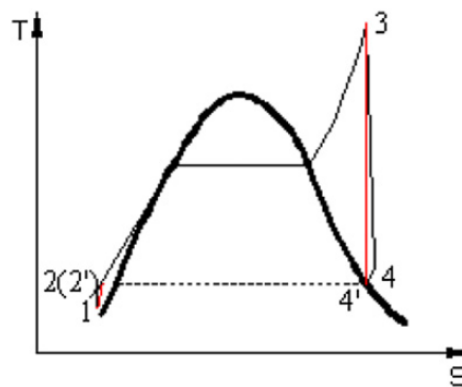


Fig. 3. T-S diagram of Rankine steam cycle system^[2]

In the steam turbocharging system, water is used as bottom cycle working medium, and the T-S diagram corresponds to the thermodynamic processes of working medium water is shown in Fig. 3.^[2] Combining Figs. 5 and 6, the thermodynamic processes of steam turbocharging bottom cycle are described as follows. Process 1-2: in the pump, liquid working medium water is compressed to a certain pressure, and this process corresponds to process 1-2 in the T-S diagram. Process 1-2 represents the ideal process (isentropic compression) while process 1-2 is the real compression process. Process 2-3: in the heat exchanger, liquid working medium water is heated into superheated steam by IC engine exhaust, and this process can be regarded as an isobaric process with the pressure loss ignored. Process 3-4: in the turbine, superheated steam expands and outputs effective work. In the T-S diagram, process 3-4 represents the ideal expansion process (isentropic expansion), and process 3-4 is the real expansion process (irreversible expansion).

III. LITERATURE REVIEW

Jian in Fu et al.^[1] first proposed the concept of using open steam power cycle for IC engine exhaust gas energy recovery. In which they implemented open steam power cycle using fourth cylinder for expansion of steam generated from exhaust gas energy. Then, Jianqin Fu et al.^[2] carried out the research further and used open steam power cycle for turbocharging and proposed a new concept of steam turbocharging for exhaust gas energy recovery. They experimentally showed IC engine performance enhancement potentials of steam turbocharging. Jianqin Fu et al.^[3] compared various turbocharging approaches like steam assisted turbocharging, steam turbocharging and exhaust turbocharging and found that steam turbocharging has the highest performance enhancement potentials.

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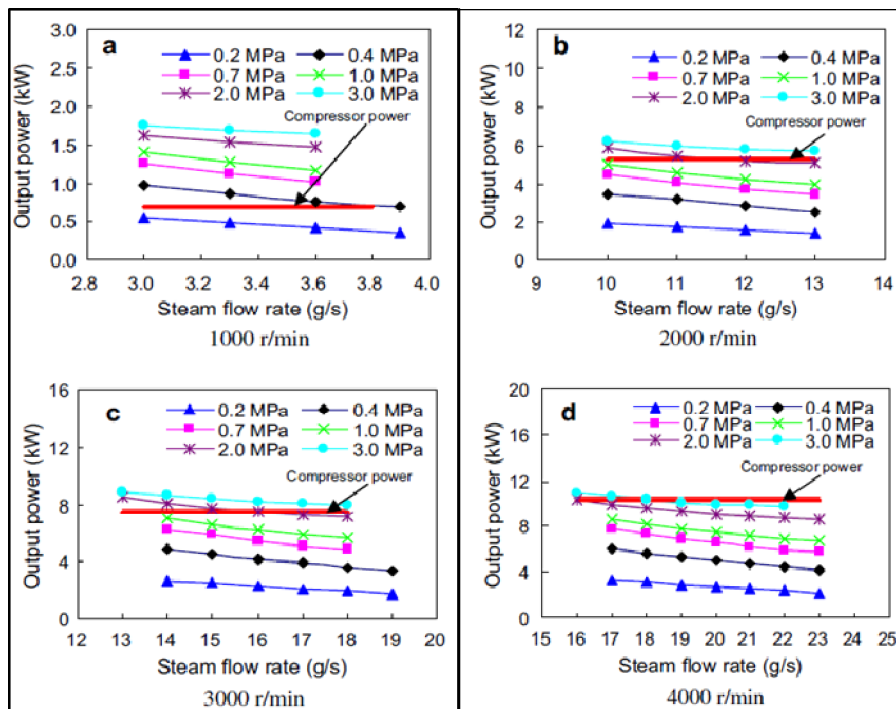
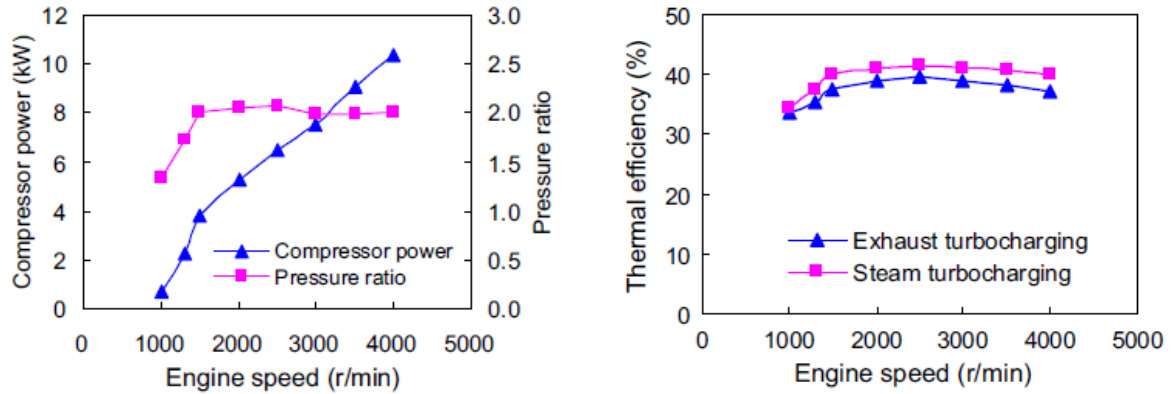


Fig no. 4

Fig no. 5

IV. SUMMARY

In this report, a novel concept of steam turbocharging was proposed to boost IC engine intake pressure. Compared to other boosting pressure means, e.g. exhaust turbocharging, it has lots of advantages and can effectively improve IC engine performances. Based on the analysis above, some conclusions are drawn:

(1) Because exhaust turbocharging system reuses IC engine exhaust energy through exhaust direct expansion, its performances are only determined by exhaust parameters, especially the exhaust pressure. However, steam turbocharging system recovers IC engine exhaust energy based on heat transfer and steam power cycle. And its

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performances can be optimized by selecting bottom cycle system parameters, such as steam pressure and flow rate. Moreover, this technology can be directly applied on IC engine without changing its main structure.

(2) When the steam turbocharging system is applied on IC engine, both the power and thermal efficiency of IC engine are enhanced on the basis of exhaust turbocharging engine.

(3) In the exhaust turbocharging system, turbine output work is at the cost of increasing IC engine exhaust process work. At medium-speed and high-speed, almost half of turbine output work comes from the piston promotion work and the remaining is from exhaust expansion work. At low-speed, almost all turbine output work comes from piston promotion work since the exhaust energy is very low. Consequently, exhaust turbocharging system has direct influence on IC engine working processes. In the steam turbocharging system, all the turbine output work comes from exhaust thermal energy. Steam turbocharging system uses exhaust thermal energy to generate steam for turbine through heat transfer. By this means, it has very little effect on IC engine working processes.

(4) By coupling a motor on the transmission shaft, steam turbocharging system has better performance in the whole speed range. In this way, the motor can effectively manage bottom cycle energy flow, and part of extra output power can be recovered by motor. As a result, IC engine fuel efficiency can be further improved. Usually, higher steam pressure and lower steam flow rate correspond to more extra bottom cycle output power.

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