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Study of two-stage turbine characteristic and its influence on turbo-compound engine performance

Rongchao Zhao [a,b], Weilin Zhuge [a], Yangjun Zhang [a,*], Mingyang Yang [b], Ricardo Martinez-Botas [b], Yong Yin [c]

[a] State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing, China
[b] Imperial College London, UK
[c] Dongfeng Commercial Vehicle Technical Center, Dongfeng Motor Co., Ltd, Wuhan, China

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ABSTRACT

Turbo-compounding is an effective way to recover waste heat from engine exhaust and reduce fuel consumption for internal combustion engine (ICE). The characteristics of two-stage turbine, including turbocharger turbine and power turbine, have significant effects on the overall performance of turbo-compound engine. This paper investigates the interaction between two turbines in a turbo-compound engine and its impact on the engine performance. Firstly an analytical model is built to investigate the effects of turbine equivalent flow area on the two-stage turbine characteristics, including swallowing capacity and load split. Next both simulation and experimental method are carried out to study the effects of high pressure variable geometry turbine (HP VGT), low pressure variable geometry turbine (LP VGT) and combined VGT on the engine overall performance. The results show that the engine performance is more sensitive to HP VGT compared with LP VGT at all the operation conditions, which is caused by the larger influences of HP VGT on the total expansion ratio and engine air–fuel ratio. Using the HP VGT method, the fuel reductions of the turbo-compound engine at 1900 rpm and 1000 rpm are 3.08% and 7.83% respectively, in comparison with the baseline engine. The corresponding optimum values of *AR* are 2.0 and 2.5.

1. Introduction

With increasingly stringent legislations on engine emissions, fuel consumptions and higher petroleum price, it is urgent to improve the engine efficiency by developing advanced technology. During the past decade, a number of studies have focused on waste heat recovery (WHR) technology [1]. It is commonly recognized that engine exhaust takes away a large proportion of fuel energy. How to extract the most of energy from the exhaust and maximize the engine efficiency becomes one of the most concerned issues [2].

Various kinds of technology have been developed or even implemented to recover engine waste heat [1–7]. These technologies mainly include Organic Rankine Cycle (ORC), turbo-compounding and thermoelectric generator. In addition, a novel configuration Brayton cycle was proposed by Binyang [5] to recover the waste heat from the exhaust and it reduced the fuel consumption effectively. As for Organic Rankine cycle, it can not only recover waste heat from the exhaust but also from engine cooling water. Furthermore, ORC will not cause significantly higher exhaust back pressure, thus it achieves the best performance in waste heat recovery [7]. However, due to high cost, systems complexity and arrangement difficulty in limited car space, there will be a long way to go before it can be widely used in automobile. As for thermoelectric generator, due to expensive material and low conversion efficiency, further research is required before practical application in automotive industry [1].

Compared with ORC and thermoelectric generator, turbocompound configuration is relatively simple, compact and costless.

The fuel savings obtained by turbo-compound method ranged from approximately 2–6% [8–20]. Particularly, 10% of fuel reduction was obtained at engine full load condition in literature [10]. The turbo-compound method is most successfully applied on heavy-duty diesel engine due to its short paid-pack period.

The total costings of the turbo-compound systems applied on heavy duty vehicle engine are estimated to be USD 1700. It includes USD 600 on power turbine, USD 450 on fluid coupling and USD 650 on gear reduction and etc. The current price of the diesel in China is approximately 1 dollar. Assuming that one truck

* Corresponding author. Tel.: +86 10 62797359.
E-mail address: yjzhang@tsinghua.edu.cn (Y. Zhang).

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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)
- k adiabatic exponent
- $\dot{m}$ air mass flow rate (kg/s)
- N revolution speed (rpm)
- p pressure (Pa)
- P power (kW)
- R gas constant (J/kg K)
- T temperature (K)

Acronyms
- *AR* area ratio, $C_{LPT}A_{LPT}/C_{HPT}A_{HPT}$
- BSFC brake specific fuel consumption
- VGT variable geometry turbine
- HPT high pressure turbine
- LPT low pressure turbine
- MFP mass flow rate parameter, $\dot{m}\sqrt{T_{0,in}}/p_{0,in}$
- TST two-stage turbine

Greek symbols
- η efficiency
- π expansion ratio

Subscripts and superscripts
- 0 stagnation state
- 1–6 locations from compressor inlet to turbine exit

runs 200,000 km one year and the fuel consumptions is 40 L/100 km, the annual costing of fuel is up to USD 80,000. The relationships between the fuel savings and the paid-back period can be estimated as Table 1.

For these reasons, turbocompounding has been successfully applied in heavy duty diesel engine and drawn increasingly more attentions to exploit its potential [5–17]. Wei [9] numerically compared the performance of three different turbocompounding schematics, including integrated, series and parallel configurations. Results showed that the parallel configuration achieved the best fuel performance. Hopmann [10] and Millo [11] carried out their research based on integrated configuration. An electric motor/generator was integrated into the turbocharger shaft to extract surplus power from the turbine. The electricity it produces was used to run a motor mounted on the engine crankshaft. At speedup conditions, the electric motor can help to accelerate the turbocharger. In their research, 10% and 6% fuel reduction were attained respectively. Ismail [12,13] also compared the potential of series and parallel configurations in a numerical way. Contrary to Wei Wei's research, it is shown that the series architecture is superior to the parallel one. This is probably due to different adjustment methods, engine types and turbine characteristics. The common conclusion is that a smaller power turbine is required in parallel case, compared with the series one. The performance of series configuration was also reported in literature [14] and [15]. 1.9% and 2.76% of fuel saving were achieved respectively.

The aforementioned literature mainly discussed the fuel savings results attained by different layouts of turbo-compounding. However, there are still a lot of challenges in further exploiting the potential of turbo-compounding. Different research including systems optimization, component design and control were carried out to resolve some certain issues of turbo-compounding [16–21]. In Ishii's report [16,17], the effects of key parameters, including the turbine expansion ratio, compressor pressure ratio and engine compression ratio on the engine performance was analyzed using a numerical method. Results showed that there existed optimum values of turbine expansion ratio, compressor pressure ratio to achieve lowest fuel consumption. Mamat [18,19] found that the conventional turbine efficiency at low expansion ratio condition is ultra-low, which is not suitable for turbo-compounding. To resolve the problem, a special power turbine was designed to achieve high performance at low pressure ratio conditions. Katsanos [20] numerically investigated the effects of power turbine revolution speed on engine performance and found that there exited an optimum value of power turbine speed to achieve lowest BSFC at different engine load conditions. Furthermore, Boretti [21] proposed a continuously variable transmission to connect the power turbine shaft and engine crankshaft, in order to achieve best engine performance at engine different operation conditions.

Table 1
The relationship between fuel savings and paid-back period.

Fuel savings (%)	2	3	4	5
Annual cost savings (USD)	1600	2400	3200	4000
Paid-back period (year)	1.06	0.71	0.53	0.43

One of the most concerned issues in turbo-compound engine is the expansion ratios in turbocharger turbine and power turbine (i.e., load spilt between two turbines), as discussed in the literature [16,17]. However, two important questions regarding to this issue have not been answered, according to the authors' knowledge. The first one is what decides the load spilt in two turbines. It should be concerned to the characteristic of two turbines. Understanding this question can help us to attain the optimal load spilt by choosing two right turbines. The second question is how the load spilt will change as the engine operation changes. It can be understood that there will be optimal load splits corresponding to certain engine operation condition. However, the optimal load splits at different engine operation conditions may correspond to different turbines. In other words, it is impossible to achieve the optimal load splits without changing the turbines as engine operation condition changes.

In this paper, the characteristic of a two-stage turbine will be analyzed using an analytical method firstly, aiming at understanding the effects of area ratio (*AR*) on the load split between two turbines. After that, simulation model of turbo-compound engine was established to study the effects of HP VGT and LP VGT on the engine performance. Engine experiment was also carried out to investigate the effects of HP VGT and the experiment results were used to calibrate the engine simulation model.

2. Analytical method and simulation model descriptions

The schematic of the turbo-compound diesel engine is shown in Fig. 1. It can be seen that the power turbine (LPT) is fitted downstream the turbocharger turbine (HPT) to recover waste heat from the exhaust. The power turbine shaft is connected to the engine crankshaft by gear reduction and fluid coupling. In this way, the recovery energy is transferred to the crankshaft to increase the engine power output. In this section, theoretical analysis of two-stage turbine and description for the engine simulation model will be presented in detail.