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Research Paper

Influence of altitude on two-stage turbocharging system in a heavy-duty diesel engine based on analysis of available flow energy

Mingyang Yang [a,*], Yuncheng Gu [a], Kangyao Deng [a], Zhenhuan Yang [b], Sheng Liu [b]

[a] Shanghai Jiao Tong University, Shanghai, 200240, China
[b] China North Engine Research Institute, Tianjin, 300400, China

HIGHLIGHTS

- Influence of altitude on characteristics of two-stage turbines is firstly demonstrated.
- Mechanism of influence of altitude on two turbines is understood by the energy analysis.
- The energy fed to turbocharger is more sensitive to high pressure turbine.
- Energy split to low pressure turbine is more sensitive to the variation of altitude.

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ABSTRACT

Understanding characteristics of a regulated two-stage turbocharging system is key to maximize its potential for power recovery of an engine at high altitudes. The target of this paper is to understand the influence of the altitude on the performance of a regulated two-stage turbocharging system in Internal Combustion Engine. The investigation is performed in perspective of available flow energy in a heavy-duty diesel engine via analytical and experimental methods as the altitude increases from 0 km up to 4.5 km. Results demonstrate significant effects of the altitude on the flow energy fed to the turbocharging system and energy split between two turbines: the energy fed to the system increases with the altitude due to the increase of exhaust temperature and pressure ratio, but the energy deficit of power recovery also increases with the altitude. The overall available flow energy is more sensitive to the high pressure turbine because of its relatively smaller effective flow area. But the energy split to the low pressure turbine is more sensitive to the altitude, which is caused by behaviors of pressure ratio split between two turbines. New directions of optimized regulating method of a two-stage turbocharging system are suggested according to the investigation for the engine performance at different altitudes.

1. Introduction

There are large areas in China with high altitude up to 5 km above the sea level, where construction trucks are widely employed for the development of infrastructures. However, the performance of Internal Combustion Engine (ICE) deteriorates when the altitude increases due to the reduction of the ambient pressure and the temperature. Extensive researches have shown that the brake thermal efficiency of ICE reduces remarkably with the increase of the altitude [1,2]. Generally, the fuel consumption of a naturally aspirated engine increases by 2–12% depending on engine speeds as the altitude increases by every 1 km, and the deterioration becomes more dramatic as the altitude goes higher [3]. Turbocharging is the main method of power recovery for ICE at high altitude. The amount of fresh air can be recovered to some extent by enhancing the boost at high altitude and hence for the engine performance. However, a fix-geometry turbocharger which works well at low altitude may encounter problems such as over-speed or overheat as the altitude increases [4,5]. At the meantime, operating conditions of the turbocharger migrate with the altitude and the compressor may be forced to run beyond safe regions (choke or surge). Although the intake can be compensated by the enhancement of boosting, it remains a challenge that the power of the engine is recovered in a wide range of altitudes by a fix-geometry, single stage turbocharger, especially for engines with high power density.

Regulated two-stage turbocharging system has been applied to improve engine performance in wide range of altitudes [6,7]. Compared with a single-stage turbocharger, higher boosting pressure

* Corresponding author.
E-mail address: myy15@sjtu.edu.cn (M. Yang).

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Nomenclature

A	area (mm^2)
BSFC	brake specific fuel consumption (g/(kW·h))
C_p	specific heat (J/(kg·K))
Ea	available flow energy (kW)
Ed	demanded energy (kW)
HC	high pressure compressor
HT	high pressure turbine
ICE	internal combustion engine
LC	low pressure compressor
LT	low pressure turbine
m	mass flow rate (kg/s)
P	pressure (bar)
PR	pressure ratio
RPR	ratio of the pressure ratio of two turbines
ER	ratio of the available flow energy of two turbines
T	temperature (K)
VNT	variable nozzle turbine
WG	waste gate

Greek letters

α	excess air coefficient
η	efficiency
λ	ratio of the equivalent flow area
ρ	density
φ	mass flow coefficient of the throttle/turbine

Subcripts

amb	ambient
exi	exit
H	high pressure turbine
in	inlet
L	low pressure turbine
s	static
tc	turbocharger
Tot	total
WG	waste gate
1	station upstream the two-stage turbine
2	station in the middle of two turbines
3	station at exit of the two-stage turbine

can be more easily achieved by sequential compression in two-stage turbocharger, thus it has good potential for wider operational range and higher efficiency because of relatively low pressure ratio for each turbocharger [8]. On the other hand, because there are more freedoms of the adjustment in a two-stage turbocharging system, the control strategy is the core of maximizing the advantages of the system. The strategy has to be tailored for engine performance not only at different engine loads and speeds as being studied in many literatures, but also at different altitudes which on the other hand is occasionally studied.

Extensive researches have been carried out on control methods of the regulating devices such as bypass valves and waste gates in two-stage turbocharging system [9–12]. The regulation on the high pressure stage is the most widely applied architecture. The waste-gated low pressure turbine can be occasionally noticed in literatures, of which the purpose is to control the boost pressure only when the high pressure stage is fully bypassed [13]. However, these two turbochargers are coupled closely in the system. The characteristics of each turbocharger and their interactions are important to obtain a complete scenario before going for detailed mapping of control strategies on either of them. Galindo studied the influence of the architecture of a two-stage turbocharger on engine performance [14]. The impacts of turbine efficiency, overall pressure ratio and the intercooling on the engine performance were checked in details by an analytical method. It was found that the optimized pressure ratio of the low pressure turbine increased linearly with the overall pressure ratio. Inspired by findings, it was concluded that either the waste gate or VGT could be applied on high pressure turbine to achieve the optimized engine performance, which is the case for a traditional two-stage system. The discussions in the investigation mainly focused on the performance of engine performance. Zhao carried out a numerical investigation on the two-stage turbine (a turbocharger radial turbine plus an axial power turbine) in a turbo-compound diesel engine [15]. The pressure ratio split between two stages was confirmed to be depended on the overall pressure ratio. Furthermore, effects of the high pressure turbine (HT) and the low pressure turbine (LT) on the engine performance were discussed. It was concluded that HT has more evident effect on the brake specific fuel consumption (BSFC). Although different effects on the engine performance by two stages have been demonstrated, the mechanism of the phenomenon has not been comprehensively discussed. Furthermore, because there was no compressor connected to the power turbine, the influence of these discrepancies on the compressors in the two-stage turbocharging system can't be explored. Finally, the influence of the altitude, which is an extra dimension of mapping the control strategy except for the engine load and the speed, has not been involved in all these studies. Therefore, it is necessary to study detailed characteristics of two-stage turbocharging system under different operational conditions in a range of altitudes. The guidance on the optimized turbocharging architecture as well as control strategy can be obtained from the investigation.

At high altitudes, the reduction of the fresh intake can be contributed to the imbalance of the available energy upstream the turbine and the demanded energy for higher boosting. The variation of the energy with the altitude consequently influences the operation of the two-stage turbocharger in an engine, which justifies the necessity of the turbocharging regulation at different altitudes for the optimization of engine performance. Therefore, it is possible to study the influence of the altitude on engine performance in perspective of the flow energy in the turbocharging system. Indeed, the analysis via the perspective of the energy has already been proved as a useful method for the understanding of engine performance and the guidance of its optimization [16–18]. The energy and the exergy are analyzed in working processes of an engine and the irreversibility can be traced, thus can guide the performance improvement of the engine. Comprehensive investigations have been carried out by Rakopoulos on the available energy (availability) of ICE with different types of fuels via the combination of the first and the second law of thermodynamics. Deep insights have been obtained by the method, which helps monitoring the influence of engine parameters on irreversible processes and hence the engine performance [19,20].

In this paper, the influence of the altitude on a regulated two-stage turbocharging system in a heavy duty diesel engine is analyzed in the perspective of the available flow energy. The paper is organized in four sections. Investigation methods are firstly introduced and validated/calibrated, followed by discussions about the influence of altitude on the available flow energy fed to the turbocharging system and the energy split between two stages,