Applied Thermal Engineering 128 (2018) 1196–1207

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Analysis on altitude adaptability of turbocharging systems for a heavy-duty diesel engine

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HIGHLIGHTS

- Method of altitude-adaptability evaluation and turbo-engine matching at altitudes is developed.
- Altitude-adaptability of 4 turbocharging systems is quantified based on the method.
- Operation region at plateau is limited by cylinder pressure, turbo-speed and exhaust tempearture.
- Influence of turbine area on operation region is contrary to that of turbo efficiency.
- Fuel margin is the root of influence of the area and efficiency on operational boundaries.

ARTICLE INFO

Article history:
Received 9 June 2017
Revised 27 August 2017
Accepted 13 September 2017
Available online 14 September 2017

Keywords:
Diesel engine
Turbocharging
Altitude adaptability
Operational region

ABSTRACT

This paper aims to understand discrepancies of altitude adaptability among several widely applied single-stage turbocharging systems, and to develop a method of performance evaluation and turbocharger-engine matching at different altitudes. The investigation is carried out on a 6-cyclinder V-type turbocharged heavy-duty diesel engine via experimentally validated simulation method. It is concluded that the operational region with engine power recovery at different altitudes is bounded by three limits, which are the maximum cylinder pressure, turbocharger speed and exhaust temperature. The operational region is studied for the evaluation of altitude adaptability and turbocharger-engine matching at different altitudes. The influence of the turbine effective flow area and turbocharger efficiency on the operational boundaries are discussed. It is concluded that the influence on the intake mass flow rate and fuel margin is the root for the influence on the boundaries. At last, comparisons among four turbocharging systems (a fixed geometry, two waste-gate and a variable geometry) are carried out based on the theory of the operational region. Results show that the variable geometry turbocharging (VGT) has the best altitude adaptability with regard to the maximum altitude with power recovery and BSFC. Its superior results from the capability of turbine area variation as well as the potential for higher efficiency. A method of optimized turbocharger-engine matching tailored for altitude adaptability are obtained from the investigation.

1. Introduction

There are large areas in China with high altitude up to 5 km above the sea level. Construction trucks are widely used for developments of infrastructures in these areas, but the performance of their engines is dramatically influenced by the altitude as a result of the variations of ambient conditions. Experimental results show that the output power of a natural aspirated engine reduces by 5–10% as the altitude rises by every 2 km [1]. Turbocharging is one of the main methods for engine power recovery at high altitudes. The intake mass flow rate can be recovered to some extent by turbocharging as the altitude rises, thus the engine performance can be improved compared with that of the natural aspirated one. Results show that the degradation of engine performance can be remarkably alleviated (by about 24%) by employing turbocharging [2,3].

Several types of turbocharging systems are normally applied for engine power recovery at high altitudes. However, a turbocharger tends to encounter severe problems as overspeeding or overheating

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https://doi.org/10.1016/j.applthermaleng.2017.09.065
1359-4311/

Nomenclature

A	area [mm^2]
BSFC	brake specific fuel consumption [g/(kW·h)]
P	pressure [bar]
N	turbocharger speed [RPM]
T	temperature [K]
ICE	internal combustion engine
VGT	variable geometry turbocharger
WG	waste-gate turbocharger
FG	fixed geometry turbocharger
CA	crank angle
η	turbocharger efficiency [–]

Subscripts

ext	exhaust
tur	turbine
cyl	cylinder

when the altitude goes high [4–7]. Experimental results of a heavy duty turbocharged diesel engine demonstrates that the exhaust temperature can increase by more than 30% as the altitude raise from sea level to 4.5 km. The reduction of intake mass flow rate results in the postponed fuel ignition and less exhaust gas, and hence the exhaust temperature increases dramatically. In order to overcome these difficulties, adjustable geometry turbocharging methods are introduced for the engine operation over wide range of altitudes. The bypassed/waste-gated turbocharging (WG) is a widely applied method for such a purpose. When the engine is operated at high altitudes, the bypass valve/waste gate is closed to guarantee sufficient boosting and hence the intake mass flow rate. However, the device has to be opened to avoid overboosting and high pumping loss at low altitudes. The turbo-engine matching methodology and control strategy of the valve/waste gate have been studied extensively for the satisfied altitude adaptability [8,9]. Variable geometry turbocharger (VGT) is another effective device for power recovery at high altitudes. The turbine area can be adjusted conveniently via changing nozzle opening, thus is able to adapt to different operational conditions [9–12]. Zhang investigated the performance of a 6-l diesel engine with VGT at different altitudes [13]. The results proved that the rated power of the engine can be improved by 1.3% at 5 km by the VGT via the optimization of turbo-engine matching and control strategy. Regulated two-stage/sequential turbocharging is also applied for the engine power recovery at high altitudes [14–18]. It is confirmed that the rated power, the maximum torque as well as the torque at low speeds are all evidently improved by the state of art control strategy on the system.

The influences of different turbocharging systems on the engine performance at different altitudes have been demonstrated extensively in previous investigations. Moreover, discrepancies of the capability on altitude adaptability among these methods can be indicated from the researches. Chen carried out a detailed comparison of engine performance equipped with the two-stage turbocharger and a single stage turbocharger at different altitudes via numerical method [19]. The results showed that two-stage turbocharging is notably superior over the single stage for engine output torque and BFSC at high altitudes. In general, quite few investigations have been performed to understand and quantify the discrepancies of altitude adaptability among turbocharging systems. Instead, extensive researches focus on the turbo-engine matching methodologies or control strategies of a specific type of turbocharging system. The effective flow area of a turbine and turbocharger efficiency are the two most important factors of a turbocharging system for engine performance. Small turbine area can improve the boost pressure, but increase the pumping loss at the same time because of high backpressure [20,21]. High efficiency of turbocharging system has positive effect on the reduction of pumping loss. However, when the engine is operated at different altitudes, how these factors of the turbocharging system influence the altitude adaptability of the engine is needed to be further studied. It is necessary to deepen these understandings in order to maximize the potential of the capability of turbocharging on power recovery at different altitudes.

This paper studies the altitude adaptability of turbocharging systems in a heavy-duty diesel engine via experimentally validated numerical method. The paper is organized in three sections: the simulation method is introduced and validated firstly, followed by the development of theory of engine available operational regions. Finally, based on the theory developed in previous sections, the direct comparison on the altitude adaptability among four turbocharging systems is performed.

2. Simulation method of the turbocharged engine

A 6-cyclinder heavy-duty V-type turbocharged diesel engine is employed for the investigation. Main parameters of the engine are list in Table 1. There is a single-stage turbocharger in each branch of the manifold. Different altitudes are simulated by different ambient conditions at the inlet and exit of manifolds. Normally, the ambient pressure and temperature are the two factors related with the influence of the altitude. Furthermore, it has been confirmed that the ambient pressure is the predominant contributor to the influence [5]. Therefore, the ambient pressure is the only factor considered for altitude simulation in the investigation.

Numerical method is applied for detailed analysis of turbocharging systems in the engine. The commercial software GT-Power which is specialized for engine simulation is employed for the investigation. The 1-D pipe network connected in the same topology with actual configurations is used to model engine manifolds. The mesh size of the pipe network is 0.4 times of the cylinder bore diameter, which can guarantee a reasonably good prediction [22]. The Woschni model is applied to model heat transfer in cylinders. The semi-predictive neural-network-assisted DI-Wiebe model is employed to model the combustion, which has been proved reliable of predicting combustion at different ambient conditions [23,24]. Performance maps of the compressor and the turbine from experiment are used for the model of turbocharger. Fig. 1 shows the layout of the engine model.

Table 1
Main parameters of the engine.

Engine parameters	Value
Number of cylinders	6
Arrangement	V-type
Compression ratio	18
Bore of cylinder	150 mm
Fire sequence	1-5-3-6-2-4
Number of turbocharger	2