

# Research and Application of Diesel Engine Turbocharging Technology in Plateau Environment

Fengjun Qi, Changting Li, Zaiqiang Miao \*

Vehicle Application Department, Army Academy of Armored Forces, School of Noncommissioned Officers, Changchun, Jinlin, 130117, China

\* leect1991@163.com

**Abstract:** This article summarizes the changes and correction methods of turbocharger compressor characteristics in plateau environments, providing a basis for the plateau matching of diesel engines and turbochargers. Analyze the current research status of plateau matching between fixed cross-section turbochargers, variable cross-section turbochargers, and two-stage turbocharging systems and diesel engines, and explore the potential of variable cross-section turbocharging (VGT), ordinary two-stage turbocharging (TST), and adjustable two-stage turbocharging (RTST) for diesel engine plateau power improvement. Through comparative analysis, the two-stage adjustable turbocharging system based on VGT combines the advantages of two-stage turbocharging and VGT technology, and has the characteristics of high pressure ratio and wide flow rate, which can significantly improve the comprehensive performance of diesel engines on high altitudes.

**Keywords:** Diesel engine; Plateau; Power improvement; Variable cross-section turbocharging; Two stage adjustable boost.

## 1. Introduction

The plateau area of China accounts for approximately 37% of the national territory, with the Qinghai Tibet Plateau covering an area of approximately 2.4 million km<sup>2</sup> and an average elevation of over 4000m. When a diesel engine operates on high altitudes, the decrease in atmospheric pressure and air density leads to a decrease in intake air quality, a decrease in air fuel ratio, and combustion deterioration, resulting in a decrease in diesel power and fuel economy, an increase in heat load, and an increase in carbon smoke emissions. As the "heart" of various vehicles, engineering machinery, agricultural machinery, generator sets and other mechanical equipment, diesel engines' adaptability to high altitude environments directly determines the effective performance of mechanical equipment in high altitude areas. Therefore, improving the plateau adaptability of diesel engines is the key to improving the overall performance of mechanical equipment. Numerous studies have shown that turbocharging technology has become a key technology for diesel engine power recovery at high altitudes.

The altitude of the major developed countries in the world is generally below 3000m, and 100% of heavy-duty vehicle diesel engines use turbocharging technology. Its advanced turbocharging technology allows diesel engines to have a large power reserve, which can maintain the power below 3000m without decreasing. However, there is relatively little research on the related issues of diesel engines above 3000m. Due to the special plateau environment in China, research has mainly been carried out on the changes and corrections of turbocharger compressor characteristics in plateau environments, as well as the matching of single stage and multi-stage turbochargers with diesel engines at high altitudes, focusing on the recovery of diesel power in plateau areas.

## 2. Changes and Correction of Turbocharger Compressor Characteristics in Plateau Environment

### 2.1 Changes in compressor characteristics with altitude

In plateau environments, with the increase of altitude, the intake volume of diesel engines decreases and their power significantly decreases. Exhaust gas turbocharging is an effective method for diesel engine power recovery at high altitudes. However, the effectiveness of power recovery is closely related to the performance of turbochargers. In order to study the impact of plateau environment on turbocharger performance, Huazhong University of Science and Technology [2] calculated and analyzed the changes in Reynolds number of compressors at different altitudes and their impact on turbocharger performance based on the main parameters of the 11GJ turbocharger compressor. The research results indicate that the Reynolds number of small turbochargers decreases sharply with the increase of altitude, resulting in a significant decrease in compressor efficiency, early occurrence of surge, and narrower operating range. Therefore, it is proposed that the "general characteristic curve" of compressors based solely on Mach number equality should not be directly used in high-altitude areas.

The Xining Plateau Engineering Machinery Research Institute [3] conducted simulation tests on 80J-III turbochargers to verify the conclusion that Reynolds number decreases with altitude, and obtained the relationship between the adiabatic efficiency, pressure ratio, flow rate, surge line and other parameters of the turbocharger compressor with altitude. The results show that for every 1000m increase in altitude, the adiabatic efficiency of the compressor decreases by 0.79% to 1.64%, the pressure ratio decreases by 1.16% to 2.69%, the flow rate decreases by 0.74% to 9.02%, and the compressor surge line narrows by 0.51% to 4.83%.

Therefore, when a turbocharged diesel engine operates in highland areas, the increase in exhaust temperature and the decrease in turbine back pressure of the diesel engine cause the speed of the exhaust turbocharger to increase with altitude. At the same time, the speed of the compressor coaxial with the turbine also increases synchronously, thereby increasing the boost pressure, partially compensating for the impact of the decrease in intake charge caused by the increase in altitude. However, at the same time, the performance parameters of the turbocharger have also undergone changes, such as an increase in temperature before the turbine, an increase in turbocharger speed, a decrease in compressor efficiency, and a rightward shift in the surge line, which can easily cause turbocharger overspeed and surge.

### 2.2 Plateau correction of compressor characteristics

Under high altitude atmospheric conditions, the Reynolds number of the internal flow of the turbocharger decreases, the influence of gas viscosity increases, the viscous friction increases, and the flow boundary layer thickens, resulting in a decrease in efficiency and a narrowing of the flow range when the turbocharger operates at high altitude. The performance MAP map is significantly different from that of the plain. The performance changes of the turbocharger lead to inaccurate matching of diesel engine turbocharging, resulting in a decrease in effective inflation and deterioration of combustion. In order to achieve the best match between diesel engines and turbochargers under plateau environmental conditions, it is necessary to perform plateau correction on the compressor characteristics. Wiesner [4] proposed in 1979 an empirical formula for converting adiabatic efficiency along the isokinetic line of a compressor:

$$\frac{1-\eta_K}{1-\eta_{K0}} = a + (1-a)\left(\frac{Re_0}{Re}\right)^\gamma \quad (1)$$

In the formula,  $a$  is a constant, ranging from 0.15 to 0.57;  $\gamma$  is a constant, 0.17-0.50;  $\eta_K$  is the adiabatic efficiency of the compressor;  $Re$  is the Reynolds number; The corner mark "0" represents the test condition value.

In equation (1),  $a$  and  $\gamma$  are two constants, but the numerical range is large. How to select corresponding values based on the structure and characteristics of different compressors becomes the key to accurately correcting compressor efficiency.

Beijing University of Aeronautics and Astronautics [5] derived the efficiency correction formula for turbochargers and compressors in plateau engines through model theory:

$$\frac{1-\eta_K}{1-\eta_{K0}} = \left(\frac{Re_0}{Re}\right)^{0.25} \quad (2)$$

And a comparative analysis was conducted with the Wiesner conversion formula. The results show that within an altitude of 6000m, the efficiency curves calculated by the two formulas have good synchronicity and overlap throughout the entire flow range, and this equation more clearly represents the relationship between  $Re$  and the efficiency of the turbocharger compressor, providing a basis for studying the plateau matching of diesel engines and turbochargers.

### 3. Matching single stage turbochargers with diesel engines at high altitudes

Due to changes in atmospheric conditions on the plateau, the matching characteristics of turbochargers, gas consumption characteristics, and combustion characteristics of diesel engines have also changed compared to those on the plain, resulting in abnormal performance of diesel engines. Therefore, the matching problem between turbochargers and diesel engines at varying altitudes and operating conditions has always been a focus of attention.

#### 3.1 High altitude matching between fixed cross-section turbochargers and diesel engines

At present, around the plateau matching problem of fixed section turbochargers and diesel engines, the State Key Laboratory of diesel engine high turbocharging technology, Weichai Power Co., Ltd., Military Transportation College and other units have carried out a lot of theoretical calculation and test work, and put forward the plateau matching principles and limitations of fixed section turbochargers and diesel engines. Research has shown that fixed section turbochargers should not only have sufficient overtemperature and overspeed capabilities, but also have a 10% to 15% surge margin when used at high altitudes; Matching turbochargers with high pressure ratio, high flow rate, and high efficiency can effectively improve the high altitude power performance of diesel engines, but there is also a phenomenon of excessive turbocharging in plain areas. Therefore, through local improvement and selection matching of the turbocharger, only a portion of plateau power can be restored, but it cannot balance the performance of the diesel engine on both plain and plateau. In practical use, there are still problems such as insufficient diesel power, poor economy, high exhaust temperature, slow transient response, and turbine overtemperature and overspeed. In addition, the matching between turbochargers and diesel engines is mostly focused on fixed altitude and fixed operating conditions, which cannot meet the working requirements of diesel engines with varying altitude and operating conditions.

#### 3.2 High altitude matching between variable cross-section turbochargers and diesel engines

Variable geometry turbo charger (VGT) turbocharger controls the turbocharger speed and intake pressure by changing the flow cross-sectional area of the turbocharger turbine, expanding the efficient working range of the turbocharger. Under certain altitude conditions, it can improve the low-speed torque characteristics and economy of diesel engines, improve their acceleration performance, reduce exhaust temperature, and prevent turbine overspeed. Tsinghua University [6] and the State Key Laboratory of High Turbocharging Technology for Diesel Engines [7] designed a variable section turbine based on the original fixed section turbine, and conducted performance comparison tests of diesel engines at different altitudes. The results show that variable cross-section turbochargers effectively solve problems such as torque difference, compressor surge, and turbine overtemperature and overspeed in the low speed zone, but the limitations of compression ratio and

flow rate limit the power recovery potential at high altitudes; Compared with the original machine, the rated power and maximum torque are increased by 1.77% and 5.49% respectively at an altitude of 3000m, and by 1.28% and 2.91% respectively at an altitude of 5000m. Iveco, an Italian company, adopted VGT technology and developed control strategies at different altitudes, enabling the Crusor10 diesel engine to have a certain altitude power compensation capability and meet Euro IV emission requirements.

#### **4. Two stage turbocharging system and diesel engine plateau**

As the altitude increases, the atmospheric pressure decreases, and using only single stage turbocharging technology cannot provide sufficient intake pressure for diesel engines. The two-stage turbocharging technology uses two compressors in series to charge the intake air twice, greatly improving the high altitude intake pressure of the diesel engine, and can basically restore the rated power of the diesel engine to the plain level. It is a key technology for improving diesel power in plateau areas. The two-stage turbocharging system is a composite turbocharging system composed of two turbochargers connected in series. According to the different forms of two-stage turbochargers, they can be divided into ordinary two-stage turbocharging (TST) and adjustable two-stage turbocharging (RTST). Among them, the ordinary two-stage turbocharged system (TST) consists of two ordinary turbochargers (TC+TC); The adjustable two-stage turbocharging system (RTST) consists of a VGT and a regular turbocharger (VGT+TC). Foreign countries have conducted early research on two-stage turbocharging technology, and some major companies such as Borgwarner and Honeywell have applied two-stage turbocharging technology to large trucks and sedans, greatly improving various performance indicators of vehicles. After Opel Company [9] matched its automotive diesel engine with a two-stage turbocharging system, the rated power of the diesel engine can be increased to 156kW, with a maximum torque of 400N · m at a speed of 1400r/min, an average effective pressure of 2.6MPa, and an acceleration time of only 6.5s per 100 kilometers, greatly eliminating the problem of turbocharging. Borgwarner and BMW jointly developed a two-stage adjustable turbocharged diesel engine based on VGT, which improves the power performance of the diesel engine by about 25%, reduces fuel consumption by 20%, and has fast responsiveness at low speeds, while having a large power reserve at high speeds[10-12].

Many domestic universities, such as Shanghai Jiao Tong University, Beijing University of Technology, Kunming University of Technology, Jilin University, and Military Transportation College, have conducted research on the selection and matching of two-stage turbocharging systems, the selection and design of turbine control valves, and the analysis of their regulation capabilities, as well as the development of software for engine matching. The research results indicate that the two-stage turbocharging system effectively improves the performance indicators of diesel engines. The different opening degrees of the turbocharging valve in the two-stage turbocharging system have a significant impact on the turbine expansion ratio, flow distribution, turbine efficiency changes, and overall performance. This provides a basis for optimizing the regulating ability of the two-stage turbocharging system. Although a large amount of research has been conducted on two-stage turbocharging technology both domestically and internationally, research on two-stage turbocharging technology for plateau environmental conditions has only just begun. Professor Ma Chaochen from Beijing Institute of Technology has designed a multi valve two-stage turbocharging system for high-altitude environments ranging from 0 to 5500m. The high-pressure stage of the system uses the original turbocharger unchanged, and the turbine regulating valve is a mechanical exhaust valve. The opening of the low-pressure stage turbine regulating valve decreases with altitude, and it is completely closed at 2000m above sea level, switching from single stage turbocharging to two-stage turbocharging, ensuring the intake volume of high-altitude diesel engines. The results show that compared to single stage turbocharging, two-stage turbocharging at an altitude of 5500m[13-14].

## 5. Analysis of the Potential of Turbocharging Technology for Improving Diesel Engine Power at High Altitude

Through comparison of several turbocharging technologies, both VGT turbocharging technology and two-stage turbocharging technology can improve the plateau power performance of diesel engines, making them advanced technologies for plateau power recovery. Table 1 lists the performance comparison of VGT, TST, and RTST turbocharging technologies[15-16].

Table 1. Comparison of Performance Technologies of Three Boosting Technologies

Index	VGT	TST	RTST
Boost ratio	<3.5	>4 (mechanical strength allowed)	>4 (mechanical strength allowed)
Efficient Zone Flow Range	Efficient Zone Flow Range	narrow	wide
Power increase/(kW · L-1)	Limited improvement (<35)	Significant improvement (>40)	Significant improvement (>40)
Medium and low speed torque	Increase by 8% to 25%	Increase by more than 20%	Increase by more than 25%
Low speed fuel consumption rate	5% to 10% decrease	More than 9% decrease	The fuel consumption rate can be reduced under all operating conditions
Transient response characteristics	preferably	difference	good
Control strategy requirements	Single control parameter	No need for complex electronic controls	Increase in control parameters
Installation space requirements	Same as the original single stage supercharger	enlargement	enlargement
Connecting pipelines (lines)	Same as the original single stage supercharger	Add intake and exhaust, lubrication pipelines	Add intake and exhaust, lubrication pipelines, and control circuits
High altitude application potential	Strong adaptability to changing working conditions, weak adaptability to changing altitude	Strong adaptability to changing altitude, weak adaptability to changing working conditions	Strong adaptability to changing altitude and working conditions

From the table, it can be seen that the VGT turbocharger can achieve adaptive turbocharging under variable operating conditions, greatly improving the high altitude adaptability of the vehicle's diesel engine. However, in order to restore the power of diesel engines to the level of plains in plateau areas, the turbocharging ratio of the turbocharging system should be at least 4 or higher. Therefore, the VGT turbocharger is difficult to meet the requirements and requires the use of two-stage turbocharging technology. At the same time, if a conventional two-stage turbocharging (TST) system is used, it will be difficult to meet the goal of diesel engines having optimal power and economy at varying altitudes and operating conditions. Therefore, a two-stage adjustable turbocharging (RTST) system is required.

## 6. Conclusion

(1) When a diesel engine operates at high altitudes, as atmospheric pressure decreases, the intake volume decreases, resulting in a decrease in power and economy, and an increase in exhaust temperature. In order to improve the working efficiency of the engine, it is necessary to use turbocharging technology to increase the intake volume. This article systematically sorts out and analyzes three turbocharging technologies: variable cross-section turbocharging, ordinary two-stage

turbocharging, and adjustable two-stage turbocharging, laying the foundation for the next step of improving the engine's performance on plateau.

(2) The two-stage adjustable turbocharging system based on variable cross-section turbocharging combines the advantages of two-stage turbocharging and variable cross-section turbocharging technology. It has the characteristics of high pressure ratio and wide flow rate, and can comprehensively improve the performance indicators of diesel engines in various working conditions on high altitudes, achieve real-time control of diesel engines at varying altitudes and working conditions, and effectively improve the power and economic performance of engines on high altitudes. Therefore, the two-stage adjustable turbocharging system based on variable cross-section turbocharging has great research and development prospects.

(3) This article analyzes the potential of three turbocharging technologies for improving the plateau power of diesel engines, and compares the characteristics of the three turbocharging technologies. Although adjustable two-stage turbocharging has the greatest potential for improving the plateau power of diesel engines, its installation space, control parameters, and connecting pipelines are relatively difficult and complex. Therefore, different usage environments and requirements should choose a more suitable turbocharging technology. Through this study, ideas and references are provided for the subsequent research and development of turbocharging technology in plateau environments.

## Reference

- [1] Liao Li. High altitude diesel engine turbocharging technology and application [J]. Equipment Management and Maintenance, 2019 (8): 124-126.
- [2] Wang Jun, Shen Lizhong, Wen Yijun, et al. Study on the Matching and Adaptability of High Altitude Boosting for Small Agricultural Diesel Engines [J]. Agricultural Engineering Journal, 2019, 35 (16): 70-77.
- [3] Zhang Zhongjie, Liu Ruilin, Yang Chunhao, et al. Experimental Study on the Characteristics of a Variable Altitude Two Stage Centrifugal Compressor [J]. Automotive Engine, 2020 (2): 42-48.
- [4] Dong Surong, Liu Zhuoxue, Liu Ruilin, et al. Optimization of Compressor Structure under High Altitude Conditions and Its Impact on Diesel Engine Performance [J]. Combustion Science and Technology, 2019, 25 (3): 260-26.
- [5] Liu Yongzhen, Xu Qiangren, Ma Yingqun, et al. A study on bulging control of shock wave losses in the leading edge channel of supersonic compressor cascades [J]. Journal of Aerodynamics, 2019, 34 (10): 2294-2304.
- [6] Liu Haijun, Hou Xianjun, Chen Guisheng, et al Simulation of the working process of variable two-stage turbocharging coordinated main injection timing for diesel engines in plateau environments [J]. Internal Combustion Engine Engineering, 2020, 41 (1): 27-35.
- [7] Jin Rong, Zhang Junyue, Hu Lifeng, et al. Research on High Altitude Adaptive Diesel Engine Turbocharging Technology [J]. Internal Combustion Engine Engineering, 2011, 32 (4): 27-31.
- [8] Jiao Yufei, Liu Ruilin, Zhang Zhongjie, et al Collaborative optimization of diesel engine turbocharging and fuel injection parameters under plateau environmental conditions [J]. Journal of Agricultural Engineering, 2019, 35 (17): 66-73.
- [9] Liu Zhihao, Wei Mingshan, Ma Chaochen, et al. Simulation of single and two-stage turbocharged diesel engines at different altitudes [J]. Journal of Internal Combustion Engines, 2010, 28 (5): 447-452.
- [10] Cao Siqi, Liu Yuqiang, Zhi Huaibin, et al Experimental Study on Improving High Altitude Performance of Diesel Engines with Oxygenated Polymethoxy Dibutyl Ether Fuel [J]. Automotive Engines, 2020 (5): 41-46.
- [11] XU Xiang, SUO Wen-chao, YANG Ding-fu, et al. Heat transfer simulation of vehicle heat exchanger in plateau environment [J]. Journal of system simulation, 2018, 30(8): 3146-3153.
- [12] LIU Jian-min, KANG Qi, WANG Pu-kai, et al. Simula-tion of diesel engine cooling system in plateau environ-ment[J]. Vehicle engine, 2018(3): 16-22.

- [13] Cao Jiabin, Su Shichuan, Zang Ruibin, et al The Effect of Injection Strategy on the High Altitude Combustion Characteristics of a Heavy Duty Diesel Engine [J]. Science and Engineering, 2020, 20 (17): 6878-6885.
- [14] Dong Surong, Liu Ruilin, Zhou Guangmeng, et al Combustion and emission characteristics of coal based composite fuel diesel engines at different altitudes [J]. engineering Journal of Thermophysics, 2018,39 (05): 1161-1167.
- [15] Shen Haitao Research on combustion optimization technology for diesel engines based on intake and injection parameter control [D]. Jilin University, 2018.
- [16] Ma Jiaming, Yang Chunhao, Zhang Zhongjie, et al Current Status and Development Trends of Combustion Optimization Research on High Altitude Diesel Engines [J]. Internal-combustion Engine and Accessories, 2019 (05): 58-60.