Research status and development trend of available exhaust energy management for diesel engine at different altitudes

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Abstract. In order to improve the boosting pressure, intake flow rate and matching characteristics of a diesel engine and turbocharging system at varying altitudes, it is very important to utilize and manage available exhaust flow energy. The advanced air management system can effectively utilize exhaust flow energy and improve the intake pressure of the diesel engine at high altitudes. In this paper, the key thermodynamic parameters of air management systems, management of exhaust flow energy and control of air path at different altitudes are reviewed. At last, two aspects containing control strategy, control algorithm of the air management system were put forward.

1. Introduction

Usually the performance of diesel engines used in highland regions deteriorates because of high altitude and low atmospheric pressure. The engine power and fuel economy decrease, and soot emission and exhaust temperature increase due to the decrease of air-fuel ratio and deterioration of combustion caused by the reduction of air density and later combustion. With the decrease of Reynolds number at high altitudes, the matching characteristics of the turbocharger and the diesel engine change, the flow range of the compressor gradually narrowed, the slope of the surge line increased, and the range of high efficiency area became smaller [1].

In order to improve the matching characteristics of turbocharger and diesel engine plateau and restore the power of diesel engine in plateau, the general method is to match the high flow turbocharger [2] for a diesel engine at fixed operation condition and altitude, but it is impossible to achieve good matching characteristics at high and low speed on plateau, which lead to the torque decreasing seriously in the low speed zone, turbo lag, compressor surge and efficiency declining [3]. Therefore, advanced air management systems such as variable geometry turbocharger (VGT), compound turbocharging and regulated two-stage turbocharger are gradually applied to diesel engines at altitudes. Table 1. shows the performance comparison of the advanced air management systems at high altitudes [4]. It includes the VGT system, the ordinary two-stage turbocharging (TST) system, the mechanical compound turbocharging (MC2T) system, the electric auxiliary turbocharging (EC2T) system and regulated two-stage turbocharging system based on VGT (RTST).
Table 1. Comparison of advanced air management system at high altitudes and containing notesa.

| Diesel engine performance                  | Advanced air management system |
|--------------------------------------------|--------------------------------|
|                                            | VGT  | TST  | MC2T | EC2T | RTST |
| Pressure ratio                             | <3.5 | >5   | >4   | >5   | >5   |
| Area flow range at high efficiency         | ++   | ++   | +++  | +++  | +++  |
| Torque at partial load and low speed       | ++   | +    | +++  | +++  | +++  |
| BSFC at low speed                          | ++   | +    | +++  | ++   | +++  |
| Transient acceleration characteristics     | ++   | ++   | +++  | ++   | +++  |
| Solving ability of compressor surge and    | +    | ++   | ++   | +    | +++  |
| turbine overspeed                          |      |      |      |      |      |
| lifetime and reliability                   | ++   | +++  | +++  | +    | ++   |
| Application potential of plateau           | +    | ++   | ++   | +++  | +++  |

a Note: The number of "++" indicates the extent of improvement or deterioration.

EC2T and RTST have the highest application potential for plateau by comparing the technical parameters of different advanced air management systems. EC2T can accurately control the boost pressure and eliminate turbo lag, but there exist problems, such as the lack of motor speed, the intense vibration of the turbocharger bearing and the poor reliability of the motor under high exhaust temperature. RTST can achieve step utilization of exhaust energy and reasonably allocate exhaust energy according to the changes of altitudes and operating conditions.

The turbocharging process of diesel engine contains gas state variations and energy transfer transformation. The gas has undergone compression expansion, entropy increasing and enthalpy drop process, and the energy has undergone conversion and transfer process of internal energy and mechanical energy. It is very important to utilize and manage exhaust gas energy flow in order to accurately control the pressure of the turbocharging system. This paper mainly aimed at the current situation of the regulated two-stage turbocharging system (TST, RTST) at different altitudes and the relationship of thermal parameters and diesel exhaust energy flow and air management path control are reviewed.

2. Analysis of key thermal parameters of air management system at different altitudes

2.1. Plain

The regulated two-stage turbocharging systems (TST, RTST) manage exhaust energy between the high and low turbine by changing flow area regulated by turbine bypass valve and the VGT vanes. The reasonable utilization of the exhaust energy can achieve continuous adjustable pressure under whole operating conditions. The higher boost pressure overcomes the disadvantages of poor torque performance at low speed, poor EGR introduction capability and poor transient response [5-7].

At present, the analysis of the key thermal parameters of the regulated two-stage turbocharging system includes:

1) Regulation characteristics of turbine bypass valve and VGT vanes of regulated two-stage turbocharging system

2) Relationship between key thermodynamic parameters of regulated two-stage turbocharging system.

The research of the key thermodynamic parameters of the regulated two-stage turbocharging system in plain environment were presented in the Table 2. At present, the mainstream view [8-10] thinks that the pressure ratio of high / low pressure varies from 6:4 to 4:6 with the increase of compressor intake flow.

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Table 2. Current research of key thermodynamic parameters of regulated two-stage turbocharging system.

| Researchers | Altitudes | Turbocharging system | Adjustment parameters | Thermal parameters |
|-------------|-----------|----------------------|-----------------------|--------------------|
| Hashimoto et al [11] | 0m | WGT+FGT | HP-valve | fuel economy, emission |
| Niklas et al [12] | 0m | VGT+WGT | VGT vanes | exhaust temperature |
| Ma et al [13] | 0m | WGT+FGT | HP-valve | expansion ratio distribution |
| Liu et al [14] | 0m | WGT+FGT | HP-valve | boost pressure, airflow ratio, engine efficiency |
| GALINDO et al [15] | 0m | WGT+FGT | expansion ratio distribution | effective thermal efficiency |
| He et al [16] | 0m | WGT+FGT | efficiency of the intercooler | total pressure ratio, total efficiency |
| Feng et al [17] | 0m | WGT+FGT | expansion ratio, intercooling efficiency | pump gas loss pressure |

Feng et al [17] analyzed the influence of pressure ratio distribution, inter-stage cooler, isentropic efficiency and exhaust gas temperature on the pumping losses by establishing a thermodynamic model of regulated two-stage turbocharging system. Ma et al [18-19] and Liu et al [20] studied the influence of the opening of the HP-valve on the expansion ratio distribution, the turbine flow range and the turbine adiabatic efficiency of the TST system. The results show that the adjustment range of the turbine flow can be above 30% when the HP turbine expansion ratio is between 1.2 and 2, and the operating points of two compressors can run in high efficiency region. Wang et al [21] calculated the influence of the different distributions of exhaust energy on the performance of two-stage turbocharged diesel engine by combination of experiment and simulation, and the proportion of the optimum exhaust energy of the two-stage turbocharging system was obtained under certain operating conditions.

2.2. Plateau

Intake characteristics and combustion process of diesel engine were influenced by atmospheric pressure and air temperature at varying altitude. The utilization of exhaust energy is also quite different from that of the plains. The altitude at abroad is generally low, and there is little research on the thermodynamics of regulated two-stage turbocharging system at high altitudes. GALINDO J et al [22] studied the switching strategy of the control valve of turbocharging system under transient operating conditions at high altitudes. However, there are some problems in the parallel sequential turbocharging system, such as lack of pressure ratio (<4), pressure and torque drop in the process of valve switching.

Shi et al [23] studied the influence of the bypass flow rate of high pressure turbine on the flow area and the power ability of the turbine at high altitudes. The HP-valve control strategy of TST system was designed for the two operating conditions, and power recovery of the diesel engine at high altitudes are affected by the total efficiency change of the turbocharging system and the increase of pump gas loss. Li et al [24] points out that TST regulation ability at high altitudes is related to altitude height, combustion margin, gas system efficiency and strengthening degree. A turbine equivalent matching model was established to study the control strategy of HP bypass valve by adjusting the exhaust energy distribution relationship between high and low-pressure turbine at altitudes of 0m to 4500m. Zhang et al [25] pointed out thermal efficiency and pump loss were affected by opening of HP bypass valve of TST system. Yang et al [26] studied the influence of altitude (0m—4500m) on the total energy and energy distribution (high and low-pressure turbine) of TST from the angle of exhaust energy by means of theoretical analysis and test. Di et al [27] matched RTST for a diesel engine at
high altitudes and studied the influence of VGT vanes opening on the matching characteristic of turbocharger, intake parameters, residual loss (heat loss, friction loss and pump gas loss), combustion process and emission characteristics by using numerical simulation.

3. Exhaust flow energy and air path management of diesel engine at different altitudes

3.1. Plain
Control strategies of air management systems should be designed in order to effectively utilize available exhaust flow energy at whole operating conditions and altitudes. At present, control strategies of air management systems are mainly aimed at plain environment. According to different control objectives, the air management systems control strategy can be divided into as following [28-30]:

1. Regulation law with limitation of maximum boost pressure
2. Regulation law with the goal of economy
3. Regulation law with the goal of power
4. Other regulation laws (target of intake and exhaust negative pressure, air-fuel ratio).

The VGT+WGT system [31] was developed by BWM and BorgWarner (As shown in Figure 1), and five control strategies of air management systems were designed under the different operating conditions (As shown in Figure 2.).

Canova et al [32-33] analyzed the influence of the opening of the VGT vanes and the turbine bypass valve of VGT+WGT system on intake and exhaust pressure. The operation range of the engine is divided into three adjustment regions based on the targets of maximum boost pressure and the maximum intake flow. Closed loop PID control strategies is designed to realize collaborative control between VGT vanes, HP bypass valve, and EGR valve.

As shown in Table 3, Control strategies for air management system were studied by many research institutes. Shanghai Jiao Tong University has carried out a systematic research on boost pressure control strategies of the regulated two-stage turbocharging system (As shown in Figure 3).
Table 3. Different control strategies for air management systems.

| Researcher           | altitude | Turbocharging system | Control target                                      | Control strategy                                      |
|----------------------|----------|----------------------|-----------------------------------------------------|-------------------------------------------------------|
| P. Kotman et al [34] | 0m       | WGT+FGT              | Boost pressure                                      | Feedforward control based on flatness                 |
| A. Plianos et al [35]| 0m       | WGT+FGT              | Boost pressure                                      | Local linear two Gauss method (LQG)                   |
| Dieter et al [36]    | 0m       | WGT+FGT              | Boost pressure                                      | Endocardial control (IMC) nonlinear method           |
| THOMASSON A et al [37]| 0m   | WGT+WG               | Efficiency of turbocharger, pump gas loss           | PID closed loop feedback + feedforward; the surface conditions are divided into four regions. |
| PHILIPPE et al [38]  | 0m       | WGT+WG               | BSFC, Emission performance                          | Two control strategies of closed loop and open loop  |
| MOHAMED et al [39]   | 0m       | WGT+WG               | Trade-off BSFC and NOx/smoke                        | Divide the operating condition into five regulating areas |
| Albin et al [40]     | 0m       | WGT+WG               | Trade-off pump gas loss and transient response time | Model predictive control (MPC) based boost pressure  |
| SCHMITT F et al [41] | 0m       | Double VGT+WGT       | Trade-off dynamic response at low speed and power output at high speed | Divide the operating condition into five regulating areas |

Liu et al [42] divided the whole operating conditions into four adjustment regions based on the principle of maximum pressure and designed the power control strategies of regulated two-stage turbocharging system (As shown in Figure 4). The results showed that the stability of the controller is reduced by 4.6s compared with that of the single stage turbocharger when the boost pressure is increased by 22kPa.

![Figure 3. WGT+WGT system.](image-url)
In order to improve the pressure and power output of the diesel engine and reduce the emission of NOx, the two input and two output VGT/EGR nonlinear controller (MIMO) was designed by Wang et al [43] based on the quantitative feedback theory. The classical PID gain and phase margin were extended to MIMO system design. In order to reduce NOx emission and increase fuel consumption, Alexandros et al [44] matched a RTST with the diesel engine and designed a LQG controller achieve synergistic control of the VGT vanes and EGR valve. Guo et al [45] studied the application of fuzzy control technology in VGT control.

Zhao et al [46] designs a global explicit predictive controller (EMPC) based on minimizing the fuel consumption of 7.1L heavy duty diesel engines. The parameters of EMPC contains input manifold pressure, exhaust manifold pressure and intake mass flow as input, VGT vanes opening, EGR valve position and turbine power as output. The results show that the EMPC control process is more stable and rapid compared with PID. Dickinson P. et al [47] applied the MPC control strategy to the VGT+VGT system, and evaluated the control quality of the MPC controller for the response time of boost pressure, and the pump gas loss and the low speed torque under the transient condition. Ordinary linear MPC control has limited control range, and the nonlinear characteristics of diesel intake and exhaust lead to poor control accuracy. Albin, T. et al [48] proposed nonlinear model predictive control (NMPC) for two-stage turbocharging system, and compared three models of linear invariant MPC (LTIMPC), linear time-varying MPC (LTVMPC) and NMPC, and NMPC in both control quality and response time is better.

3.2. Plateau
Liu et al [49] matched multi-valves of TST system with a diesel engine, and control strategy of turbine bypass valves of TST is formulated to optimize total energy of exhaust gas based on the combustion characteristics of the diesel engine at high altitudes. The transient response simulation model of regulated two-stage turbocharged diesel engine was established by Li et al [50], and the influence of altitude on the transient response characteristics of boost pressure was calculated and analyzed. Comparing the open loop control with closed loop control on the improvement of the transient characteristics of the diesel engine at variable altitudes.

The results show that the closed loop control strategy using the boost pressure is reduced from 3.20s to 2.32s compared with the open loop control strategy at 3 000m. In the process of transient
response, the combined operation of engine compressor and compressor can meet the requirements of optimizing the performance of diesel engine with the two-stage adjustable turbocharging system at variable altitudes. Liu et al [51-52] aimed to design a boost pressure control strategies for the VGT+WGT system at altitude of 0m–5500m (as shown in Table 4).

| Altitude(m) | Working region | Engine speed (r/min) | RTST Working condition | VGT vanes | HT by-pass valve | LT by-pass valve | LT compressor by-pass valve |
|-------------|----------------|----------------------|-------------------------|-----------|-----------------|-----------------|-----------------------------|
| 0~2500      |                | 1 800~1400           | HT Working              | regulated | closed          | opened          | opened             |
|             |                | 2 1400~2100          | LT & Joint Working     | fixed     | regulated       | regulated       | closed             |
| 2500~5500   |                | 1 800~1400           | HT & LT Joint Working  | regulated | closed          | closed          | closed             |
|             |                | 2 1400~2100          | Fixed                  | regulated | closed          | closed          | closed             |

Lin et al [53] studied a VGT based on regulated two-stage turbocharging system (VGT+FGT) under transient process at high altitudes. The influence of three VGT vanes adjustment schemes on the performance of diesel engine is compared and analyzed under constant speed loading. (as shown in Figure 5). The results show that the advantage of the scheme one (at the initial stage of loading to keep the VGT vanes opening constant to the middle of the load, and then increase linearly to the corresponding opening after loading) is more obvious in improving the transient loading performance of the diesel engine (as shown in Figure 6).

Figure 5. Schematic diagram of three adjustment paths for VGT blades.

Figure 6. Boost pressure response under at constant load acceleration condition.

4. Summary and prospect

4.1. Summary
(1) The research status of the regulation characteristics and key thermodynamic parameters of the turbine bypass valve and VGT vanes for air management system at different altitudes is summarized. The turbine bypass valve and VGT vanes of the air management system can influence of pump gas loss and effective combustion heat efficiency by changing the turbine flow area, adjusting the key
thermodynamic parameters of the turbocharging ratio, the total efficiency of turbocharger and the vortex front temperature.

(2) The air management system control strategy is relatively mature under the plain environment. According to the different control objectives, the air management system control strategy is divided into four types of regulation. Among them, the research institutes mainly aim at plain surface conditions and design different adjustment areas for air management system. Under the plateau environment, the corresponding air management system control strategy is designed according to the diesel engine's external characteristics.

(3) At present, there are mainly five types of control algorithms for diesel engine air management system, which include PID closed loop feedback and feedforward control, intimal control (IMC), fuzzy control, local linear Gauss control (LQG), model predictive control (MPC).

4.2. Prospects
(1) The analysis of the thermodynamic parameters of air management systems mainly aims to plain environment. The intake characteristics and combustion characteristics of the diesel engine changed with the altitudes, which directly affected the key thermodynamic parameters such as the exhaust temperature, the expansion ratio, the inlet pressure, the inlet temperature of the compressor, the pressure ratio distribution and so on. The next step is to analyze the influence of control parameters and key thermodynamic parameters on pump air loss and combustion heat efficiency of the air management system at variable altitudes.

(2) The design of control strategy of air management system is mainly aimed at the plain environment. The control strategy of air management system will be more complex with changing of altitudes and working conditions. Future research should focus on the control area of air management system under the altitude, speed and load.

(3) The above control technologies of regulated two-stage turbocharging at high altitudes are mainly based on the PID controller. At present, the research of multi-system control algorithm for diesel engine mainly includes PID control, local linear two type Gauss distribution control (LQG), fuzzy control, neural network predictive control, model predictive control (MPC) and so on (Table 5.). Advanced control strategies such as synovial control and MPC control will be ideal algorithms to solve the multi parameter cooperative control of diesel engine at variable altitudes.

Table 5. Comparison and analysis of advanced control algorithms and containing notes a.

| Evaluation index       | Control theory | PID control | adaptive control | fuzzy control | sliding mode control | Neural network predictive control | MPC control | \( H_\infty \) Control |
|------------------------|----------------|-------------|------------------|--------------|---------------------|----------------------------------|-------------|------------------------|
| Robustness             | +++            | +++         | ++               | +++          | +++                 | +++                              | +++         | +++                    |
| Control accuracy       | +              | +++         | ++               | ++           | ++                  | ++                               | +++         | ++                     |
| Convergence speed      | +              | +           | ++               | +++          | +                   | ++                               | +           | ++                     |
| Multi-objective Control Capability | + | + | + | +++ | +++ | +++ | +++ | +++ |
| Nonlinear control capability | + | + | +++ | +++ | +++ | +++ | +++ | +++ |

Notes: The number of "+" indicates the extent of improvement or deterioration.
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