Research on Cooperative Control Feasibility of Methanol Internal Combustion Engine with Dual Electric Turbo Compound System

Yong Song, Jianghao Sun, Xiqing Zhang, Zhanlong Li, Tuo Xu, Yao Wang

***Abstract*—To address the problem that cooperative control both power performance and economy of the methanol internal combustion engine (ICE), a dual electric turbo compound (dual-ETC) system is proposed. And the external characteristics of the methanol ICE with the dual-ETC system under typical characteristic speed conditions were investigate. Taking the methanol ICE developed and improved based on a certain type of natural gas ICE as the research object, a one-dimensional thermo-dynamic simulation model is established and calibrated by simulation software GT-Power. The speed influences of the turbine and the compressor on the main performance parameters of the methanol ICE are studied. It is found that the turbine speeds of the dual-ETC system have little influences on the main performance parameters, whereas the compressor speeds exert more significant influences. Additionally, the turbine efficiencies demonstrate a trend of initially increasing and then decreasing as turbine speed rises. For the external characteristics of the methanol ICE with the dual-ETC system, it is found that the torque increase and the torque increase rate are larger, and the economy and the power performance are better under the maximum speed condition of the compressor at the upper and the lower boundary speeds of the peak net torque range. Compared to the comparison engine, by adjusting the compressor speed, the power performance at the low speed (the torque increases by about 7.24%) and the economy at the high speed (the comprehensive fuel consumption decreases by about 6.26 kg/h) are increased. These findings suggest the possible approach for the cooperative control of the external characteristics of the methanol ICE with the dual-ETC system. The above research results verify the correctness and the effectiveness of the proposed system, and the cooperative control feasibility of methanol ICE with dual-ETC system.**

***Index Terms*—dual-ETC system, methanol ICE, GT-Power, external characteristics, thermodynamic simulation**

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I. INTRODUCTION

Petroleum has been used as the driving energy of internal combustion engines (ICEs) for hundreds of years. However, with the rapid development of the automobile industry and the widespread use of ICEs, fossil fuels have been consumed in large quantities, and the world is faced with serious energy shortages and environmental pollution problems [1]. In the face of the increasing depletion of fossil energy sources, the search for the development of renewable and clean alternative fuels has become an important goal in the field of ICEs. As an emerging clean energy source, methanol has the characteristics of low carbon, high octane, high oxygen content, low pollution and no smoke emission, etc [2]. It is a kind of renewable synthetic energy that can realize the carbon neutral cycle, known as the "Liquid Sunshine". Its application in ICEs is an important direction for the development of methanol economy in the future [3].

The effective power of a methanol ICE depends on the product of the effective torque and the angular velocity of the crankshaft, as well as on the effective work emitted per unit cylinder working volume within a unit time. The effective work depends on the amount of air entering the cylinder and the amount of methanol fuel per unit of time, the construction of the engine cylinders and the intake and exhaust pipes, the crankshaft rotational speed, the cylinder pressure and temperature, and so on. By utilizing the exhaust gas energy, the exhaust gas turbochargers can effectively enhance the intake pressure and cylinder intake flow of ICEs per unit time, so as to improve the power performance, economy and emission performance of ICEs, and this technology has been widely popularized and applied [4-5].

Currently, the methanol ICE is pneumatically connected to the turbocharger, so there are still problems such as response lag and low exhaust energy utilization due to exhaust energy limitation [6-8]. Research has shown that the electric turbo compound (ETC) system can significantly improve the low operating condition economy, transient characteristics and other index of ICEs, is an important direction for the future development of supercharging technology [9-10]. Because the ETC technology is characterized by the integration of electric motors (including electric motors and generators) and traditional turbochargers, to achieve partial decoupling or even complete decoupling of the operation of the engine and turbocharger, the electromechanical compound supercharging technology can fundamentally solve the problem that the reciprocating piston engine and the rotating turbomachinery turbocharger are difficult to match the whole working condition [11]. At present, there are many forms of ETC systems in domestic and foreign researches. Yu et al. proposed an online optimization control strategy that can determine the operating power of the compressor according to the supercharging pressure, and then used the model prediction algorithm to control the power of the turbine and the electric motor by an in-depth study on the electrically-assisted turbocharging (EAT) system. Compared with traditional exhaust gas turbocharging, the tracking error of diesel boost pressure can be reduced by 87.2% after using this system [12]. Frigo S et al. evaluated the effects of single-ETC system and dual electric turbo compound (Dual-ETC) system on the economy of an automotive diesel engine. The results showed that the fuel consumption rate of a diesel engine with single-ETC system could be reduced by 5.5% and that of a diesel engine with a dual-ETC system could be reduced by 8.5% at a full-load engine speed of 4,000 rpm [13]. Xiao et al. of Ford Company investigated the cutting out process of the electric supercharger by simulation, under the condition that the inlet pressure and flow rate of the diesel engine are both smooth transitions, the transient response of the electric supercharger to the turbocharged diesel engine is given [14]. Mazanec J. M. et al. connected a 4.5L diesel internal combustion engine (ICE) equipped with an electric compressor in series with a traditional turbocharger, integrating it into a 48V mild-hybrid powertrain architecture. The system was optimized using the commercial one-dimensional simulation software GT-SUITE. The results indicated an 18% reduction in the total fuel consumption compared to the same time period with a 6.8L engine [15]. PASINI G et al. selected a compression ignition engine as the research object, by studying the two supercharging schemes of single-ETC and dual-ETC, the research results show that dual-ETC has a greater potential for energy saving, especially in the mid-load and high load conditions, the fuel economy of diesel engine can be improved by 8% [16]. Yang et al. investigated the effect of the hybrid electric supercharging system on diesel engine torque, air-fuel ratio and economy in reference [17] and found that the working performance of low-speed large torque region of the diesel engine can be increased by about 18%. Li et al. conducted research and optimization on the matching between electric-assisted turbochargers and high-speed engines. The results showed that the optimized EAT significantly improved the acceleration performance of the engine, with the stability time increased by 5.1s, the maximum torque increased by 31.91%, and fuel consumption decreased by 3.37% [18]. Liu et al. analyzed the effects of dual-ETC system on the characteristics of marine diesel engine through numerical simulation, and the results showed that the maximum output power of the diesel engine was significantly increased under the condition of low rotational speed. After using dual-ETC system in transient characteristics, the time required for diesel engine speed to be loaded from 450 rpm to 10100 rpm is reduced from 70 s to 12 s [19].

The dual-ETC system makes the mechanical connection between the turbine and the compressor completely separate by the way of motor driving the compressor and the turbine connecting to the generator, breaking the strict limitations of the exhaust gas turbocharging system in terms of energy balance, flow rate balance and speed equivalence [20]. Therefore, it is of great significance to study the influences of external characteristics of methanol ICE with dual-ETC system. In this paper, a spark-ignition high-power methanol ICE is taken as the research object, and conducts a research on the comprehensive fuel consumption and maximum output characteristic change of the methanol ICE after adopting the dual-ETC system; A cooperative control method is proposed to control the power performance at low speed and the economy at high speed by controlling the compressor speed for methanol ICE, and the feasibility of applying the dual-ETC system to the methanol ICE is explored.

II. Construction and Calibration of One-dimensional Thermodynamic Simulation model of Methanol ICE

A. Construction of One-dimensional Thermodynamic Simulation Model

The method that evaluating and simulating the power, economy and thermal coupling performance of the ICE through the simulation software GT-Power has been widely recognized by the industry. Therefore, this paper adopts GT-Power to carry out thermodynamic simulation of a spark-ignition high-power methanol ICE based on the development and improvement of a natural gas ICE, the basic parameters of the engine are shown in Table I. The one-dimensional thermodynamic model of the target methanol ICE is established by using GT-Power software, which mainly includes the intake system (including intercooler), the exhaust system, cylinders and exhaust gas turbocharging system. There is no intercooler simulation module in GT-Power, so multiple pipes are used to simulate the cooling effect of the intercooler, so that the outlet temperature of the pipes is consistent with the outlet temperature of the intercooler. Because the EngCylComb-SIWeibe combustion model in GT-Power is suitable for ignition gasoline engine and gas engine, this paper uses this model to simulate the combustion characteristics of methanol in cylinders. The established one-dimensional thermos-dynamic model of the methanol ICE is shown in Fig.1.

TABLE I
THE SPECIFICATIONS OF THE STUDIED METHANOL ICE

Items	Value
Engine type	Straight-six engine, turbocharger
Engine ignition mode	Spark ignition
Engine firing order	1-5-3-6-2-4
Bore	127mm
Stroke	165mm
Compress ratio	12.5
Maximum torque	2000N·m

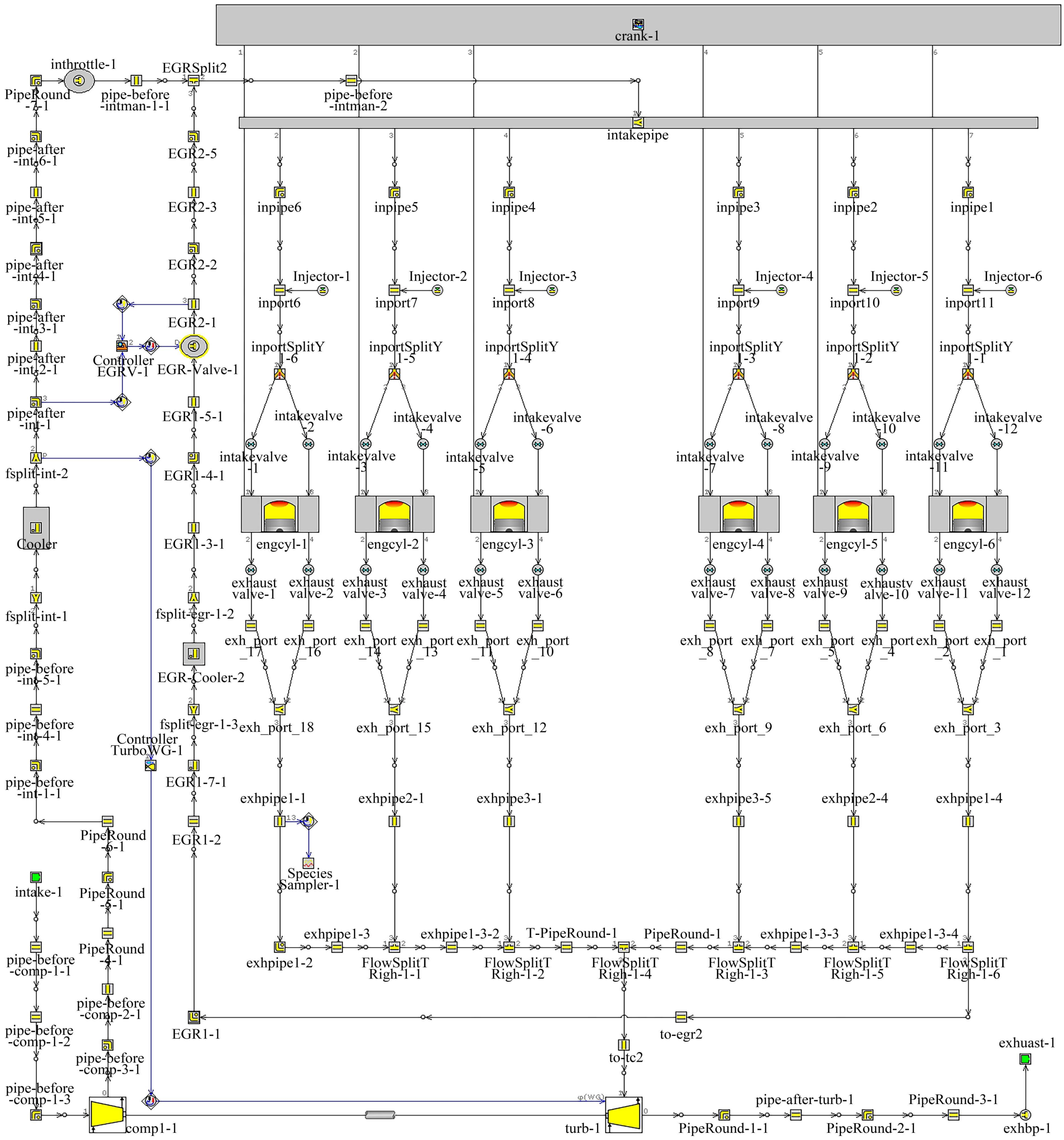

Fig. 1. One-dimensional thermodynamic simulation model of methanol ICE

B. *Calibration of One-dimensional Thermodynamic Simulation Model*


Fig. 2. Methanol ICE test platform

In order to calibrate the one-dimensional thermodynamic simulation model of the methanol ICE, the Zero-carbon Power Integrated Test Platform was utilized to establish the external characteristic test system for the methanol ICE. The external characteristic test of the methanol ICE was carried out, and the data obtained was utilized for the model calibration. The system includes CJ560 dynamometer, intake flow meter, intercooler temperature automatic adjustment device, engine coolant temperature automatic adjustment device and so on. When the automatic adjustment device for engine coolant temperature raises the coolant temperature to the target value, the test conditions, including ambient temperature and pressure, are recorded before starting the ICE. When the ICE runs steadily under the typical characteristic speed full load condition (including the minimum stable speed (700rpm), the upper and the lower boundary speed of the peak net torque range (1100rpm, 1300rpm) and the maximum net power speed (1900rpm)), the test and data acquisition are performed. The number of tests is three times, and the calibration data is the mean of the three sets of test data.

The parameters such as ambient temperature, ambient pressure, excess air coefficient and EGR rate during the test are input into GT-Power, and the minimum stable speed (700rpm), the upper and the lower boundary speed of the peak net torque range (1100rpm, 1300rpm) and the maximum net power speed (1900rpm) are selected for external characteristic simulation calculation. The external characteristic power of the above speed conditions is calibrated by adjusting the control strategy of the turbocharger exhaust bypass valve, the heat transfer coefficient of the intake and exhaust pipelines and the emission model, etc. The calibration results are shown in Fig. 3. From Fig. 3, it can be seen that the simulated values of the output power of the calibration point of the various conditions are roughly the same as the experimental values, with the relative errors of less than 2%.

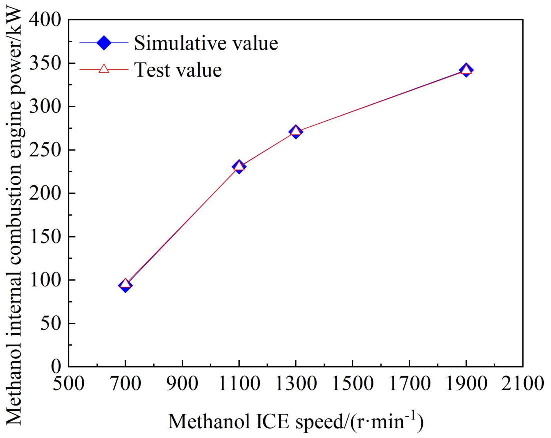

Fig. 3. Typical characteristic speed power calibration of one-dimensional thermodynamic model

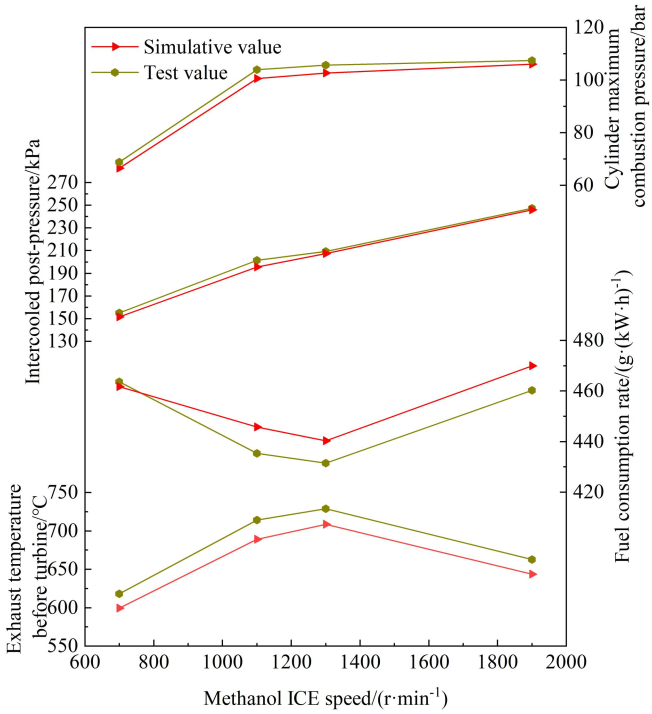

Fig. 4. Comparison of experimental value and simulation value of one-dimensional thermodynamic model

In order to verify the prediction accuracy of the one-dimensional thermodynamic model after calibration, the experimental values and simulation values of the parameters are compared (see Fig.4). These parameters include the exhaust temperature before the turbine, the fuel consumption rate, the post-cooling pressure and the maximum combustion pressure of the methanol ICE under the calibration conditions. It can be seen from Fig. 4 that the relative errors between the performance parameters predicted by the model and the experimental values under the calibration conditions are less than 4 %. The results show that the accuracy of the model after calibration can meet the requirements of subsequent research (in engineering, the simulation errors of the model are generally required to be less than 5 %).

C. Construction of the Simulation Model of the Dual-ETC System

When the ICE employs the exhaust gas turbocharger as its supercharging system, it is essential to match the turbocharger with the ICE to ensure efficient and stable operation of both the turbine and the compressor. Three key conditions (including energy balance, flow balance, and speed equality) allow the ICE to maintain a stable operating state without altering the throttle opening at a fixed speed.

(1) Energy balance of turbine and compressor

$$W_T \times \eta_{TKm} = W_K \quad (1)$$

where W_T is the power transferred from the turbine to the turbine shaft, W_K is the power consumed by the compressor and η_{TKm} is the mechanical efficiency of turbocharger.

(2) Flow balance through turbine and compressor

$$\dot{m}_T = \dot{m}_K + \dot{m}_f \quad (2)$$

where $\dot{m}_T$ is the turbine mass flow rate, $\dot{m}_K$ is the compressor mass flow rate and $\dot{m}_f$ is the corresponding fuel mass flow rate.

(3) The speed of turbine is equal to that of compressor

$$n_T = n_K = n_{TK} \quad (3)$$

where n_T is the turbine speed, n_K is the compressor speed and n_{TK} is the turbocharger speed.

Based on the above conditions, after the throttle is fully opened and ICEs run smoothly, the intake flow, supercharged pressure and fuel injection amounts of ICEs reach the maximum values of themselves under the constant speed condition, and the power performance of ICEs cannot be further improved. After using the dual-ETC system, the parameters such as power and pressure ratio of the compressor and intake flow rate can be changed by controlling the compressor speeds, so that the external characteristic curve of the turbocharged ICE changes accordingly, which improves the flexibility of the supercharging system.

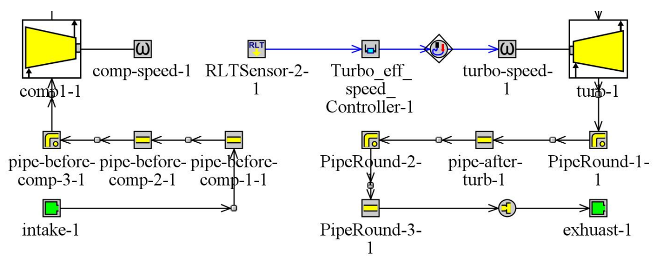

Fig. 5. Simulation model of the dual-ETC system

The methanol ICE used in the test adopts the intake form of double vortex exhaust gas turbocharging. To simulate the influences of the dual-ETC system on the working characteristics of the methanol ICE, the turbine shaft of the turbocharger is removed in the one-dimensional thermodynamic model. The SpeedBoundaryRot template is then utilized to independently control the speeds of the compressor and the turbine. The parameter configurations of the selected compressor and turbine in this system are the same as that of the comparison engine, and the simulation model of the dual-ETC system is shown in Fig. 5. The power consumption of the electric motor used in the compressor and the power generated by the generator at the turbine end can be obtained from the compressor power, the turbine power and their corresponding drive system efficiencies.

The electric power capacity of turbine in the dual-ETC system comes from the conversion of the exhaust energy of ICEs. The total exhaust energy (Q_{ex}) of ICEs includes three parts: the residual kinetic energy (Q_k), the residual pressure energy (Q_p) and the residual heat energy (Q_h). The total exhaust energy equation is shown in Equation (4).

$$Q_{ex} = Q_k + Q_p + Q_h \tag{4}$$

The three parts of the energy contained in the exhaust gas of ICEs are related to the parameters such as the mass flow rate, the pressure and the temperature of the exhaust gas. The energy calculation formula of each part is as follows.

The residual kinetic energy is:

$$Q_k = 0.5 m_{ex} v_{ex}^2 \tag{5}$$

where m_{ex} is the mass flow rate of the exhaust gas and v_{ex} is the speed of the exhaust gas.

The residual pressure energy can be expressed:

$$Q_p = m_{ex} \frac{\kappa}{\kappa - 1} \cdot R_g T_{ex} \left[1 - \left(\frac{p_0}{p_{ex}} \right)^{\frac{\kappa}{\kappa-1}} \right] \tag{6}$$

where κ is the ratio of specific heat, R_g is the exhaust gas constant, p_0 is the standard atmospheric pressure, p_{ex} is the exhaust gas pressure and T_{ex} is the exhaust gas temperature.

The residual heat energy is denoted as:

$$Q_h = m_{ex} \int_{T_0}^{T_{ex}} C_{v_{ex}} \mathrm{d}T \tag{7}$$

where T_0 is the environment temperature and $C_{v_{ex}}$ is the specific heat capacity at constant volume of exhaust gas.

During the operation of the ICEs, the turbine can only partially recover the exhaust energy. The ratio of the recovered energy to the total energy of the exhaust gas is called turbine efficiency, so the turbine recovery energy (Q_{turbo}) can be presented as Equation (8).

$$Q_{turbo} = Q_{ex} \cdot \eta_{turbo} \tag{8}$$

where η_{turbo} is the turbine efficiency.

The compressor power (P_{com}) depends on many parameters such as air mass flow rate, inlet constant pressure specific heat capacity and gas temperature of compressor inlet and outlet. The specific calculation formula is shown in Equation (9).

$$P_{com} = \dot{m}_K C_{p_{in}} (T_2 - T_1) = \frac{\dot{m}_K C_{p_{in}} T_1}{\eta_b} \left[\left(\frac{p_2}{p_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \tag{9}$$

where $C_{p_{in}}$ is the inlet constant pressure specific heat capacity, T_1 is the gas temperature of compressor inlet, T_2 is the gas temperature of compressor outlet, p_1 is the gas pressure of compressor inlet, p_2 is the gas pressure of compressor outlet, η_b is the compressor isentropic efficiency and γ is the adiabatic exponent of gas.

Fig.6 shows the working principles diagram of the dual-ETC system, in which the compressor and the turbine are respectively powered and transmitted by direct current (DC) bidirectional power supply. Therefore, the system needs to consider the energy consumption of the compressor, the power capacity of the turbine and the energy efficiency of the methanol ICE to calculate its overall energy consumption level. The specific calculation method is shown in Equations (10) ~ (13).

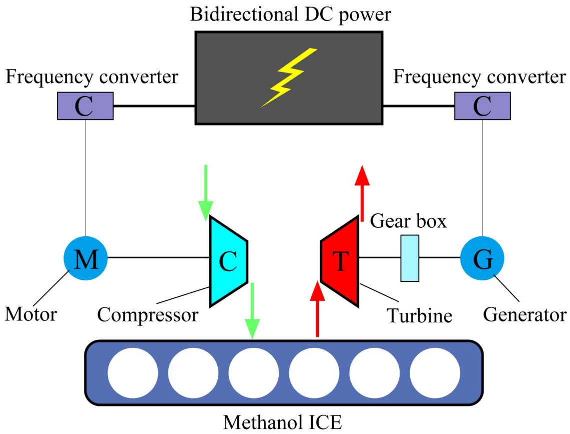

Fig. 6. Working principle diagram of the dual-ETC system for the methanol ICE

$$F = F_{ME} + F_{AE} \tag{10}$$

$$F_{ME} = P_{ME} \cdot S_{ME} \tag{11}$$

$$F_{AE} = S_{AE} \cdot \left(\frac{P_{com}}{\eta_c \cdot \eta_m} - P_{turbo} \cdot \eta_m \cdot \eta_g \cdot \eta_c \right) \tag{12}$$

$$F = P_{ME} \cdot S_{ME} + S_{AE} \cdot \left(\frac{P_{com}}{\eta_c \cdot \eta_m} - P_{turbo} \cdot \eta_m \cdot \eta_g \cdot \eta_c \right) \tag{13}$$

where F is the comprehensive fuel consumption of the methanol ICE with the dual-ETC system, F_{ME} is the methanol ICE intrinsic fuel consumption, F_{AE} is the energy consumption of the dual-ETC system, P_{ME} , P_{com} and P_{turbo} are respectively the power of the main body of the methanol ICE, compressor and turbine of the methanol ICE, S_{ME} is the fuel consumption rate of main body of the methanol ICE, S_{AE} is the simulative fuel consumption rate of the power generation, η_c, η_m and η_g are respectively frequency converter efficiency, motor efficiency and mechanical transmission efficiency.

Considering the problem of insufficient energy supply in the working process of the dual-ETC system, it is assumed that the bidirectional DC power supply is supplemented by a methanol ICE. This part of energy is determined by the fuel consumption rate of the methanol ICE, the efficiency of the frequency converter, the mechanical efficiency and the motor efficiency. The variation of fuel consumption rate under the typical characteristic speed conditions of the comparison engine is shown in Fig. 4. The fuel consumption rate of the comparison engine is approximately 436 g/(kW·h) at 1300 rpm. Therefore, the fuel consumption rate for power generation can be considered as 436 g/(kW·h). In addition, the efficiency of the frequency converter, the mechanical transmission efficiency and the motor efficiency are assumed as 98 %, 97 % and 90 %.

In above analysis, the thermodynamic modeling of the methanol ICE with the dual-ETC system is completed, based on which relevant external characterization studies can be carried out.

III. Influences of Turbine and Compressor Speeds on the Main Performance Parameters of the Methanol ICE

It is reported that when a dual-ETC system is utilized within an ICE, the speeds of both the turbine and compressor significantly influence the ICE's power performance, economy and emission performance. Consequently, the speed operation strategies of the turbine and the compressor are the primary focus of this study. To master the speed influences of the turbine and the compressor, the main performance parameters of the methanol ICE are studied.

A. Influences of the Turbine Speed on the Main Performance Parameters of the Methanol ICE

When the comparison engine adopts the double vortex exhaust gas turbocharging system, the maximum net power speed of the ICE is 1900 rpm, and the turbocharger speed is 115,300 r/min. To investigate the effects of the turbine speed on the main performance parameters of the methanol ICE, in the dual-ETC system, the compressor speed is set equal to the turbocharger speed under the maximum net power speed condition of the comparison engine. Specifically, the compressor operates at a fixed speed of 115,300 r/min, while the turbine speed is varied within a range of 105,000 to 125,000 r/min, with increments of 4,000 r/min. The changes of the main performance parameters of the methanol ICE at the set speed of the turbine are shown in Table II.

It can be seen from Table II that the main performance parameters of the methanol ICE change little, such as fuel consumption rate, cylinder maximum combustion pressure, exhaust temperature before turbine, supercharged pressure and pressure before turbine. However, with the increase of turbine speed, the power and the efficiency of the turbine increase significantly, while the increase rate of the turbine efficiency decreases gradually, and the comprehensive fuel consumption of the system also decreases progressively. Therefore, the turbine speed has little effect on the main performance parameters of the methanol ICE in a certain speed range, and the methanol ICE with the dual-ETC system may obtain the optimal comprehensive fuel consumption operating point, at the maximal turbine efficiency working point. The relationship between the turbine speed and efficiency is shown in Fig.7.

$$y = -1903.9294x^6 + 15424.089x^5 - 51706.534x^4 + 91750.023x^3 - 90930.104x^2 + 47795.96x - 10370.645 \quad (14)$$

where x is the turbine speed and y is the turbine efficiency.

As can be seen from Fig.7, the turbine speed interval is located in the range of 1.05×10^5~1.55×10^5r/min, the turbine efficiency with the increase of the turbine speed shows a trend of increasing first and then decreasing. When the turbine speed is about 1.31×10^5r/min, the turbine efficiency reaches the peak. The fitting equation of the relationship between the turbine speed and efficiency curve is shown in Equation (14), and the decision coefficient of the formula R^2= 0.9999.

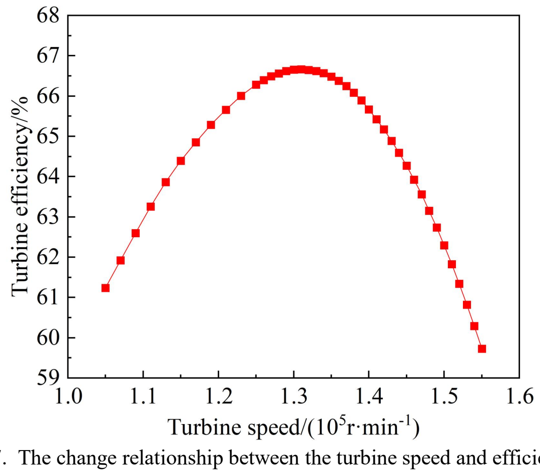

Fig. 7. The change relationship between the turbine speed and efficiency

TABLE II
The influences of the turbine speed on the main performance parameters of the methanol ICE

Items	Value						Unit
Compressor speed	115300						r/min
Turbine speed	1.05	1.09	1.13	1.17	1.21	1.25	10^5r/min
Compressor power	35.90	35.90	35.90	35.90	35.90	35.90	kW
Fuel consumption rate	468.98	469.11	469.25	469.37	469.51	469.65	g/(kW·h)
Cylinder maximum combustion pressure	106.10	106.09	106.09	106.09	106.09	106.09	bar
Exhaust temperature before turbine	644.18	644.32	644.39	644.42	644.81	644.70	℃
Supercharged pressure	2.45	2.45	2.45	2.45	2.45	2.45	bar
Pressure before turbine	2.76	2.76	2.77	2.77	2.78	2.79	bar
Turbine power	34.01	34.81	35.54	36.12	36.62	36.99	kW
Turbine efficiency	61.24	62.60	63.86	64.86	65.66	66.28	%
Comprehensive fuel consumption	165.86	165.55	165.26	165.03	164.83	164.68	kg/h

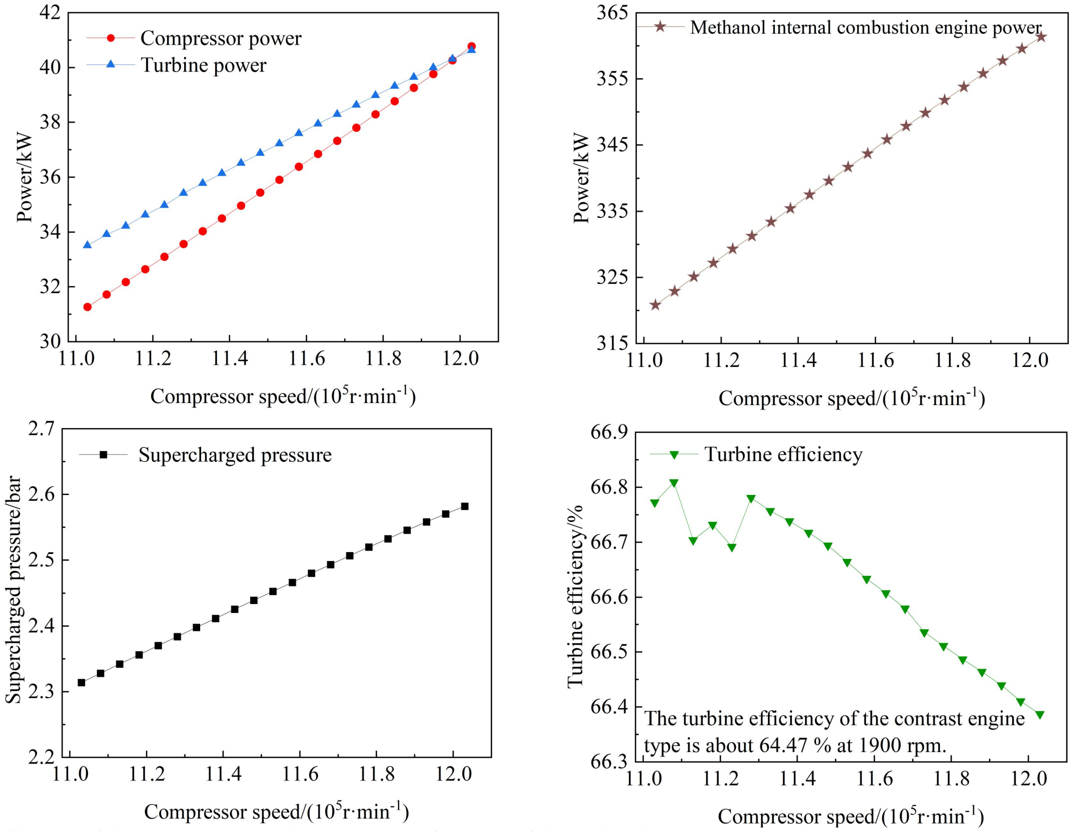

Fig. 8. The influences of the compressor speed on the main performance of the methanol ICE at 1900rpm

B. Influences of the Compressor Speed on the Main Performance Parameters of the Methanol ICE

In order to explore the influences of the compressor speed on the main performance parameters of the methanol ICE, in the dual-ETC system, the initial speed of the turbine simulation is set to be equal to the turbocharger speed under the maximum net power speed of the comparison engine. As the speed of the compressor increases, the intake flow rate and the fuel injection quantity of the methanol ICE also increase. To make the maximum combustion pressure in the cylinder not to exceed the body's bearing capacity, the compressor speed is set to vary in the range of 11.03×10^4 to 12.03×10^4r/min at intervals of 500r/min under the maximum net power speed condition. To make the turbine operate efficiently, the turbine efficiency can be maintained at a high level by controlling the turbine speed. The turbine efficiency control target in this paper is more than 66.3 %. Because the PID control method (proportion integral derivative) can adjust the speed quickly and effectively, this method is used to regulate the turbine simulation speed. The influences of the compressor speed on the main performance parameters of methanol ICE are shown in Figs.8~9.

As illustrated in Fig. 8, the turbine efficiency stabilizes between 66.5% and 66.9%, with a decreasing trend as the compressor speed increases. Furthermore, the turbine efficiency is improved by about 1.9% to 2.4% relative to the comparison engine, meeting the requirements of the turbine efficiency control. The methanol ICE supercharged pressure, ICE power, turbine power and compressor power all increase linearly with the compressor speed increase. In addition, the increase rate of the compressor power is higher than that of the turbine, and the difference between the turbine power and the compressor power decreases gradually. When the compressor speed is about 11.99×10^4r/min, the difference begins to show a negative value. On the other hand, the gradual decrease of the difference between the turbine power and the compressor power leads to the gradual increase of the energy consumption of the dual-ETC system. As shown in Fig.9, the reason for this phenomenon may be the low turbine efficiency, which is not enough to provide sufficient power for the compressor operation.

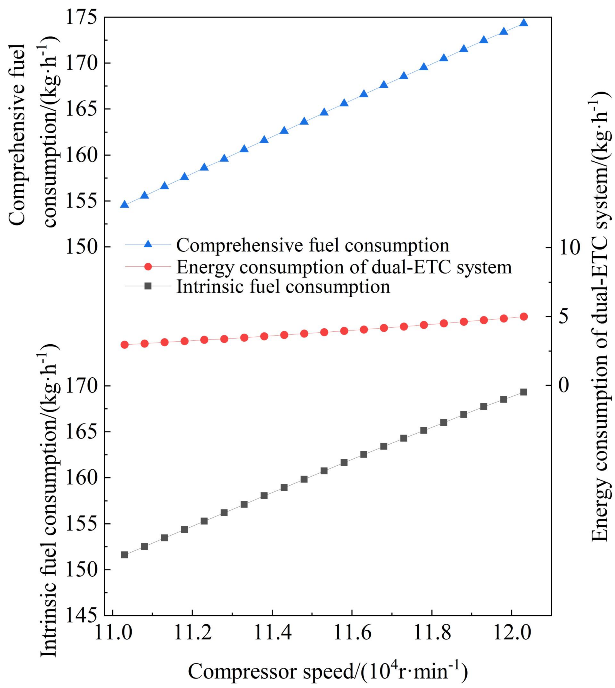

Fig. 9. The influences of the compressor speed on the energy consumption of methanol ICE at 1900rpm

Fig.9 illustrates that both the intrinsic fuel consumption and the comprehensive fuel consumption of the methanol ICE increase rapidly as the compressor speed rises. By contrast, the energy consumption of the dual-ETC system increases more slowly with the increase of the compressor speed. Among them, the increase of the intrinsic fuel consumption is due to the increase of the inlet flow rate caused by the increase of the compressor speed, and the methanol injection quantity also increases. The intrinsic fuel consumption and the energy consumption of the dual-ETC system increase with the increase of compressor speed, which will lead to the increase of comprehensive fuel consumption.

In the aforementioned research, the effects of the compressor speed on the main parameters of the methanol ICE are studied. The relationships between the compressor speeds and the comprehensive fuel consumption under the typical characteristic speed conditions are shown in Fig.10.

It can be seen that the comprehensive fuel consumption increases linearly with the increase of compressor speed from Fig.10, which is similar to Fig.9. The results show that the compressor speed and the comprehensive fuel consumption increase linearly under the typical characteristic speed conditions.

After the above analysis, the turbine speed has little influence on the main performance parameters of the methanol ICE with the dual-ETC system when the compressor speed is fixed. By adjusting the turbine speed through PID control, the turbine efficiency can be maintained at a high level and the energy consumption of the dual-ETC system can be reduced. However, with the increase of the compressor speed, the energy consumption of the dual-ETC system still shows a slow upward trend. The reason is that the turbine efficiency increases while the compressor power also increases slowly and the compressor power increase rate is higher than that of the turbine. From the study of the typical characteristic speed conditions of the methanol ICE, the increase of the comprehensive fuel consumption is caused by the increase of the intrinsic fuel consumption and the energy consumption of the dual-ETC system.

IV. Study on External Characteristics of the Methanol ICE with the Dual-ETC System

It can be seen from the above research that the turbine speed in the dual-ETC system only affects the turbine efficiency and the comprehensive fuel consumption. The discrete-grid method is used to find the optimal operating speed of the turbine in the calculation. In order to grasp the influences of the dual-ETC system on the external characteristics of the methanol ICE, the influences of the compressor speed on the external characteristics of the methanol ICE are studied under the condition of optimal operating speed of the turbine and the comparison with the external characteristics of the comparison engine is carried out under the same conditions.

A. The Influences of the Compressor Speed on the External Characteristics of the Methanol ICE

To ensure that the exhaust temperature before the turbine, cylinder maximum combustion pressure, the compressor and the turbine speed of the methanol ICE do not exceed their strength limits, the compressor speed change does not exceed 5000r·min^{-1} compared with the turbocharger of the comparison engine under various working conditions. During the simulation calculations, the discrete grid method is used to determine the optimal operating speeds of the turbine under the conditions of constant compressor speeds, so that the turbine efficiencies reach the each optimal values. On this basis, a study is conducted to investigate the effect of the compressor speed variation on the external characteristic parameters of the methanol ICE under different speed conditions, and the results are shown in Fig. 11.

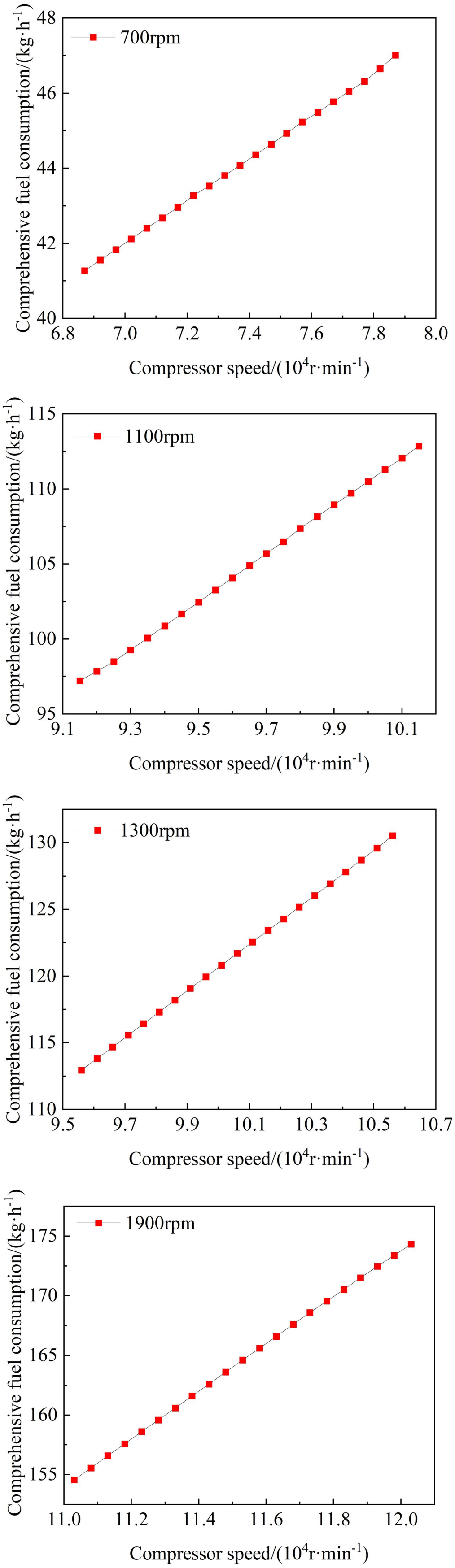

Fig. 10. The influences of the compressor speed on comprehensive fuel consumption under the typical characteristic speed conditions of the methanol ICE

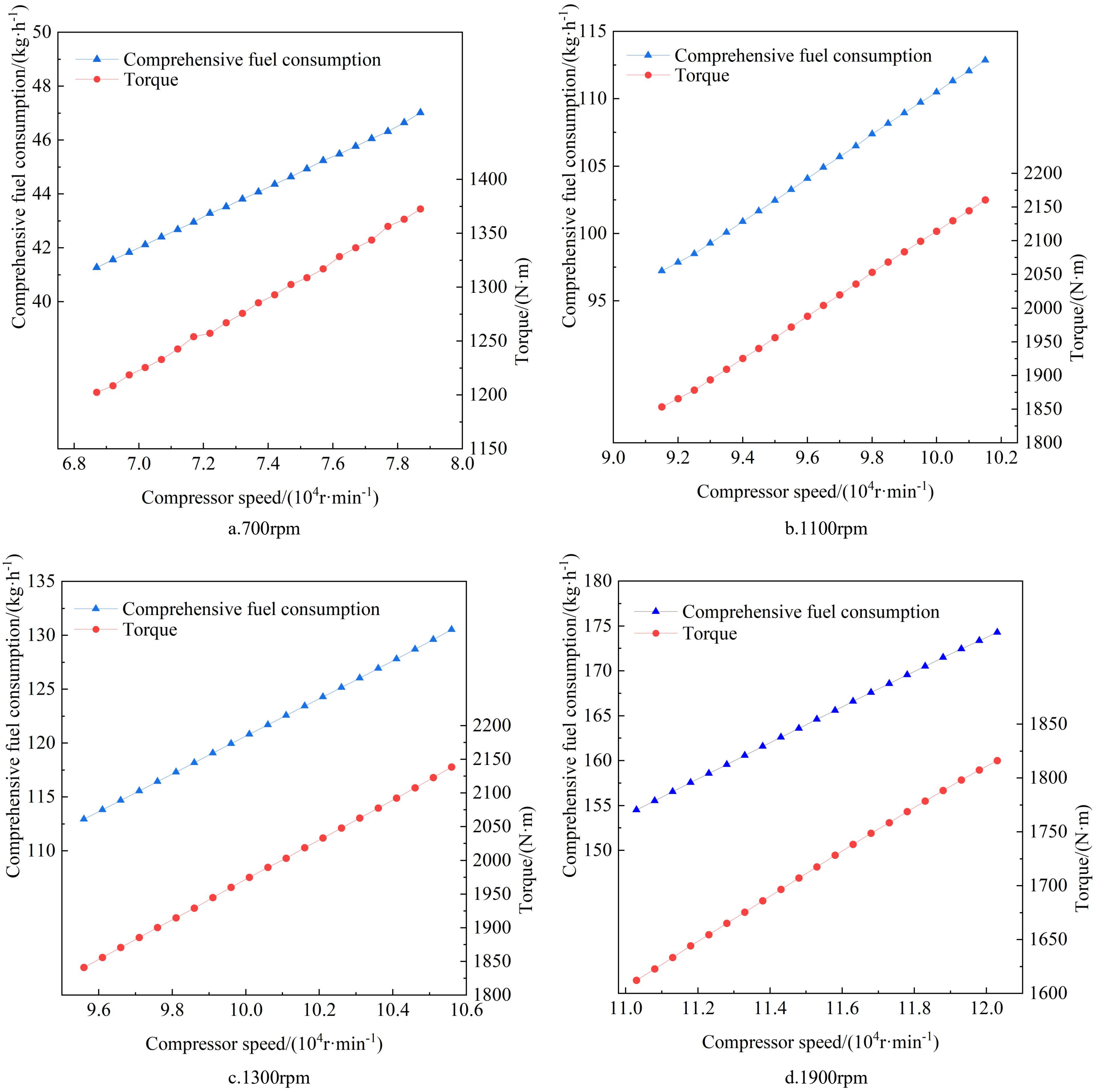

Fig. 11. Relationship between the torque and the comprehensive fuel consumption at each typical characteristic speed conditions of the methanol ICE

As shown in Fig.11 that when the methanol ICE operates at the typical characteristic speeds, the torque and the comprehensive fuel consumption of the methanol ICE show a linear upward trend. The reason may be that the range of the compressor speed selected in the research process is small, and the compressor efficiency does not change much. This trend can meet the needs of the methanol ICE to increase the torque or reduce the comprehensive fuel consumption by changing the compressor speed under different speed conditions. For example, under the condition of 1100 rpm of the methanol ICE, when the compressor speed is increased from 9.15×10^4 to 10.15×10^4 r/min, the torque is increased by about 16.59 %, while under the condition of 1300 rpm of the methanol ICE, when the compressor speed is reduced from 10.56×10^4 to 9.56×10^4 r/min, the comprehensive fuel consumption can be reduced by about 17.58 kg/h. The comprehensive fuel consumption increase and the torque increase rate of the compressor at the highest and lowest speeds under the typical speed conditions of the methanol ICE are listed in Table III. The torque increase rate indicates the percentage of the torque increase at the maximum speed of the compressor compared with the torque at the lowest speed of the compressor under the same typical working condition of the methanol ICE.

TABLE III
THE COMPREHENSIVE FUEL CONSUMPTION INCREASE AND THE TORQUE INCREASE RATE AT MAXIMUM AND MINIMUM COMPRESSOR SPEED FOR THE TYPICAL CHARACTERISTIC SPEED CONDITIONS OF THE METHANOL ICE

Typical characteristic speed/rpm	Comprehensive fuel consumption increase/(kg/h)	Torque increase rate/%
700	5.74	14.15
1100	15.64	16.59
1300	17.58	16.17
1900	19.79	12.66

According to Table III, when the methanol ICE is at low speed (700 rpm), the increase of the unit comprehensive fuel consumption (kg/h) of the methanol ICE increases the torque by about 2.47 % at the maximum speed point of the

TABLE IV
COMPARISON OF PARTIAL EXTERNAL CHARACTERISTIC PARAMETERS BETWEEN THE METHANOL ICE WITH THE DUAL-ETC SYSTEM AND THE COMPARISON ENGINE

Items		Value				Unit
Compressor speed	Typical characteristic speed	700	1100	1300	1900	rpm
The highest speed corresponding to the typical speed of ICE	The increase in comprehensive fuel consumption	3.70	10.11	11.20	13.52	kg/h
	Torque increase	92.68	158.28	147.83	96.69	N·m
	Torque increase rate	7.24	7.90	7.43	5.62	%
The lowest speed corresponding to the typical speed of ICE	The decrease in comprehensive fuel consumption	2.04	5.52	6.38	6.26	kg/h
	Torque decrease	77.48	149.10	149.89	107.47	N·m
	Torque decrease rate	6.05	7.45	7.53	6.25	%

compressor compared with the minimum speed point of the compressor. The results show that the increase of the unit comprehensive fuel consumption at low speed makes the power performance of the ICE increase obviously. At the high speed (1900 rpm) of the methanol ICE, the comprehensive fuel consumption at the minimum speed point of the compressor is significantly lower than that at the maximum speed point of the compressor (about 19.79kg/h). The results show that the reduction of the compressor speed can effectively improve the economy of the methanol ICE at high speed. The above results indicate that the variation of the compressor speed can realize the improvement of the power performance at low speed and the economy at high speed of the methanol ICE, which provides the possibility of cooperative control of the power performance and the economy of the methanol ICE.

B. Comparison of External Characteristics of the Methanol ICE

To grasp the difference in the external characteristics of the methanol ICE with the dual-ETC system and the comparison engine, the external characteristic parameters of the ICE with dual-ETC system at the highest and lowest speeds of the compressor at the typical characteristic speed are compared with the corresponding speed conditions of the comparison engine. The external characteristics of the methanol ICE with the dual-ETC system at the highest and lowest speeds of the compressor under typical characteristic speed conditions are shown in Fig. 12. The external characteristics parameters contain the comprehensive fuel consumption rate, the comprehensive fuel consumption, the torque and the power, where the comprehensive fuel consumption rate indicates the ratio of the comprehensive fuel consumption of the methanol ICE to its power under the same conditions.

As can be seen in Fig. 12, the comprehensive fuel consumption rate of the methanol ICE with the dual-ETC system is higher than that of the comparison engine when the compressor is operated at the highest and lowest speeds, and both of them reach the minimum value at the ICE speed of 1300 rpm. In addition, the power, the torque and the comprehensive fuel consumption increased at the highest speed of the compressor for the typical characteristic speed conditions, while the change is opposite when the compressor is at the lowest speed. After adopting the dual-ETC system, compared with the comparison engine, when the compressor speeds are the maximum and minimum respectively, the differences in comprehensive fuel consumption gradually increase with the increase of the speed of the methanol ICE. At the same time, after the methanol ICE is equipped with the dual-ETC system, the external characteristic parameters of the methanol ICE are no longer fixed. By changing the compressor speed, the external characteristics of the methanol ICE can be varied within a certain range. The variable range can provide the basis of achieving cooperative control of the methanol ICE power performance and economy.

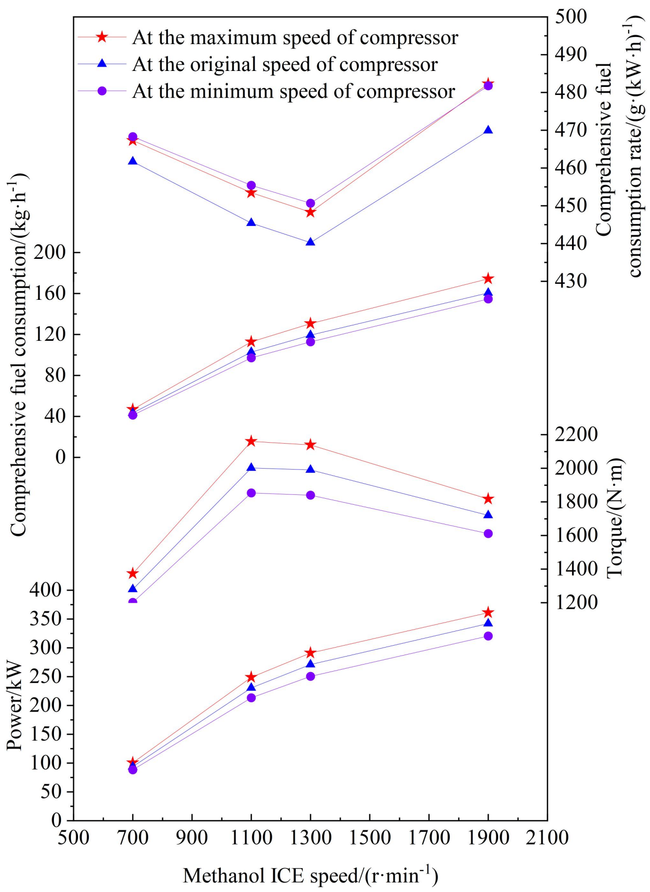

Fig. 12. Influences of maximum and minimum speeds of the compressor on the external characteristics of the methanol ICE

As shown in Table IV, when the methanol ICE operates at a low speed of 700 rpm, while the compressor functions at its maximum speed, the comprehensive fuel consumption of the methanol ICE increases by approximately 3.70 kg/h.

Concurrently, the torque rises by about 7.24%, indicating an enhancement in the power performance of the methanol ICE at low speeds. When the methanol ICE operates at the upper and the lower boundary speeds (1100rpm, 1300rpm) of the peak net torque range, the torque increase and the torque increase rate under the maximum speed condition of the compressor are larger, and the comprehensive fuel consumption rate is lower (see Fig.12), which indicates that the economy and the power performance of the methanol ICE are better under this condition. When the methanol ICE runs at the maximum net power speed (1900 rpm), the comprehensive fuel consumption reduces by about 6.26 kg/h compared with the comparison engine at the lowest compressor speed, which improves the economy of the methanol ICE at high speed. However, the torque decreases by about 6.25 % compared with the comparison engine, which declines the power performance of the methanol ICE at high speed.

On the above analysis, compared with the comparison engine, the methanol ICE with the dual-ETC system can improve low-speed power performance and high-speed economy of the methanol ICE by changing the compressor speed. This characteristic makes the external characteristics of the methanol ICE change within a certain range with the change of the compressor speed, which is conducive to the cooperative control of the power performance and the economy of the methanol ICE.

V. Conclusion

To master the effect of the dual-ETC system on the external characteristics of the methanol ICE, a one-dimensional thermodynamic simulation model of the methanol ICE with the dual-ETC system is established. The influences of the turbine and the compressor speed on the main performance parameters of the methanol ICE are studied. The influences of the compressor speed on the external characteristics of the methanol ICE is analyzed. The external characteristics of the methanol ICE with the dual-ETC system and the comparison engine are compared. The following conclusions are drawn:

(1) The change of the compressor speed has a greater effect on the main performance parameters of the methanol ICE, while the influences of the turbine speed are smaller.

(2) Under the typical characteristic speed conditions, the comprehensive fuel consumption, the power and the torque of the methanol ICE with the dual-ETC system show a gradually increasing trend with the increase of the compressor speed. The change of the compressor speed can improve the power performance of the methanol ICE at low speed and the economy at high speed. The results show that the external characteristics of the methanol ICE with the dual-ETC system have the possibility of cooperative control.

(3) The methanol ICE with the dual-ETC system has a lower comprehensive fuel consumption rate at the upper and the lower boundary speeds in the net torque peak range. When the boundary speed is in the peak range of net torque and the compressor is the highest speed, the torque of the methanol ICE is the largest.

(4) Compared with the comparison engine, the maximum net power speed of the methanol ICE with the dual-ETC system and the minimum speed of the compressor, the comprehensive fuel consumption greatly reduces. Under the condition of the lowest stable speed and the highest compressor speed, the maximum torque increase rate can be obtained by increasing the unit comprehensive fuel consumption of the methanol ICE.

The above results indicate that the proposed cooperative control idea is valid to enhance the power performance of the methanol ICE at low speed, while optimizing economy at high speed through compressor speed regulation. Furthermore, the suggested dual-ETC system is feasible for application in the methanol ICE. However, the shortages remain, including the low efficiency of the turbine and the need of additional power of the compressor. These may be attributed to the low efficiency of the turbine selected for the comparison engine.

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