Parameter Design of Core Components of Proton Exchange Membrane Fuel Cell (PEMFC) for Commercial Vehicles

Jiayu Lu, Binbin Sun, Di Huang, Tianqi Gu, Pengwei Wang and Wentao Li

***Abstract*—PEMFC has the advantages of zero emission and high efficiency, and has become the focus of research on new energy vehicles. In order to design and develop high power and high efficiency PEMFC for commercial vehicles, this paper focuses on the parameter design and selection matching of the core components of the battery. Firstly, the number of fuel cell stack pieces and reaction area were determined to meet the power performance designed. Secondly, according to the requirements of PEMFC power and economic design indexes, the key parameters of battery cathode system air compressor, intercooler,the hydrogen circulation pump humidifier and back-pressure valve were calculated and determined. Further, to ensure the heat dissipation requirements of PEMFC, the key parameters of the radiator and cooling water pump of the hydrothermal management system were designed and the components were selected. Finally, the performance analysis of the designed PEMFC was carried out. The results show that the maximum and average power of the PEMFC system are 43.08 kW and 15.70 kW, respectively. Under the NEDC cycle, the maximum and average power of the fuel cell stack is 54.23 kW and 18.24 kW,respectively. The maximum and average efficiency of the PEMFC is 49.69 % and 47.66 %, and the hydrogen consumption in the cycle is 0.29 kg. The designed PEMFC meets the requirements of power and economic performance.**

***Index Terms*—PEMFC, parameters design, fuel cell stack, cathode system, anode system, hydrothermal management system**

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I. INTRODUCTION

PEMFC rapidly rises due to its high efficiency, cleanliness, no pollution and other characteristics, and has now entered the stage of large-scale development, and is considered to be one of the most market promising automotive power solutions [1-2]. Developed countries and regions such as Japan, South Korea, and the United States start earlier in fuel cell research and industrialization applications, and have formed a Technological leadership [3-4]. At present, the research and application of PEMFC in China are mainly focused on the low-power and short-range application scenarios such as city buses [5]. The research and application of high-power and long-range fuel cell commercial vehicles are relatively insufficient, and the existing technology reserve cannot support the large-scale production and application of high-power fuel cell commercial vehicles [6].

The medium and heavy commercial vehicles applied in long-distance scene operation present higher challenges in terms of PEMFC fuel power, economy and reliability due to high power demand, complex driving road conditions and poor operating environment [7]. PEMFC presents greater challenges in terms of parameter design of PEMFC core components due to severe coupling of hydrogen-air-cooling system, complex system control and sensitive conditions [8-9].

Designing reasonable PEMFC core components is the key to achieve efficient operation of PEMFC [10]. The core idea is to design the parameters, optimize and select component for core components such as fuel cell stack, air compressor, and hydrogen circulation pump according to the PEMFC performance design index requirements [11]. At present, the design method of PEMFC core components parameters can be summarized as follows: first, according to the PEMFC power performance index requirements, calculate and determine the range of PEMFC key components characteristic parameters and carry out simulation verification, and then adjust the system parameters and select components based on the verification results [12]. Second, the design, verification, optimization and selection of component parameters are completed according to the PEMFC power performance index requirements [13]. However, the above two methods only consider the one-sided factors of PEMFC power or economy, and do not take into account the overall performance of PEMFC, which will indirectly affect the battery efficiency characteristics or hydrogen consumption.

Therefore, in order to design the PEMFC with both economy and power, in the first part of this paper, the calculation methods of key parameters such as the number of PEMFC stack pieces and the area of PEMFC stack are presented. The design methods of key parameters of the cathode system air compressor, intercooler, humidifier and back-pressure valve are described in the second part. The third part focuses on the analysis and design of the parameters matching of the hydrogen circulation pump for the anode system. The fourth part designs and selects the key parameters of the radiator and the cooling water pump of the hydrothermal management system. Finally, the performance analysis of the designed PEMFC is presented in the fifth part.

II. Parameters Design of Fuel Cell Stack

As shown in Tab. 1, the developed PEMFC performance index parameters are given. In this paper, the parameters of the core components such as PEMFC stack, cathode system, anode system, and hydrothermal management subsystem are designed and matched for selection according to the design requirements in the table.

Table Ⅰ Fuel cell parameter index requirements

Parameter	Value	Parameter	Value
Power output of the NEDC cycle/kW	≥ 45	Fuel cell stack rated voltage/V	170
Hydrogen consumption in NEDC cycle/kg	≤0.35	Rated current density/A·cm^{-2}	1.00
Maximum efficiency in NEDC cycle/%	≥ 45	Maximum allowable pressure drop of humidifier/bar	0.2
Average efficiency in NEDC cycle/%	≥ 40	Allowable pressure difference between cathode and anode/bar	0.2

The fuel cell stack is one of the most important components of the PEMFC. The output voltage of a single fuel cell is 0.6 ~ 0.7 V. The PEMFC stack is composed of several single cells, and the stack output voltage is the product of the single cell voltage and the number of cells. When the PEMFC operates under rated conditions, the stack voltage is the product of the single cell voltage and the number of cells. Based on the single cell output voltage, the number of single cells can be calculated.

$$V_{\text{stack,rated}} = n_{\text{cell}} V_{\text{cell}} \tag{1}$$

where, $V_{\text{stack,rated}}$ denotes the rated voltage of the fuel cell stack; n_{cell} denotes the number of single cells; V_{cell} denotes the single cell voltage.

Based on the output voltage of the single cell, the calculation finds the number of single cell pieces $n_{\text{cell}} = 265.63$, and the number of single cell pieces is 266 after rounding the result. According to the polarization curve in the figure, the open-circuit voltage of the single fuel cell is 0.973 V. According to equation (1), the open-circuit voltage of the fuel cell stack is 258.82 V.

The proton exchange membrane is the core component of the PEMFC stack and plays a decisive role in the performance of the stack. The size of the membrane area is influenced by the design power and current density of the fuel cell stack. The area of the membrane can be deduced based on the power performance design index requirements of the fuel cell stack.

$$P_{\text{stack,rated}} = n_{\text{cell}} V_{\text{cell}} i A \tag{2}$$

where, $P_{\text{stack,rated}}$ denotes the rated power of the fuel cell stack; i denotes the current density of the fuel cell stack; A denotes the area of the exchange membrane.

In summary, Tab. 2 gives the PEMFC stack parameters that meet the requirements of power performance and voltage design index requirements.

Table Ⅱ Fuel cell stack parameters

Parameter	Value	Parameter	Value
Output voltage/V	170 ~ 258.82	Output current/A	0 ~ 300
Number of single cell/pcs	266	Single cell exchange membrane area/cm^2	300

III. Parameters Design of Cathode System

A. Parameters Design of Air Compressor

The air compressor is the most important component in the cathode system, and its role is to output the oxidant of appropriate flow rate and pressure for the system. Increasing the pressure of oxidant can not only improve the cell efficiency, but also the power density. After determining the fuel cell stack parameters, the air compressor is the first core component to be designed. The PEMFC has strict requirements for the air compressor, including no lubricant, high efficiency, miniaturization, low noise, large characteristic range, fast dynamic response and so on. Based on the above performance requirements, a centrifugal air compressor is selected in this paper.

The air flow rate provided by the air compressor should be higher than the air flow rate required for the maximum output power of the fuel cell. Therefore, the maximum flow rate output by the air compressor should meet:

$$m_{\text{comp,out}} = \frac{S_{O_2} M_{\text{Air}}}{y_{O_2} 4F} I n_{\text{cell}} \tag{3}$$

where, $m_{\text{comp,out}}$ denotes the air mass flow rate output from the air compressor; S_{O_2} denotes the air stoichiometric ratio; M_{Air} denotes the air molar mass; y_{O_2} denotes the oxygen molar fraction; F denotes the Faraday constant; and I denotes the fuel cell stack output current.

The typical stoichiometric ratio is 2 ~ 3 when the fuel cell stack is added to air. In order to prevent the selected air compressor from not meeting the actual application, S_{O_2} is taken as 3 and substituted into the known data to obtain, the outlet mass flow rate of the air compressor $m_{\text{comp,out}} \geq 86$ g·s^{-1}.

Another important parameter of air compressor is the compression ratio. Based on the determined maximum flow rate of the air compressor, it can predict the pressure drop when the air passes through the inter-cooler and humidifier. Further, by adding it to the working pressure of the fuel cell stack, the pressure required for the air compressor can be calculated.

$$P_{\text{comp,out}} = P_{\text{coller,down}} + P_{\text{hum,down}} + P_{\text{stack}} \tag{4}$$

where, $P_{\text{comp,out}}$ denotes air compressor output air pressure; $P_{\text{coller,down}}$ denotes the pressure drop when air passes through the intercooler; $P_{\text{hum,down}}$ denotes the pressure drop when air passes through the humidifier; P_{stack} denotes fuel cell stack working pressure.

The maximum pressure drop of the intercooler is 10 kPa, the maximum pressure drop of the humidifier is 20 kPa, and the working pressure of the fuel cell stack of the high pressure fuel cell system is usually around 200 kPa, and the working pressure of the fuel cell stack is about 220 kPa. Thus the outlet pressure of the air compressor $P_{\text{comp,out}} \geq$ 250 kPa can be determined.

The air compressor compression ratio should meet:

$$\lambda_{\text{comp}} = \frac{P_{\text{comp,out}}}{P_{\text{comp,in}}} \tag{5}$$

where, λ_{comp} denotes the air compressor compression ratio; $P_{\text{comp,in}}$ denotes the air pressure into the air compressor.

Since the source of air entering the air compressor is the surrounding environment, the inlet pressure of the air compressor is taken as the surrounding environment pressure, and the standard atmospheric pressure is taken as the inlet pressure, which is calculated as $\lambda_{\text{comp}} = 2.47$. In addition to the rated working point, it is generally necessary to consider the overload working point and leave a margin for the maximum working point, which is generally designed according to 110 % kW, at this time, $m_{\text{comp,out}} = 95\text{g} \cdot \text{s}^{-1}$, $\lambda_{\text{comp}} = 2.7$.

The relationship between volume flow rate and mass flow rate needs to meet:

$$V_{\text{comp,out}} = \frac{3\, m_{\text{comp,out}}}{50\, \rho_{\text{Air}}} \tag{6}$$

where, $V_{\text{comp,out}}$ denotes the air compressor outlet volume flow rate; ρ_{Air} denotes the air density.

In summary, the air compressor type was finally determined and the core parameters of the air compressor to meet the design requirements were obtained, as shown in Tab. 3.

Table III Compressor parameters

Parameter	Value	Parameter	Value
Type	centrifugal	Maximum volume flow rate（$\text{m}^3 \cdot \text{min}^{-1}$）	4.4
Maximum mass flow rate（$\text{g} \cdot \text{s}^{-1}$）	95	Maximum compression ratio	2.7

B. Parameters Design of Intercooler

The main function of the intercooler is to cool the high temperature air compressed by the air compressor so that the air can reach the suitable temperature into the stack. For air cooling, there are currently two types of cooling methods: air cooling and cooling water cooling. As part of the hydrothermal management system, the intercooler in a fuel cell system usually uses cooling water from the hydrothermal management system to cool the high-temperature air. The high-temperature air and cooling water enter the intercooler through different pipes. The two pipes are separated by a bulkhead and they exchange heat as they flow. The cooling water carries away the heat from the high temperature air.

The key to the intercooler parameters design is that the heat dissipation of the intercooler should meet the heat dissipation demand generated by the maximum flow of the air compressor. Generally, the temperature at the inlet of the fuel cell stack is not higher than 333 K. When the air passes through the humidifier, there is heat exchange in addition to humidity exchange, so the air temperature will rise after the humidifier, and the air temperature at the outlet of the intercooler will be further reduced. The maximum temperature rise of the humidifier is 10 K, which requires the outlet temperature of the intercooler to be less than 323 K. The inlet temperature of the air compressor is the environment temperature, therefore, this paper takes the outlet air temperature of the intercooler to be 303 K for design.

$$T_{\text{comp,out}} = T_{\text{comp,in}} \cdot \lambda_{\text{comp}}^{\frac{\text{k}-1}{\text{k}}} \tag{7}$$

where, $T_{\text{comp,out}}$ denotes the air temperature after the air compressor; $T_{\text{comp,in}}$ denotes the air temperature into the air compressor; k denotes the adiabatic index.

The adiabatic index of air is 1.4, and substituting the known data obtains $T_{\text{comp,out}} = 393$ K. The temperature rise of the air compressor is 90 K. According to the outlet temperature of the air compressor and the outlet temperature of the intercooler, the required cooling power of the intercooler can be calculated. The intercooler heat dissipation power $Q_{\text{cooler}} =$ 5.19 kW, in the intercooler selection, the maximum heat dissipation power of the intercooler should meet more than 5.19 kW.

$$Q_{\text{cooler}} = c_{\text{Air}} \cdot m_{\text{comp,out}} \cdot \left(T_{\text{comp,out}} - T_{\text{cooler,out}}\right) \tag{8}$$

where Q_{cooler} denotes the intercooler heat dissipation power; $T_{\text{cooler,out}}$ denotes the air temperature after the intercooler; c_{Air} denotes the air specific heat capacity, and the air specific heat capacity at 300 K is 1.005 $\text{kJ} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$.

The cooling water provided by the cooling water pump is used for the heat dissipation of the intercooler. The cooling water is deionized water, according to the required cooling power of the intercooler. The specific heat capacity of cooling water is 4.1868 $\text{kJ} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$, the density of cooling water is 1000 $\text{kg} \cdot \text{m}^{-3}$, and the temperature difference between the inlet and outlet of the intercooler is 5 K.

Substituting the above data, the volume flow rate of cooling water required for the intercooler is 14.9 $L \cdot min^{-1}$.

$$V_{\text{cooler,water}} = \frac{60000\, Q_{\text{cooler}}}{c_{\text{water}} \cdot \rho_{\text{water}} \cdot \Delta T_{\text{cooler,water}}} \tag{9}$$

where, $V_{\text{cooler,water}}$ denotes the volume flow rate of cooling water required for the intercooler; c_{water} denotes the specific heat capacity of cooling water; ρ_{water} denotes the density of cooling water; $\Delta T_{\text{cooler,water}}$ denotes the temperature difference between the cooling water entering the intercooler and leaving the intercooler.

C. Parameters Design of Humidifier

When chemical reactions occur inside the fuel cell, hydrogen ions need to combine with water to transfer from the cathode to the anode through the exchange membrane, so the exchange membrane must be in a wet state, otherwise the reactions will not be carried out, which seriously affects the performance of the fuel cell system. When the humidifier parameters are designed, it is necessary to meet the humidity requirement of the gas entering the stack. In this paper, the required gas humidity into the fuel cell stack is 85 % ~ 95 %. In order to leave a margin for practical application, the calculation assumes that the air is humidified to saturation, i.e., the humidified air humidity is 100 %. Because the air from the atmosphere itself exists some water, the amount of the water contained in the outlet gas of the intercooler should be removed in the calculation of the amount of the required humidifying water , and the amount of the humidifier humidification water required to meet:

$$m_{\text{v,hum,in}} = m_{\text{v,hum}} - m_{\text{v,Air}} \tag{10}$$

where, $m_{\text{v,hum,in}}$ denotes the required water flow rate of humidifier; $m_{\text{v,hum}}$ denotes the required water flow rate of air to reach saturation; $m_{\text{v,Air}}$ denotes the flow rate of water vapor in the outlet gas of intercooler.

$$m_{\text{v,hum}} = \omega_{\text{s}} \cdot m_{\text{comp,out}} \tag{11}$$

where, ω_{s} denotes the saturated air water content.

$$\omega_{\text{s}} = \frac{M_{\text{v}}\, P_{\text{sat}}}{M_{\text{Air}}\left(P_{\text{stack}} - P_{\text{sat}}\right)} \tag{12}$$

where, M_{v} denotes the molar mass of steam; P_{sat} denotes the saturation pressure of water vapor at a certain temperature .

$$P_{\text{sat}} = \mathrm{e}^{aT^{-1} + b + cT + dT^2 + eT^3 + f\ln\left(T_{\text{stack,in}}\right)} \tag{13}$$

where, a、b、c、d、e、f are coefficients: $a =$ -5800.2206, $b =$ 1.3914993, $c =$ -0.048640239, $d =$ 0.41764768×10^-4^, $e =$ -0.14452093×10^-7^, $f =$ 6.5459673; $T_{\text{stack,in}}$ denotes the fuel cell stack inlet air temperature.

Substitute known data to obtain: At 333 K, $P_{\text{sat}} =$ 19.944 kPa; $\omega_{\text{s}} =$ 0.0622; $m_{\text{v,hum}} =$ 5.35 $g \cdot s^{-1}$. At 303 K, assuming 50 % relative humidity of the gas before entering the humidifier, $P_{\text{sat}} =$ 4.21 kPa . Then, the amount of water in the air before entering the humidifier can be determined.

$$m_{\text{v,Air}} = \omega_{\text{s,303}} \cdot m_{\text{cooler,out}} \tag{14}$$

where, $\omega_{\text{s,303}}$ denotes the air water content at 303 K.

$$\omega_{\text{s,303}} = \frac{M_{\text{v}}\, P_{\text{sat}}}{M_{\text{Air}}\left(P_{\text{stack}} - \varphi P_{\text{sat}}\right)} \tag{15}$$

where φ denotes the relative humidity of the gas.

Substituting known data can finally determine the water content of the air before entering the humidifier $\omega_{\text{s}} =$ 0.00603, water flow rate in the air $m_{\text{Air}} =$ 0.519 $g \cdot s^{-1}$. Humidification water flow rate is 4.831 $g \cdot s^{-1}$, and when the humidifier is selected, humidification water flow rate is greater than 4.831 $g \cdot s^{-1}$.

D. Parameters Design of Back-pressure Valve

The back-pressure valve is located at the cathode outlet of the fuel cell stack. The cathode pressure and flow rate are controlled by controlling the opening of the back-pressure valve to keep the pressure in the stack at the optimum operating pressure. At the same time, it is also necessary to ensure that the exhaust gas at the cathode can be discharged in time, which is a very important part of the cathode system. The calculation of the back-pressure valve parameters should be met: when the maximum gas flow rate is added to, the pressure drop of the back-pressure valve can meet the back-pressure requirements. Therefore, the K_{V} value of the valve needs to be determined. The K_{V} value is a flow characteristic parameter that indicates the flow characteristics of the valve, for compressible air in the fuel cell.

When $P_2 > 0.5\, P_1$,

$$K_{\text{V}} = \frac{Q_{\text{N}}}{3.34}\sqrt{\frac{\rho_{\text{N}} \cdot T_{\text{valve}}}{\left(P_1 - P_2\right)\left(P_1 + P_2\right)}} \tag{16}$$

where Q_{N} denotes the gas flow rate in standard condition; ρ_{N} denotes the gas density in standard condition; T_{valve} denotes the gas temperature passing through the valve; P_1 denotes the gas pressure before entering the valve; P_2 denotes the pressure at the outlet of the pressure reducing valve.

When $P_2 \le 0.5\, P_1$,

$$K_{\text{V}} = \frac{Q_{\text{N}}\sqrt{\rho_{\text{N}} \cdot T_{\text{valve}}}}{2.9 P_1} \tag{17}$$

The gas flow rate in standard condition is:

$$Q_{\text{N}} = \frac{273 \cdot Q_{\text{f}} \cdot \left(P_1 + 101.32\right)}{101.32 \cdot T_{\text{valve}}} \tag{18}$$

where Q_{f} denotes the volume flow rate of air at the cathode outlet of the fuel cell stack.

The air flow rate of the stack outlet is equal to the inlet air flow rate minus the oxygen consumed by the reaction. Then, the oxygen consumption can be deduced.

$$m_{O_2,\text{cons}} = \frac{M_{O_2}}{4F} I_{\max}\, n_{\text{cell}} \tag{19}$$

where $m_{O_2,\text{cons}}$ denotes the mass flow rate of oxygen consumed by the reaction; M_{O_2} denotes the weight of oxygen molecules.

In summary, the mass flow rate of oxygen consumed is 6.62 $g\cdot s^{-1}$, so the flow rate at the inlet of the fuel cell stack cathode minus the oxygen consumption flow rate is 79.38 $g\cdot s^{-1}$. Converting the mass flow rate to the volume flow rate, the volume flow rate at the outlet of the fuel cell stack cathode is 221 $m^3\cdot h^{-1}$. When the outlet pressure of the valve is atmospheric pressure and the inlet pressure is the fuel cell stack pressure, and the air flow rate is maximum, K_V = 22.6 is calculated by substituting the known data. The back-pressure valve is selected according to the K_V value and the pipe diameter of the connection valve, and the back-pressure valve opening is less than 90 % of the total opening at the maximum air flow rate.

IV. Parameters Matching of Hydrogen Circulation Pump for Anode System

In order to ensure the normal operation of the fuel cell, the hydrogen entering the fuel cell stack reaction is usually excessive, and the unconsumed hydrogen remains at the end of the anode after the reaction is completed, which not only causes a waste of hydrogen fuel but also may cause hydrogen deflagration if it is discharged directly into the environment. The hydrogen circulation pump is mainly responsible for re-transporting the unreacted hydrogen to the inlet of the fuel cell stack and mixing it with the original hydrogen, which both improves the hydrogen utilization and humidifies the hydrogen before entering the stack. The key requirement for calculating the hydrogen circulation pump parameters is that the flow rate of hydrogen it can deliver is greater than the amount of hydrogen remaining after the fuel cell reaction is complete. The hydrogen mass flow rate required by the cell at rated power is:

$$m_{H_2,\text{in}} = \frac{S_{H_2} M_{H_2}}{2F} I\, n_{\text{cell}} \tag{20}$$

where $m_{H_2,\text{in}}$ denotes the hydrogen mass flow rate into the stack; S_{H_2} denotes the hydrogen stoichiometry ratio; M_{H_2} denotes the hydrogen molecular weight.

In this design, the hydrogen stoichiometry ratio is 3, and the hydrogen mass flow rate at the inlet of the fuel cell stack is calculated to be 2.5 $g\cdot s^{-1}$. The required hydrogen flow rate at the rated power of the battery is the maximum flow rate required by the system. Therefore, the maximum hydrogen mass flow rate to be delivered by the hydrogen circulation pump is the hydrogen flow rate left at the anode outlet of the fuel cell stack at this time.

$$m_{H_2,\text{cycle}} = m_{H_2,\text{out}} = \left(S_{H_2} - 1\right)\frac{M_{H_2}}{2F} I\, n_{\text{cell}} \tag{21}$$

where $m_{H_2,\text{cycle}}$ denotes the hydrogen mass flow rate to be circulated by the hydrogen circulation pump; $m_{H_2,\text{out}}$ denotes the hydrogen mass flow rate at the outlet of the fuel cell stack anode.

In summary, the anode outlet hydrogen mass flow rate can be determined to be 1.67 $g \cdot s^{-1}$. Further, the circulating hydrogen mass flow rate is converted to the volume flow rate. The maximum volume flow rate of the hydrogen circulation pump is calculated to be 0.45 $m^3\cdot min^{-1}$.

$$V_{H_2,\text{cycle}} = \frac{m_{H_2,\text{cycle}}}{\rho_{H_2}} \tag{22}$$

where, $V_{H_2,\text{cycle}}$ denotes the circulating hydrogen volume flow rate; ρ_{H_2} denotes the hydrogen density.

V. Parameters Matching of Hydrothermal Management System

A. Parameters Design of Radiator

The fuel cell stack generates a lot of heat during operation, and the heat generated is equal to or even more than the battery power. Therefore, the heat needs to be transferred out in time. High power fuel cell systems need to use cooling water to remove excess heat from the fuel cell stack. The cooling water after heating needs to pass through the radiator to radiate the cooling water. Fuel cell system heat production mainly consists of two parts, one is the heat generated by compressed air; the other part is the heat generated by the reaction inside the stack. These require cooling water for heat dissipation. The amount of heat dissipation required by the intercooler has been calculated in the previous section, and the amount of heat generated by the stack is equal to the difference between the total energy generated by the reaction and the electrical energy of the stack.

$$Q_{\text{stack}} = P_{\text{stack}}\left(\frac{V_{\text{refer}}}{V_{\text{cell}}} - 1\right) \tag{23}$$

where, Q_{stack} denotes the power of stack heating (kW); P_{stack} denotes the power of stack; V_{refer} denotes the theoretical voltage of single cell; V_{cell} denotes the actual voltage of single cell.

Under the rated power, the heating power of the fuel cell stack is 47.7 kW by substituting the known data. the heat balance inside the stack needs to be maintained, so the stack needs to be heat dissipated, and the main forms of heat dissipation are cooling water heat dissipation, stack thermal radiation and reaction to generate water vaporization to dissipate heat. The water generated by the reaction inside the stack will take part of the heat out of the stack, the heat dissipated is small and negligible, and the heat radiated from the reactor to the surrounding environment is smaller and negligible, and the heat generated by the stack is considered to be carried out entirely by the cooling water. The heat dissipated by the radiator is the sum of the heat generated by the stack and the heat that needs to be cooled by the intercooler.

$$Q_{\mathrm{rad}} = Q_{\mathrm{water}} = Q_{\mathrm{stack}} + Q_{\mathrm{cooler}} \tag{24}$$

where, Q_{rad} denotes the radiator cooling power; Q_{water} denotes the cooling water cooling power.

In summary, it can be calculated to determine the radiator cooling power of 52.89 kW. For the cooling power to leave a cooling margin, take the cooling power of 56 kW.

$$V_{\mathrm{Air}} = \frac{Q_{\mathrm{rad}}}{c_{\mathrm{Air}} \cdot \rho_{\mathrm{Air}} \cdot \Delta t_{\mathrm{Air}}} \tag{25}$$

where, V_{Air} denotes the volume flow rate of air into the radiator; c_{Air} denotes the specific heat capacity of air; Δt_{Air} denotes the temperature difference between the air before and after the radiator.

Air specific heat capacity value of 1.047 kJ·kg^{-1}·K^{-1}, the radiator before and after the air temperature difference taken 15 K, after calculating the air volume flow rate of 2.53 m^3·s^{-1}. Air volume flow rate is the product of the radiator area and the wind speed provided by the radiator fan. If the maximum wind speed of the radiator fan can be determined, you can calculate the radiator cooling area.

B. Parameters Design of Cooling Water Pump

The fuel cell system needs to cool two parts, one is the heat generated by the cathode compressed air and the other is the heat generated by the chemical reaction of the fuel cell stack. After cooling by the radiator, the cooling water returns to the cooling water tank, and then the cooling water pump sends the cooling water into the stack and intercooler. The size of the cooling water pump flow rate and its response speed are directly related to the performance of the fuel cell. The composition of the typical water pump includes the pump body, impeller, water seal, bearing and so on. The speed of the motor driving the water pump is controlled according to the size of the coolant flow rate required by the battery system. The flow rate of the cooling water pump should meet the requirement that the heat generated by the stack can be taken away in time when the fuel cell has the maximum output power. When cooling the stack, the required volume flow rate of cooling water needs to meet:

$$V_{\mathrm{stack,water}} = \frac{60000\, Q_{\mathrm{stack}}}{c_{\mathrm{water}} \cdot \rho_{\mathrm{water}} \cdot \Delta T_{\mathrm{stack,water}}} \tag{26}$$

where, $V_{\mathrm{stack,water}}$ denotes the volume flow rate of cooling water required by the stack; $\Delta T_{\mathrm{stack,water}}$ denotes the temperature difference between the cooling water entering and leaving the intercooler.

This design takes the temperature difference between the entering and leaving stack cooling water as 5 K, which in turn can be calculated to determine the volume flow rate of cooling water required by the intercooler as 146.2 L·min^{-1}. The volume flow rate of cooling water required by the cooling water pump is the sum of the amount of the cooling water required by the stack and the cooling water flow rate of the intercooler.

$$V_{\mathrm{water}} = V_{\mathrm{stack,water}} + V_{\mathrm{cooler,water}} \tag{27}$$

where, V_{water} denotes the cooling water flow rate required to be provided by the cooling water pump.

In summary, the maximum cooling water volume flow rate that the water pump needs to provide is 161.1 L·min^{-1}. Leaving a design margin, the rounded value is 165 L·min^{-1}.

VI. Performance Analysis

In order to analyze the dynamic and economy of the designed PEMFC under NEDC cycle conditions, the characteristics of the fuel cell vehicle demand power, PEMFC power and auxiliary lithium battery power variation under this test condition are given in Fig. 1. The positive value indicates that the vehicle is running in the driving state, and the maximum drive power required is 69.17 kW. The negative value indicates that the vehicle is running in the deceleration braking energy recovery state, and the maximum recovery power required is 29.80 kW.

The results show that during the first 132 s vehicle start-up phase, the whole vehicle demand power is provided by the lithium battery, which is because it takes some time for the PEMFC start-up to stably output the power. After the start-up is completed, the whole vehicle demand power is mainly provided by the PEMFC. When the vehicle demand power is less than a certain value, the PEMFC power will not follow the vehicle power drop, and the extra energy generated will charge the lithium battery. If the PEMFC output power is too low or even zero, the fuel cell efficiency will be greatly reduced, and the frequent start-ups will also reduce the fuel cell life, so the PEMFC output power will be maintained within a certain range. When the vehicle demand power rises rapidly or the vehicle demand power exceeds the PEMFC rated power, the PEMFC provides power to the vehicle together with the lithium battery. Under the whole driving condition, the maximum demand power of PEMFC is 43.08 kW and the maximum output power of lithium battery is 26.80 kW.

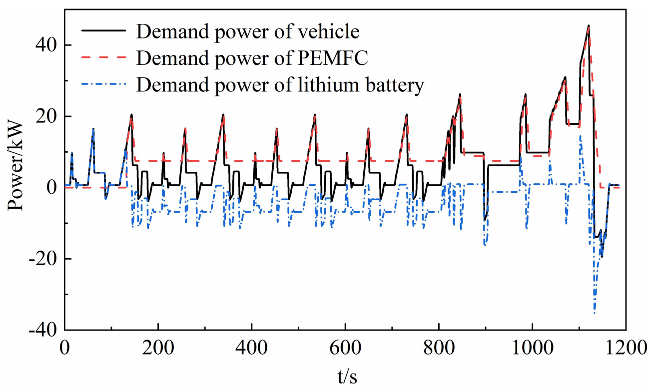

Fig. 1 Vehicle power distribution curve under NEDC

Fig. 2 shows the variation curves of PEMFC stack and system output power under NEDC conditions. The results show that the PEMFC system output power is smaller than the stack output power due to the parasitic power problem of air compressor, cooling water pump and other accessories. The average power output of the PEMFC system is 15.70 kW and the average power output of the stack is 18.24 kW. Overall, the designed PEMFC meets the dynamic performance design index requirements.

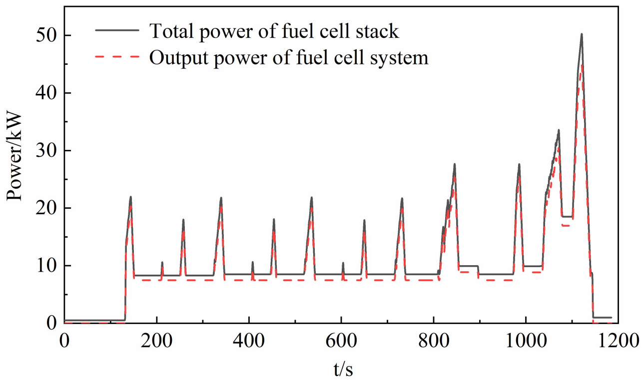

Fig. 2 PEMFC output power curve under NEDC

The output current curve of PEMFC system is given in Fig. 3. The results show that the PEMFC output current varies in the range of 0 ~ 330 A under NEDC conditions, and the overall changing trend is the same as the battery power output curve. the average output current of PEMFC is 101.72 A when the maximum output current of PEMFC is 323.08 A.

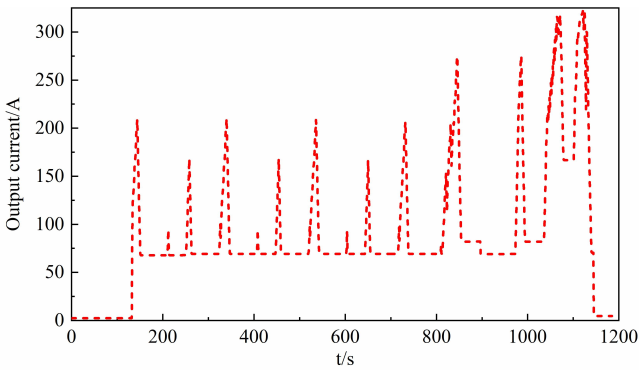

Fig. 3 Output current curve of PEMFC under NEDC

As shown in Fig. 4, the PEMFC efficiency curve under NEDC conditions is given. The results of the study show that the PEMFC system efficiency decreases as the PEMFC output power increases. The reason is that, at low power, the percentage of power lost by the auxiliary system is relatively small. At high power, the percentage of power lost by the auxiliary system increases quickly, which makes the system efficiency decrease obviously. Under NEDC conditions, the system efficiency varies from 39.77 % to 49.69 %, with an average efficiency of 47.66 %. Overall, the designed PEMFC meets the economical performance design index requirements.

As shown in Fig. 5, the hydrogen consumption for the NEDC conditions is given. The results show that the hydrogen consumption of PEMFC is 0.29 kg for operating a single NEDC condition, which meets the economical performance design index requirements.

VII. Conclusion

In order to design and develop high-power and high-efficiency PEMFC for commercial vehicles, this paper firstly designs the parameters of PEMFC stack, and determines the key parameters such as the number of the stack pieces and the area of the stack. Secondly, the air compressor, intercooler, humidifier and back-pressure valve of the PEMFC cathode system are designed and matched, and the key parameters such as air compressor type, the maximum mass flow rate and the maximum compression ratio are determined. The maximum heat dissipation power of the intercooler and the required cooling water volume flow rate are clarified. The minimum value of the humidifier humidification water flow rate is derived, and the K_V value of the back-pressure valve is designed and determined. Then, the parameters of the hydrogen circulation pump for the PEMFC anode system are designed, and the maximum volume flow rate of the hydrogen circulation pump is determined. Further, to ensure the heat dissipation requirements of the PEMFC, the key parameters of the radiator and cooling water pump of the hydrothermal management system are designed and selected, and the key parameters such as the air volume flow rate of the radiator and the maximum cooling water volume flow rate of the cooling water pump are determined. Finally, the performance analysis of the designed PEMFC was carried out. The results show that the maximum output power of the PEMFC system is 43.08 kW and the maximum output power of the stack is 54.23 kW under the NEDC cycle condition. The average power output of the PEMFC system is 15.70 kW and the average power output of the stack is 18.24 kW. The maximum efficiency of the PEMFC is 49.69 % and the average efficiency is 47.66%. The hydrogen consumption of the cycle working condition is 0.29 kg. The designed PEMFC meets the requirements of dynamic and economic design performance index.

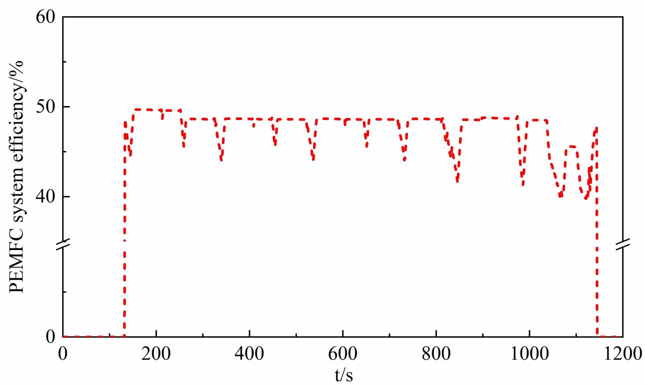

Fig. 4 Efficiency curve of PEMFC under NEDC

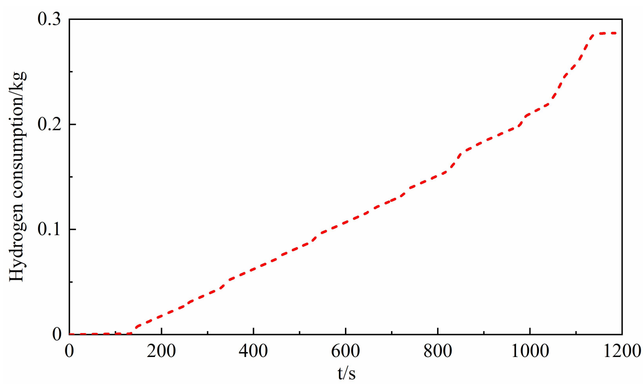

Fig. 5 Hydrogen consumption curve of PEMFC under NEDC

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