Research Status and Progress of Oxygen Sensor

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Abstract. The research progress of oxygen sensors was reviewed, the working principles of different types of oxygen sensors were summarized, and the control methods of temperature and pump current were briefly introduced. Then some problems encountered in the development of oxygen sensors were pointed out. Finally, the oxygen sensor technology was summarized and prospected.

1. Introduction

With the improvement of people's living standards, car has become indispensable to people's daily life, and the car ownership is also increasing gradually. According to statistics, by 2012, the national automobile population reached 108 million, emitting 28.655 million t of carbon monoxide (CO), 3.452 million t of HC, 5.829 million t of NOx, and 592,000 t of PM [1-2]. The emission of these pollutants intensifies the air pollution and threatens the environment on which human beings live.

Automobile oxygen sensor is a key element used in electronic fuel injection system to monitor oxygen content of exhaust gas and convert it into electrical signals [3]. The air-fuel ratio (A/F) of automobile engine is adjusted by oxygen sensor to control the combustion process in the engine, which can not only solve the problem of exhaust purification, but also improve the combustion efficiency of fuel and save energy [4].

In this paper, the development of oxygen sensor, working principles, control methods and other aspects were discussed, concentration difference oxygen sensor and wide area oxygen sensor working principles were emphatically explained, temperature and pump current control were analyzed.

2. Development overview

Automobile oxygen sensor was first invented by BOSCH in Germany in 1976, and the product was widely concerned and recognized by the society once it was released [5]. Early automotive oxygen sensors were U-shaped tubes with no built-in heaters (1st and 2nd generation products). Since the oxygen sensor itself needs to work at a temperature above 350 °C, and it takes more than 2 minutes or more from engine starting to oxygen sensor’s working temperature state heated by exhaust gas, and then the electronic fuel injection (EFI) system can enter the closed-loop control, the exhaust emission cannot be controlled during the cold start time [6].
As emissions regulations became more stringent, the researchers installed a heating rod (a 3rd generation product) inside the U-shaped tubular sensor to increase the heating rate of the oxygen sensor and reduce the cold start time to less than one minute. The 4th generation of oxygen sensor is integrated as sheet, using ceramic precision molding technology. The sensing elements and heating element are burned to an organic whole, which has the advantages of small volume, high integration and fast heating. After the EFI system was adopted, cold start time reduced to 15 seconds, but that can only satisfied the European III and European IV emissions standards [6]. The 3rd and 4th generation products fall under the category of narrow-domain oxygen sensors, which produce a jump output voltage change near $\lambda=1$, but are less responsive once output voltage is beyond the range [7].

The 1st generation to the 4th generation of oxygen sensors are different in working principles, which belong to concentration difference oxygen sensor, and have high intelligence, good reliability, long life and other advantages. However, the measurement range of air fuel ratio of concentration difference oxygen transmitter has its limitations. Its control interval and control accuracy cannot be reduced and improved indefinitely, and only the theoretical air fuel ratio can be measured and controlled [8]. Therefore, the concentration difference oxygen sensor is a narrow domain oxygen sensor, which cannot meet the requirements of the engine control system. So the wide domain oxygen sensor (5th generation product) comes into being. Due to the unique linear signal output characteristics of this type of oxygen sensor, its measuring accuracy and range are greatly improved compared with traditional concentration difference oxygen sensor [9]. Table 1 shows the performance parameters of each generation oxygen sensor.

Table 1. Oxygen sensor algebra and its related performance parameters

| The generations of oxygen sensor | Performance parameters |
|----------------------------------|------------------------|
| 1st and 2nd generation           | No heating element, cold start time > 2min, exhaust emissions can’t be controlled. |
| 3rd generation                   | The cold start time < 1min, and the preparation process of components at high temperature is complex. |
| 4th generation                   | Cold start time < 15s, small size, high integration, fast heating speed. |
| 5th generation                   | The total reaction time is < 10s, the reaction is rapid, and has the linear output characteristic, the measurement accuracy is greatly improved. |

3. Working principles

3.1. Concentration difference oxygen sensor

Concentration difference oxygen sensor was designed and developed based on Nernst principle which was proposed by German physical chemist Walther Nernst in 1889. The whole structure is multi-layered, including ZrO$_2$ matrix, Al$_2$O$_3$ insulation layer, $Pt$ heater, air channel, YSZ electrolyte, sensitive electrode, etc., and the sensitive element is made of zirconia solid electrolyte. The structure is shown in Figure 1. (a).

The working principle of concentration difference oxygen sensor follows Nernst equation, and the specific working principle is shown in Figure 1. (b). The core component of the sensor is YSZ electrolyte, which consists of internal and external electrodes to form a concentration cell.

$$ Pt \cdot P_{ref} \left| \text{YSZ} \right| P_{sen} \cdot Pt $$

(1)

The concentration difference cell’s reaction equation at the anode is:

$$ O_2^{\text{(ref)}} + 4e^- = 2O_2^{2-} $$

(2)

The reaction equation at the cathode is:
\[2O^{2-} - 4e^- = O_2^{(sen)}\]  \hspace{1cm} (3)

Therefore, the total electrode reaction is:

\[O_2^{(ref)} = O_2^{(sen)}\]  \hspace{1cm} (4)

Where, \(O_2^{(ref)}\) refers to the oxygen in the reference air, \(O_2^{(sen)}\) is the oxygen in the exhaust gas to be measured.

With the increase of working temperature, when the temperature reaches about 800°C, oxygen on the side of high concentration moves through oxygen vacancy in the form of \(O_2^-\) to the side of low concentration under the action of YSZ electrolyte ionic conductivity, forming oxygen ionic conductivity, and then a concentration potential \(U\) will be generated on both sides of YSZ electrodes:

\[U = \left(\frac{RT}{4F}\right) \ln\left(\frac{P_1}{P_2}\right)\]  \hspace{1cm} (5)

Where, \(U\) is oxygen concentration potential (V), \(R\) is the gas constant (8.314J/mol·k), \(T\) is the operating temperature, \(F\) is Faraday constant, \(P_1\) is the oxygen partial pressure of the reference gas, \(P_2\) is the oxygen partial pressure of the gas to be measured.

Figure 1. Structure, principle and working characteristic curve of concentration difference oxygen sensor [10]

Figure 1. (c) is the working characteristic curve of concentration difference oxygen sensor. When \(\lambda < 1\), oxygen concentration is low in exhaust gas, and the electrolyte oxygen pressure difference on both side of the electrolyte is big, and the output voltage \(U\approx0.9\text{V}\). When \(\lambda > 1\), there is a sharp drop in output voltage, and the output voltage \(U\approx0\text{V}\). So the concentration difference oxygen sensor is a narrow-domain oxygen sensor that produces a jump in output voltage change near \(\lambda = 1\). Once beyond this range, its reaction performance decreases [11].

3.2. Wide-area oxygen sensor

In order to achieve the feedback control within the range of all-air fuel ratio, the researchers developed a wide-area oxygen sensor based on the narrow-area oxygen sensor, which can be used for the control of thin combustion, dense combustion and combustion near the air-fuel ratio. The wide-area oxygen sensor reflects the concentration of air-fuel mixture ratio by detecting the oxygen content in engine exhaust emissions and sending corresponding voltage signals to the electronic control unit [8-10]. The wide-area oxygen sensor is composed of two major parts: the sensor battery and the pump oxygen battery, which are separated by a gap porous layer of 20 to 50 μm in the middle. The specific structure is shown in Figure 2. (a).

The working principle of the wide-area oxygen sensor is shown in Figure 2. (b). On the basis of the concentration difference oxygen sensor, an oxygen pump element is added, and the exhaust gas enters
the diffusion chamber through the diffusion barrier. At the same time, the heating element keeps the sensor at about 700℃, so that the zirconia sensitive element can achieve the best working effects.

![Diagram of Structure](image1.png)
![Diagram of Working Principle](image2.png)
![Characteristic Curve](image3.png)

Figure 2. Structure, principle and characteristic curve of wide-area oxygen sensor [12]

Working characteristic curve is shown in Figure 2. (c). We can see that, when $\lambda > 1$, the pump battery pumps $O_2$ out of the house. When $\lambda < 1$, the pump battery pumps $O_2$ from the exhaust gas to the detection chamber. When $\lambda = 1$, IP = 0, and there's no $O_2$ pumping in or out. The output characteristic curve is very smooth, and the pump current IP is almost proportional to $\lambda$ in the range of $\lambda >$ and $\lambda < 1$, which has a good linear relationship. The wide-domain oxygen sensor provides an accurate air-fuel ratio for a wide range of air coefficients ($\lambda = 0.65$-$2.4$), maximizing the role of a ternal-catalyst for reducing harmful components in the exhaust [13].

4. Control methods

Oxygen sensors, especially wide-area oxygen sensors, have strict requirements on operating temperature, and when measuring air-fuel ratio by controlling pump current, they must be equipped with a controller to work normally. Temperature and pump current control directly affect the performance of the sensor. Therefore, it has important theoretical significance and engineering application value to study the control methods of oxygen sensor.

4.1. Temperature control

For the wide-domain oxygen sensor, zirconia in the sensor starts to guide oxygen ions only when the temperature exceeds 350℃. Therefore, the heater module is generally integrated in the oxygen sensor. On the one hand, the internal temperature of the sensor is rapidly increased through the heater to realize the fast start of the sensor; on the other hand, the temperature is maintained near the working temperature to reduce the influence of exhaust gas temperature fluctuations on the sensor and ensure the stability of the output signal [14]. In general, there is no need to install a special temperature measuring element inside the oxygen sensor, and there is a one-to-one correspondence between the sensor temperature and the internal resistance. Temperature detection can be achieved by measuring the internal resistance of the oxygen concentration difference battery [15].

The temperature control of the oxygen sensor is mainly divided into three steps, which are respectively the measurement of the resistance value of the oxygen concentration difference cell, the implementation of the temperature control algorithm and the regulation of heating voltage. The internal resistance can be measured by ac drive method, and the duty ratio of PWM wave can be adjusted according to the measured value of internal resistance, and the heating voltage at both ends of heater can be changed to realize closed-loop control of temperature. Secondly, the temperature control
of the oxygen sensor is characterized by one-way heating, constant temperature maintenance and nonlinearity, etc., so slope heating and fuzzy control are often adopted for temperature control [16].

Liu Jie [16] proposed a control method of slope heating, which comprehensively considered the heating restriction conditions and the heating effect in the actual experiment. The initial heating voltage was 8V and the voltage increase rate was 0.35v /s, and the temperature was raised to near the working temperature point in the shortest time to complete the cold-start heating process. Lv Peng [17] designed a heating control circuit, IRF540 n-channel MOS tube was selected, which greatly improve the switching speed. ES63x series air-fuel ratio measurement module developed by German ETAS company is equipped with high-performance heater that can ensure that the oxygen sensor can reach the working temperature within 5s [18].

4.2. Pump current control

The pump current control module is composed of current signal conditioning circuit, accumulative current driving circuit and signal acquisition circuit. It realizes oxygen concentration difference potential detection, pump current driving, pump current detection and dc signal acquisition, which determines the accuracy of the measurement results of the oxygen sensor [19].

Min Bing et al. [20] designed a pump current conditioning circuit, using ADI company's zero drift, rail-to-rail input and output instrument amplifier as the current detection amplifier, and adopting indirect current feedback architecture to achieve real rail-to-rail input and output capacity, increasing the stability of oxygen concentration difference detection. Poggio Luca and Secco Marco from Magneti Marelli [21-22] of Italy designed an oxygen sensor controller framework to control pump current by simulating fuzzy control method, so as to reduce the interference of oxygen concentration difference potential fluctuation when measuring internal resistance, increase the accuracy of measuring internal resistance, and improve the accuracy of temperature control of sensor. Brace a. Bowling and Albert C. Grippe [23] in the United States developed A kind of controller with 56F8323DSP as core oxygen sensor, which USES control method and digital filtering method to strengthen pump current detection circuit.

5. Conclusions

The manufacturing and control technology of oxygen sensor has been gradually mature through continuous development, and the types of oxygen sensor are also constantly updated. However, the following aspects of oxygen sensor still need to be studied and improved at present.

- Oxygen sensor temperature and the pump current control strategy of technology: the study of key technology of electronic control device, segmental heating and current regulation method. Design of controller and setting of system parameters, including research of control algorithm, design and construction of control simulation platform, determination and selection of system parameters under different setting conditions.

- The core chip of the new wide-area oxygen sensor and the new reference channel technology: including the research of the stress matching of the high-temperature co-sintering of the wide-area oxygen sensor chip, the research of the new electrode material, and how to use the solid reference channel to replace the traditional air reference channel.

- The new diffusion channel model of oxygen sensor and the design of diffusion resistance: both sides of the sensor adopt volatile slurry to prepare the diffusion channel and establish the diffusion model.

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