Design and analysis of gas temperature measurement module in motor vehicle exhaust online measurement system

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Abstract: The mass flow rate of vehicle exhaust significantly influences the measurement of the exhaust pollutants emission factors, meanwhile the exhaust gas temperature measurement is most important in the measurement of exhaust gas mass flow. In order to measure the temperature of exhaust gas accurately and sensitively, a motor vehicle exhaust online measurement experimental system has been developed. The article reports on the design and analysis of gas temperature measurement module in this system. The gas temperature measurement consists of a high-precision K-type thermocouple and a weak signal amplifier circuit. The K-type thermocouple was used to measure the temperature of exhaust gas. Based on the ADS991QAQ, which was a complete instrumentation amplifier chip with a cold junction compensator for thermocouple, the weak signal of thermocouple was amplified to achieve accurate and rapid measurement of exhaust gas temperature. The real experimental results showed that the detection time is 0.5 s, the deviation is ±0.2°C, and the detection limit is 573°C. The subsequent analysis showed that the gas temperature measurement module performed well to support the system.

1 Introduction

Over the past decades, various kinds of motor vehicles have gone through an explosive growth process, thus resulting in an increasingly serious problem, i.e. the environmental pollution of exhaust gas [1]. Therefore, along with the development of motor vehicles, the exhaust gas has been a hardly avoided issue for many fields such as engineering industry, instrumental analysis [2], environmental protection [3], and even automobile industry itself [4].

To investigate the exhaust gas, much research attention has been naturally paid on the measurement of exhaust mass flow rate as well as the concentration of the gaseous pollutants (CO, HC, NOx etc.), thus resulting in the development of various kinds of measurement meters, such as turbine and vortex type flow meters [5], ultrasonic flow meters [6], hot wire flow meters [7] etc. Although these meters have been developed, there are still some disadvantages remained to overcome. For example, the turbine flow meters is unsuitable for pulsating flow especially at high temperature [8]; the ultrasonic flow meters can be easily affected by temperature and density the fluid [6]; the hot wire flow meters are always affected by the deposition of particulate matter carried by exhaust gases [7]. Besides, various kinds of pressure flow meters, such as nozzles, venture tubes, and Pitot tubes [9], have been widely used for on-board measurement of exhaust gas, but they are always seriously affected by the pulsation of the gas flow, thus resulting in great errors, due to the fact that the average volume flow rate cannot be represented by average differential pressure [10]. Currently, with the increasing depth of research and the application of modern electronic technology, the disadvantages related to these meters are being overcome [11–13]. As a result, some relatively successful meters regarding exhaust gas measurement have been developed and are now available commercially [14, 15]. However, since the exhaust gas from an engine is too complex, there is still a long way to go to make the exhaust gas flow measured more accurately.

With a view to make systematic investigation on the exhaust gas flow, our group have successfully developed a motor vehicle exhaust online measurement experimental system (MVEOME system, hereafter) by improving Pitot tube, thermocouple, pressure gauge, and differential pressure gauge in terms of the difference detection devices [16]. Since temperature is one of the key parameters that measure the exhaust gas flow, this paper reports the design and performance of temperature measurement module in the MVEOME system. As we know, the temperature of the exhaust gas from a motor (MVEOME system) is fluctuant. To realise the online temperature measurement of the gas, the temperature measurement module should be sensitive and accurate. Otherwise, the value of the measured temperature would strongly deviate from the real value, thus resulting in the poor performance or even failure of the whole MVEOME system.

2 Principle and system

2.1 Theoretically analysing the effect of temperature measurement module on the MVEOME system

The work of the whole MVEOME system was mainly based on Bernoulli’s principle and Fluid continuity equation, here, the formula of the fluid continuity equation can be written as:

\[ q_m = \frac{k}{K(\text{RE})} \left( \frac{P}{RT} \right) \times \Delta P \]  

(1)

where \( K(\text{RE}) \) is Reynolds number; \( A \) is the cross-sectional area of the flow tube; \( P \) is the upstream pressure of the exhaust gas; \( M \) is the molar mass of the exhaust gas; \( R \) is the constant of sample gas; \( T \) is the thermodynamic temperature of the exhaust gas; \( \Delta P \) is the differential pressure measured by the Pitot tube \( (P_{\text{high}} - P_{\text{low}}) \).

To explore the relationship between temperature measurement error and gas flow rate measurement error in the MVEOME system, formula (1) can be further simplified as:

\[ q_m = k \times \sqrt{\frac{P}{T}} \times \Delta P \]  

(2)

Obviously, according to formula (2), if \( P \) is kept constantly, \( q_m \) is just the function of \( T \). We can deal with this formula by the method of differential coefficient, and obtain the relationship between \( \Delta q_m \) and \( \Delta T \) as:
\[
\Delta q_m = k \times \sqrt{P\times\Delta P} \times \left[\frac{1}{T} - \frac{1}{T^2}\right] \times T
\]  
(3)

Therefore, based on this formula, we can further analyse the performance of the temperature measurement module in MVEOME system. Obviously, when \( P, \Delta P, T, \text{and} K(\text{RE}) \) are kept as constants, \( \Delta q_m \) and \( \Delta T \) have a linear relationship.

2.2 Design of MVEOME system

In the whole system, a special exhaust gas mass flow measurement path was designed by improving Pitot tube, thermocouple, pressure gauge, and differential pressure gauge. As reported previously, the MVEOME system can give us accurate experimental results of exhaust gas mass flow with relatively small deviations [16], as shown in Fig. 1.

The exhaust gas of the motor vehicle reaches the sampling tube through a thermal insulation hose. The sampling tube is a custom stainless steel tube, the diameter is same as the motor vehicle exhaust pipe, and the length is 40 cm. The exhaust gas is discharged from the right end of sampling tube, and when the gas pass through sampling tube, the pressure of it will stay stable. The stainless steel sampling tube has a fast heat dissipation and long path, it results in a large temperature fluctuation. Therefore, a temperature thermocouple is set at the inlet end of the sampling tube, and the other is set at the outlet end, the average value of the thermocouples is more conformable to the actual temperature of exhaust gas. The pressure difference is measured by the Pitot tube in the middle section, and the pressure of exhaust gas is measured by the pressure gauge at the outlet.

The measured pressure, pressure difference, and temperature are processed by the signal amplifying filter circuit and converted by AD conversion circuit. Then, the data processor is used to calculate. Finally, these data are transmitted to the upper computer to show the real-time quality flow of the vehicle exhaust.

2.3 Design of temperature measurement module in MVEOME system

As related above, the design of the MVEOME system was mainly based on Bernoulli’s principle and Fluid continuity equation. Thus, the temperature measurement for the MVEOME system is, of course, very important because Bernoulli’s principle and Fluid continuity equation are the function of temperature. In other words, the temperature measurement of the exhaust gas is one of the key factors that determine the performance of the MVEOME system. Therefore, in this work, our research was mainly focused on the temperature measurement module in the MVEOME system.

In order to obtain an accurate temperature measurement of the MVEOME system, a special temperature measurement module has been designed, as shown in Fig. 2. Two consistent thermocouple circuits were set at inlet and outlet, respectively. The thermocouple circuit consists of two parts, one part was a K-type thermocouple, which was used to detect the temperature, and the other was a chip used to amplify the thermocouple signal. The temperature signal was directly converted into a voltage signal by the K-type thermocouple, and the linear relationship between temperature signal and voltage signal was 40 \( \mu \text{V/}^\circ\text{C} \).

According to the parameter performance of the previously selected K-type thermocouple, the temperature measurement module was designed on the basis of an AD595AQ chip, which had the parameters with cold junction compensation, low impedance output 10 mV/\( ^\circ\text{C} \), and work voltage ranging from 5 to 15 V. When the work voltage was 5 V, the temperature measurement was in the range of 0°C to 300°C. Usually, the temperature of general vehicle exhaust was about in the range of 30–280°C. In this temperature range, the output voltage of K-type thermocouple was in the range of 1.203–11.381 mV. The relationship between the output of AD595AQ and the output voltage of K-type thermocouple is shown as follows:

\[
V_{\text{out,AD595}} = (V_{\text{TypeK}} + 11 \mu \text{V}) \times 247.3
\]  
(4)

According to formula (4), in this measurement temperature range, the output voltage of the AD595AQ was between 300 and 2817 mV. That is, the measurement temperature and the output voltage had a standard linear relationship. Fig. 3.

To meet the requirement of the chip, the VO and FB pins were short-circuited as an output. The voltage value of the left end of the resistance \( R_1 \) is as shown in the formula (1). The analogue voltage value of AD595AQ outputs to the one-chip computer is:

\[
V_{\text{Pin}} = V_{\text{out,AD595}} \times \frac{R_1}{R_1 + R_2}
\]  
(5)

According to the formulas as well as the linear relationship between the output voltage and the exhaust gas temperature, the real-time temperature value of the exhaust gas flow can be calculated by the corresponding single-chip microcomputer program.

3 Experiment and results

The condition of field experiment is shown as Fig. 4. A Honda CR-V, powered by a 2.4-liter engine, is used as an experimental object with the ambient temperature in the low 30 s. The vehicle runs under idle speed for about 1 h, the temperature and gas flow of exhaust gas are measured in real time.

According to formula (3), we can see that if \( T \) is fixed as a constant the value of \( \Delta T \) will determine the value of \( \Delta q_m \). Therefore, if the temperature is fixed and \( \Delta T \) is considered as the temperature measurement error resulting from the temperature measurement module, \( \Delta q_m \) is the gas mass flow error resulting from \( \Delta T \).

Under experimental conditions, the temperature of exhaust gas is approximately in the range of 300 to 550 K. Therefore, we selected \( T \) at 300 K (the minimum value) and 550 K (the maximal value).
value) to study the effect of $\Delta T$ on $\Delta q_m$. Fig. 5 shows the relationship between $\Delta q_m$ and $\Delta T$ at different temperature.

As shown in Fig. 5, when the temperature is fixed at 300 K and the measurement error is 30 K (ca. 10% of the real temperature), the flow measurement error is as high as 18 kg/h; and when the temperature is fixed at 550 K and the measurement error is 55 K (ca. 10% of the real temperature), the flow measurement error is as high as ca. 14 kg/h, indicating the strong effect of $\Delta T$ on $\Delta q_m$.

Besides, the results indicate that $\Delta q_m$ can be easily affected by $\Delta T$ at relatively low temperature, which can be clearly seen from Fig. 6, in which the slope of the curve decreases obviously with the increase of temperature.

Table 1 shows the calculated value and the corresponding measured value of the simulant exhaust gas flow rate. With the measured value used as standard value, the relative deviation of calculated value is in the range of 2.2–2.9% (column 4). According to these values, the corresponding $\Delta q_m$ is in the range of 5–12 kg/h (column 5). Suppose that $\Delta q_m$ was just caused by the temperature measurement, i.e. the relative deviation caused by other factors are negligible, the measurement error of the temperature is much smaller than 10% of the corresponding temperature. Therefore, considering so small relative deviation in the MVEOME system, we can infer the good performance of the temperature measurement module in the system.

Of course, the real situations are probably much more complicated than the above analysis, more detailed investigation is still in progress. In the next work, we will adjust the parameters or improve the design of the temperature measurement module, which should not only further justify the results of this work but make the MVEOME system improved as well.

4 Conclusion

In conclusion, based on the successful development of the MVEOME system, the performance of temperature measurement...
module was further studied. The temperature measurement module was designed on the basis of an AD595AQ chip. The theoretical analysis in combination with real experimental results indicates that the temperature measurement module performed well in the system. Except for the fluctuation of temperature, the exhaust gas from an engine is mixture, so the calculation concerning its flow rate by Fluid continuity equation is much more difficult than a simple one, which should be overcome for the development of the measurement meters regarding this field.

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6 References
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Fig. 4 The field experiment of MVEOME system

Fig. 5 Relationship between $\Delta q_m$ and $\Delta T$ at different temperature
(a) $T = 300$ K, (b) $T = 550$ K

Fig. 6 Relationship between $\Delta q_m$ and $T$ with fixed $\Delta T$ at 10 K

Table 1 | Calculated value (by MVEOME system) and the corresponding measured value (by precision flowmeter) of the simulant exhaust gas flow rate (kg/hr)

| No | Calculated value | Measured value | Relative deviation, % | Corresponding $\Delta q_m$ |
|----|------------------|----------------|-----------------------|--------------------------|
| 1  | 212              | 207            | 2.4                   | 5                        |
| 2  | 308              | 317            | 2.9                   | 9                        |
| 3  | 422              | 410            | 2.8                   | 12                       |
| 4  | 232              | 238            | 2.6                   | 6                        |
| 5  | 367              | 359            | 2.2                   | 8                        |

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