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Research on online correction algorithm with neural network multi-environment factors for CO detection of motor vehicle exhaust

LIU Guo-Hua[1,2], ZHANG Yu-Jun[1*], ZHANG Kai[1,2], TANG Qi-Xing[1,2], FAN Bo-Qiang[1,2], LU Yi-Bing[1,2], YOU Kun[1], HE Ying[1], YU Dong-Qi[1,2]

(1. Key Laboratory of Environment Optics and Technology of Chinese Academy of Sciences, Anhui Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Hefei 230031, China;
2. University of Science and Technology of China, Hefei 230026, China)

Abstract: The influence of temperature, humidity and pressure on the measurement of exhaust gas CO concentration after pretreatment is analyzed. An on-line correction algorithm with multi-environment factors of neural network for the vehicle exhaust CO detection has been proposed. First, the exhaust gas sample data has been trained offline to build the BP neural network model, and then the real-time measured temperature, humidity, pressure and decimal absorption value of the samples have been put into the model for its online correction. Then the corrected CO concentration has been achieved, so the measurement error of the NDIR sensor caused by environmental changes has been solved. Through the prototype experiment, the simulation experiment and the comparison with SEMTECH-EcoStar, the maximum relative deviation of the CO with the concentration from 0 to 0.2% is 4.8% when the temperature range is from 30 to 50℃, relative humidity is from 25 to 40%, the pressure is from 95 to 115 kPa. The experiments have been carried out in the vehicle field to get the correction factor between 0.8 and 1, which verifies the necessity and reliability of the method and provided effective technical support for the detection of the CO concentration of the high-temperature exhaust gas from motor vehicles.

Key words: CO exhaust detection, infrared absorption, multiple environmental factors, online correction, BP neural network

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机动车尾气 CO 检测中神经网络多环境因子在线修正算法研究

刘国华[1,2], 张玉钧[1*], 张 恺[1,2], 唐七星[1,2], 范博强[1,2], 鲁一冰[1,2], 尤 坤[1], 何 莹[1], 余冬琪[1,2]

(1. 中国科学院安徽光学精密机械研究所 中国科学院环境光学与技术重点实验室,安徽 合肥 230031;
2. 中国科学技术大学,安徽 合肥 230026)

摘要:分析了温度、湿度、压力对预处理后尾气 CO 浓度测量的影响,提出一种机动车尾气 CO 检测神经网络多环境因子在线修正算法,首先采用尾气样本数据离线训练得到 BP 神经网络模型,然后将实时测得的样品气温度、湿度、压力及小数吸收值代入到模型进行在线修正,得到修正后 CO 浓度,解决了 NDIR 传感器因环境变化所带来的测量误差影响.通过标样实验、模拟实验,并和 SEMTECH-EcoStar 对比检测结果,在样品气温度 30 ~50 ℃、相对湿度 25 ~40%、压力 95 ~115 kPa、CO 浓度 0 ~0.2% 范围内的最大相对偏差为 4.8%.车载外场实验,得到修正因子在 0.8 ~1 之间,验证了方法的必要性和可靠性,为机动车尾气的 CO 浓度的准确检测提供有效技术支持.

关 键 词:尾气 CO 检测;红外吸收;多环境因子;在线修正;BP 神经网络

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Biography: LIU Guo-Hua(1987-), male, Hunan, China, Ph. D. Working on optical signal processing. E-mail: ghliu@aiofm.ac.cn

* **Corresponding author**: E-mail: yjzhang@aiofm.ac.cn

Introduction

Vehicle exhaust has become one of the major pollution sources. One of the most important pollutants of motor vehicle exhaust is carbon monoxide (CO). It is estimated that the amount of CO emitted by motor vehicles accounts for 76% of the emissions from large and medium-sized cities[1-3]. CO will cause great harm to human health and the environment. Therefore, the accurate and rapid detection of motor vehicle exhaust CO is the focus of the development of emission standards and environmental protection.

Basing on Lambert-Beer's law, Non-dispersive infrared (NDIR) gas sensors have advantages as selectivity, simplicity and reliability, with the characteristic of CO gas having a strong absorption peak at the wavelength of 4.64 μm. However, gas sensors which based on NDIR are susceptible to the changes of environmental temperature, humidity, and pressure when measuring the CO concentration of motor vehicle exhausts. The absorbance signals can be detectedfor the gas-absorbed radiation by NDIR detectors. In real systems, the output of the detector is affected by environmental temperature, humidity and pressure, resulting in increased signal spurious and interference[4-5]. From the HITRAN database, it is known that below 3000 nm and in the mid-infrared band between 4500 and 8000 nm, there's a strong absorption of water, meanwhile, when the humidity becomes higher, more water vapor will gather on the surface of the optical element, which affects the reflection effect and response of the pyroelectric detector[6]. When the environmental total pressure changes in a wide range or the CO partial pressure increases, the error of NDIR sensor will increase[7].

At present, there are many ways forNDIR environmental factor correction at home and abroad. Park JS, Woo-Jin H, et al. have proposed a compensation algorithm for correcting NDIR temperature factors and improving the accuracy of the NDIR analyzer[8-9]. Skouboe A, Stolberg-Rohr T et al. have used optical filtering to compensate for humidity[10-11]. Gaynullin B has compensated for environment pressure by an experimental platform combined with an accurate calculation algorithm[12]. And there're also researcheson the resolution of the NDIR analyzer by changing the optical path at different humidity[13]. There are algorithms proposed to calibrate the offset of NDIR analyzer for the non-linearity of temperature and humidity[14]. The existing methods can improve the accuracy of detection at a certain degree. However, they are only correcting one or two environmental factors, and there are not many researches on the correction of multiple environmental factors. At the same time, the exhaust gas temperature varies with the running time, the pressure varies with the speed, and the water vapor concentration is high. It is necessary to comprehensively consider the influence of multiple factors such as the temperature, humidity and pressure on the CO concentration so that the true value of the vehicle exhaust CO can be obtained more accurately. BP neural network has a strong nonlinear mapping ability. Theoretically, if suitable nonlinear parametersare selected according to the measured data, any non-linear curve approximation with any accuracy can be achieved, so as to correct the influence of multiple environmental parameters on the NDIR gas sensor.

In order to solve this problem, an online correction method based on BP neural network for multiple environmental factors is proposed in this paper. The proposed method is applied to NDIR CO gas sensors. And an experimental system is established. With it the simulation experiments and field experiments are carried out. The results show that this method can reduce the error of vehicle exhaust CO measurement in the complex environment.

1 Theory and system

1.1 Infrared absorption theory

Gas absorption of infrared radiation follows the Lambert-Beer law:

$$I = I_0 e^{(-kxL)} \quad , \quad (1)$$

where I_0 is the incident light intensity, I is the light collected by the detector, k is the absorption coefficient at the wavelength λ, x is the gas concentration to be measured, and L is the length of the gas absorption.

Absorption coefficient k is a very complex quantity, which is not only relates to the type of gas, the wavelength of light, but also affected by other factors such as ambient temperature, humidity, and pressure. Therefore, for the measurement environment of changed temperature, humidity, pressure, k is a variable value, which can affect the light intensity I. At the same time, changes in temperature and pressure will change the gas concentration to be measured.

Actually, the gas absorption of strong light follows the formula[15]:

$$I' = \int_{\Sigma} A(\lambda)\,\mathrm{d}\lambda = C + D\log W + Q\log(P + p) \quad , \quad (2)$$

where C、D、Q are determined by the experiment of the constant, $A(\lambda)$ is the measured gas absorption at a certain wavelength, $\mathrm{d}\lambda$ is light wavelength increment (cm), $\Sigma = \lambda_2 - \lambda_1$ is light wavelength range (cm), P is the total environmental pressure (kPa), p is the measured gas partial pressure (kPa), $W = (pl/76) \cdot [273/(273 + t)]$, t is the environment temperature (℃), l is the measured gas thickness (cm).

The interference of water vapour is more complicated, assuming the influence of water vapour is $f(H)$, so the formula (2) becomes:

$$I'' = I' + f(H) \quad , \quad (3)$$

where I'' is the output light intensity. According to Eqs. 2 and 3, it can be seen that the influence of temperature, humidity and pressure on the gas concentration to be measured is complex and cannot be directly expressed by a single expression. However, the BP neural network has strong generalization ability. Therefore, in this paper it's proposed to correct the influence of the three environmental parameters on the gas concentration to be measured and improve the measurement accuracy by establishing the BP neural network model.

1.2 System components

The sampling and detecting system for the high temperature exhaust of motor vehicle is mainly composed of the sampling pretreatment device, the NDIR analysis module, the temperature and humidity sensor module, the data processing module and the upper computer. The designed system structure is shown in Fig. 1.

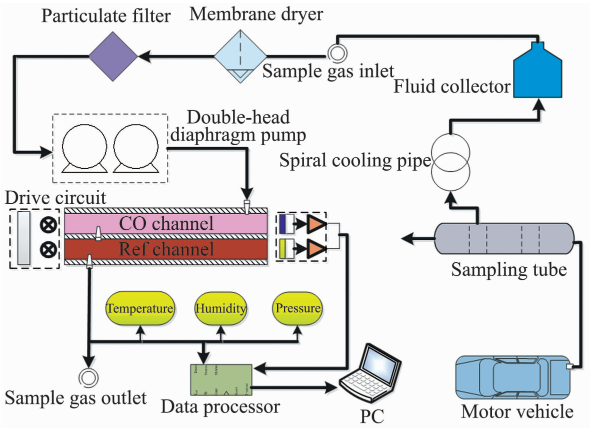

Fig. 1 Exhaust gas sampling analysis system
图 1 尾气取样分析系统

The vehicle exhaust is cooled, dewatered and de-dustedbefore it enters the NDIR gas chamber to protect the NDIR sensor and make for the long-term stable operation of the sensor. The vehicle exhaust is firstly cooled down by a spiral cooling pipe and then sent to the liquid absorber to remove most of the vapourand reach the sampling gas inlet. In the NDIR analysis module, a double-headed diaphragm pump is installed to extract the sample gas from the sampling pretreatment module, which is further dewatered by a membrane dryer anddedusted by the particulate filter and then sentinto the measuring cell. The sample chamber is of a parallel two-channel structure, and the inner walls are communicated with each other. Sampling gas is discharged from the other end of the gas chamber to the sample output port, and the outlet is with the temperature, humidity and pressure sensor. The infrared radiation signal (FA) detected by the thermopile detector and the sample gas temperature (t), Humidity (H), pressure (P) data obtained are sent to the data processor to be processed, and then transmitted to the host computer for the concentration inversion correction.

The NDIR analysis module consists of two measurement channels: the CO measurement channel and the reference channel. It converts the light intensity into voltage signals. Then, the data processing module compares the two voltage signals to obtain the fractional absorption value FA.

$$FA = 1 - \frac{I_1}{I_2} \cdot \frac{I_{20}}{I_{10}} = 1 - \frac{V_1}{V_2} \cdot \frac{V_{20}}{V_{10}} \quad , \quad (4)$$

where I_1、V_1、I_2、V_2 representsthe output light intensity of the CO measurement channel, the output voltage, the output light intensity of the reference channel and the output voltagerespectively, I_{10}、V_{10}、I_{20}、V_{20} represents the output light intensity of the CO measurement channel, the output voltage, the output light intensity of the reference channel, and the output voltage when $x=0$ (with pure nitrogen) respectively. It can be concluded that FA increases with the increase of CO concentration, which is a positive correlation. Combining equation (1), it is easy to invert the CO concentration before correction. The use of ratio method can effectively eliminate common mode interference caused by circuit environment and optical effects of the NDIR detector.

2 Multi-environment factor online correction algorithm

BP neural network is a multi-layer feedforward network trained by error inverse propagation algorithm, which hasthe characteristics of approximating any nonlinear and strongly coupled data sample model[16]. According to the system shown in Fig. 1, the condition of the vehicle exhaust is simulated after the pretreatment. Taking the sample gas temperature (30 ~ 55℃), humidity (20-45%), pressure (90 ~ 120 kPa) and decimal absorption value FA as the input, the CO standard gas concentration (0 ~ 5%) as the output, the BP neural network model of four input and one output can be established. The temperature, humidity and pressure in each group correspond to 10 groups of different standard CO gas concentrations.

The number of hidden layer nodes in the network model can be chosen according to the following empirical formula[17]:

$$n_1 = \sqrt{n+m} + a \quad , \quad (5)$$

where n is the number of input nodes, m is the number of output nodes, a is a constant between 1 and 10. The model uses 1 200 sets of real-time measured data for training, in which the hidden layer uses the tansig transfer function and the output layer uses the purelin transfer function. The training results are shown in Fig. 2.

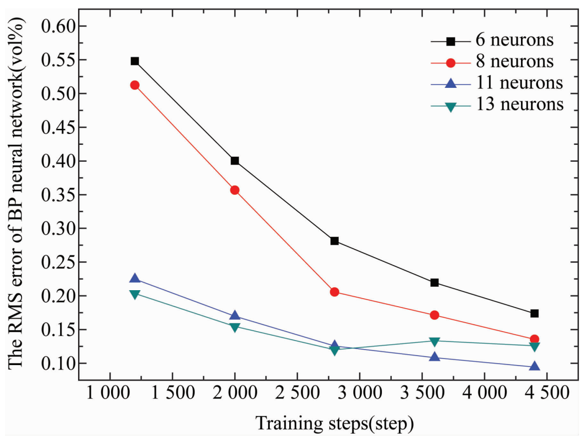

Fig. 2 The relationship between root mean square error of BP network and key parameters
图 2 BP 网络均方根误差与关键参数的关系

It's shown in Fig. 2 the root-mean-square (RMS) error of the BP neural network with different hidden layer neurons and training steps. The smallest error has been obtained with 11 neurons, decreased with the number of training steps increased. However, when the number of training steps exceeds 3 500, the RMS error decreases slowly. In actual training, 4 500 training steps are used. The final optimal parameters are as follows. The learning rate is 0.2, the hidden layer has 11 neurons and the training steps are 4500 steps. Finally the built three-layer BP neural network are shown in Fig. 3.

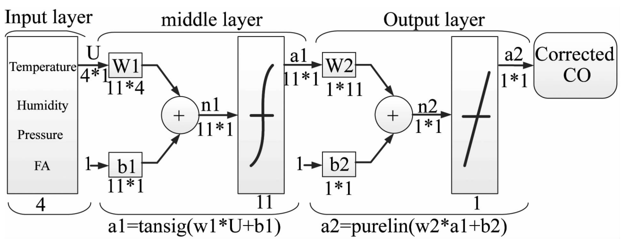

Fig. 3 Three-layer BP neural network
图 3 三层 BP 神经网络

In Fig. 3, W1 and b1 respectively denote the weights and the thresholds of the hidden layers. W2 and b2 respectively denote the weights and thresholds of the output layer. U denotes the input matrix, a1 is the transfer function of the hidden layer, a2 is the transfer function of the output layer, n1 is the number of hidden layer nodes, and n2 is the number of output layer nodes. These are all known parameters for well-trained BP models.

Based on the established BP model, the method of multi-environment factor on-line correction is designed for the vehicle exhaust CO concentration detection. The process is shown in Fig. 4.

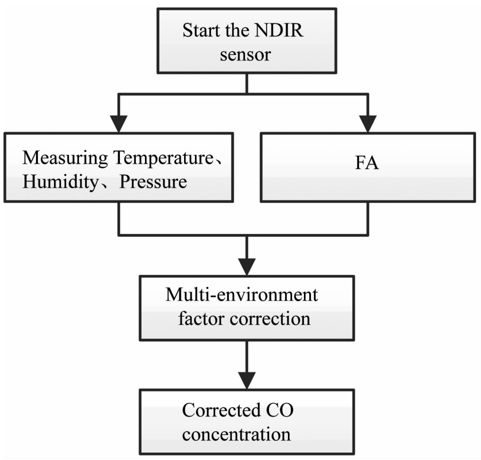

Fig. 4 Method of multi-environment factor online correction for CO concentration detection in vehicle exhaust
图 4 机动车尾气 CO 浓度多环境因子在线修正方法

With the measurement system operating, the decimal absorption value FA, and the temperature, humidity and pressure of the sample gas at the cell outlet are measured by sensors as the 4 input parameters in Fig. 3. Then, they are put into the established BP model in the data processing system, so the corrected CO concentration can beobtained.

3 Experimental verification

3.1 Prototype experiment

In order to verify the correctness of the algorithm, we have sampled 4 × 10 experimental data with different temperature, humidity and pressure conditions as the test samples which are not used in the training network, then we have carried out the prototype experiments. Four sets of temperature, humidity and pressure data have beenall selected within the actual large span and to ensure a certain representation. Each set of temperature, humidity, pressure data contains 10 different standard CO gas concentrations.

Then the data have been put into the model (Fig. 3), and the results of the correction are shown in Fig. 5. The corrected CO concentration has been calculated by the data processor after obtaining the FA value.

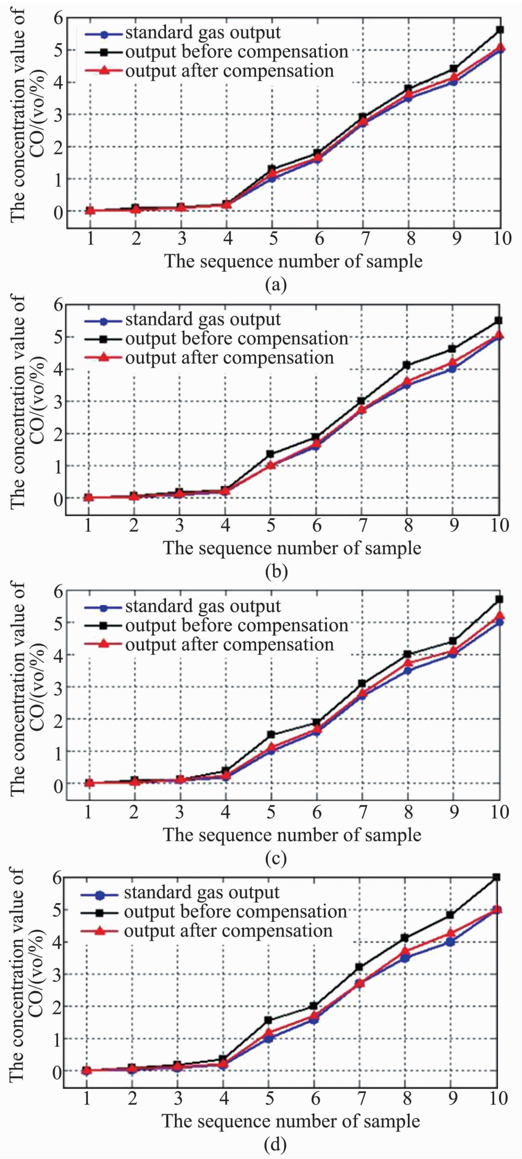

Fig. 5 Comparison of the experimental results before and after correction (a) 30 ℃, 22% RH, 117 kPa, (b) 45 ℃, 27% RH, 100 kPa, (c) 32 ℃, 35% RH, 109 kPa, (d) 53 ℃, 45% RH, 92 kPa
图 5 修正前后的试样实验对比(a)30 ℃、22% RH、117 kPa,(b)45 ℃、27% RH、100 kPa,(c)32 ℃、35% RH、109 kPa,(d)53℃、45% RH、92 kPa

Comparison of the experimental results before and after correction is shown in Fig. 5. It can be seen after the correction, the output absolute error of the NDIR sensor is significantly reduced and the average absolute error is 0.013 vol%. At 53℃, 45% RH and 92 kPa, the output absolute error of the NDIR sensor has dropped to 0.03% from the original 1%. At the same time, the maximum relative error has dropped from 22% to 5.8%. It can be proved that this algorithm can correct the non-linear error caused by temperature, humidity and pressure, which is an effective method.

3.2 Simulation comparison experiment

Gasoline engine is used to simulate high-temperature automotive exhaust environment, the model is GX100-HONDA, four-stroke air-cooled OHV. The sampling tube is placed at end of the generator exhaust port, the other portis placed in the sampling channel of sampling system. The pre-treatment gas outlet of sampling system is connected with the NDIR module, and experimental platform as shown in Fig. 6. At the same time, with the Sensors Company's SEMTECH-EcoStar Automotive Measurement System for synchronous comparison experiment.

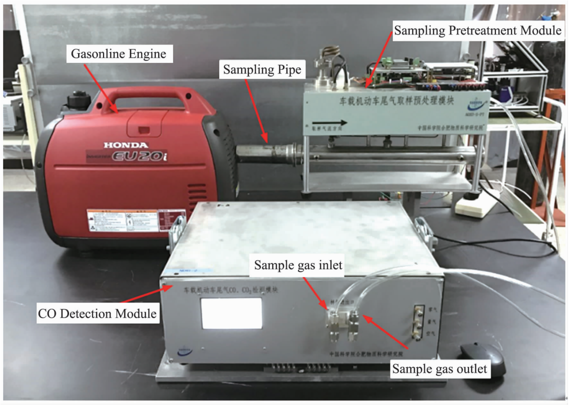

Fig. 6 Experimental verification platform
图 6 实验验证平台

The experimental platform has been started with the gasoline engine throttle being random adjusted, and then the engine has been kept running for 20min. 10 sets of data have been taken with the interval of 2min, and the comparison of the test results are shown in Fig. 7.

It's shown in Fig. 7 (a) the temperature of the sample gas in the NDIR chamber, in the range of (32 ~ 45)℃, which shows an increasing trend as the operating time increases; (b) shows the sample gas relative humidity, in the range of (22, 35)%, which shows a downward trend, mainly due to sample gas temperature rise; (c) shows the sample gas pressure, in the range of (102,112) kPa, fluctuations rang 10 kPa; (d) shows the CO concentration contrast, CO concentration of NDIR is about 15% different from SEMTECH-EcoStar before correction. But, the maximum relative deviation dropped to 4.8% after correction, verifying the feasibility and accuracy of the designed correction method.

3.3 Vehicular experiment

The sampling and detection system has been preheated for 15 minutes, after its zero and span calibration has

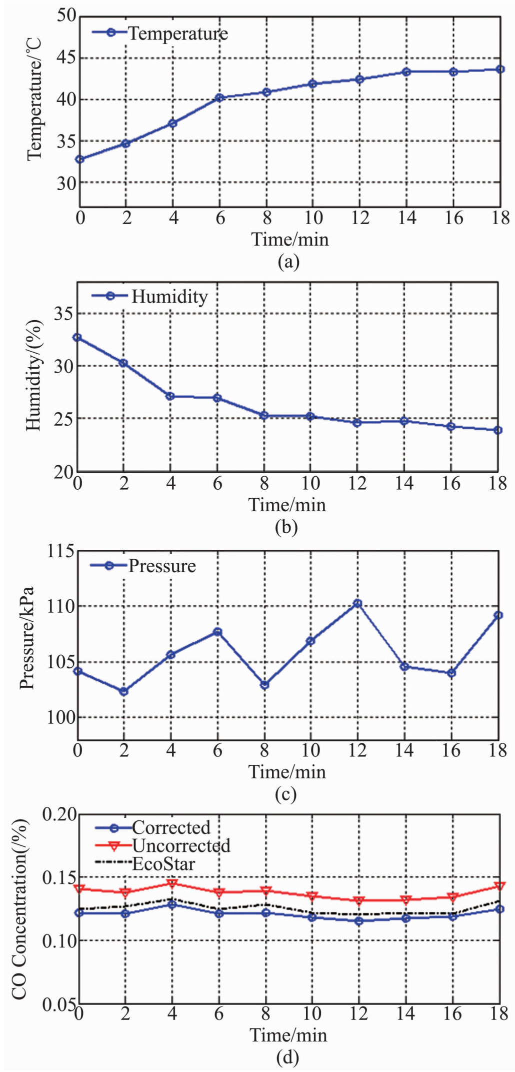

Fig. 7 Simulation comparison experiment (a) Sample gas temperature, (b) sample gas humidity, (c) sample gas pressure, (d) CO concentration contrast
图 7 模拟对比实验(a)样品气温度,(b)样品气湿度,(c)样品气压力,(d)CO 浓度对比

been completed, it has been installed in the trunk of a motor vehicle, and then the on-site testing has been carried out on a road in Hefei, as shown in Fig. 8.

The environment temperature is 24℃ and the air humidity is 40%. The vehicle speed changes at (20 ~ 60) km/h and the total travel distance is 25 km. The experiment time is from 16:04:00 to 16:34:00, and the total time is 30 minutes. It's shown in Fig. 9 the continuous detection results of the sampling and detection system during the operation at the vehicle field (2017-10-25). System's response frequency is 1Hz, and each group of data contains 1 800 parameters.

It's shown in Fig. 9 the vehicle field experiment data. Figure 9 (a) shows the automobile exhaust temperature after the pretreatment, the range of (36 ~ 44)℃, which shows anupward trend. Figure 9 (b) shows the relative humidity of the automobile exhaust after pretreatment, the range of (26 ~ 33) %, which shows a down-

Fig. 8 Vehicular sampling test
图 8 车载现场取样检测

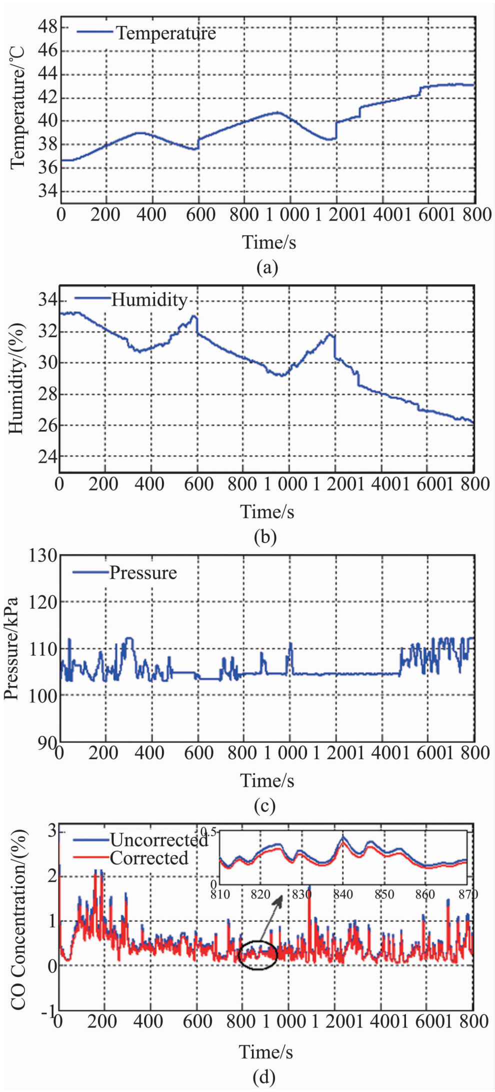

Fig. 9 Vehicle field experiments (a) Sample gas temperature, (b) sample gas humidity, (c) sample gas pressure, (d) CO concentration contrast
图 9 车载外场实验(a)样品气温度,(b)样品气湿度,(c)样品气压力,(d)CO 浓度对比

ward trend. Figure 9 (c) shows the automobile exhaust pressure after the pretreatment, the range of (104 ~ 115) kPa, fluctuates around 10 kPa. Figure 9 (d) shows the comparison of the CO concentration before and after on-line correction, and the whole trend is consistent with the data from the enlarged 60 groups (810 to 870). The corrected CO concentration was lower than before correction, and the correction factor fluctuated between (0.8, 1.0) with a mean value of about 0.87. It verified the necessity of the correction method.

4 Conclusion

There is obvious effect of the designed online correction method with multiple environmental factors of BP neural network, and its accuracy and necessity are verified by the prototype experiment, simulation experiment and vehicle experiment. Compared with the similar advanced instrument SEMTECH-EcoStar, the maximum relative deviation is only 4.8%.

There are two main reasons for the deviation:

(1) The pretreatment system used in the experimental system and SEMTECH-EcoStar are different, and their NDIR sensors are different, so the inversion of the gas chamber CO concentrations are also different.

(2) The factors of only temperature and humidity have been considered in the SEMTECH-EcoStar correction for the gas chamber CO concentration, while the temperature, humidity and pressure are considered in the designed experimental system.

The online operation of the designed experimental system is stable, with a certain engineering practicability. The proposed method is also suitable for the detection of gases such as CO_2, HC and other gases with NDIR sensors, providing effective technical support for the supervision of motor vehicles and environmental governance in our country, so there's good application prospect.

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