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Dew point measurement using dual quartz crystal resonator sensor

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ABSTRACT

In order to solve the problem that the quartz crystal resonator (QCR) dew point sensor in the measurement process cannot effectively eliminate the effect of temperature on the frequency, a new sensor based on the dual quartz crystal resonator (D-QCR) has been developed. The sensor combined Peltier module with two QCRs and the two QCRs were cooled by the same Peltier. One of these two QCRs only provides a reference frequency without gas contact and the other QCR is used for measuring dew point with gas contact. The frequency difference was calculated between the frequency difference of two QCRs at the initial state and the frequency difference of two QCR when condensation occurs. The observed value was used as the calibration value of dew point recognition. The calibration experiment proved that the 159 Hz can be used as the calibration value for the dew point identification. The nine groups of dew point environments in the range of −3.7 °C to 17 °C DP were selected to be measured. During the experiments, the maximum measurement error was less than 0.47 °C DP when compared with the MICHELL S4000 dew point meter. The results show that this method can effectively eliminate the measurement error caused by temperature. It proved that the sensor is high accurate and has a good and long-term stability.

1. Introduction

Air humidity describes the amount of water vapor in air. It is one of the main parameters measured in diverse fields, such as in biomedical applications, pharmaceutical processing, semiconductor industry, agriculture, climatology, or intelligent control in buildings, to mention a few examples. Even the marginal small values of humidity can have significant influence on living organisms or inanimate objects. But the greatest impact it has on technological processes, therefore measuring and controlling of humidity is often very important for the process [1].

Air humidity is most commonly described by either of two values–dew point temperature [2–4] or relative humidity [5,6]. The dew point measurement is widely known as the most accurate method for measuring humidity. The core parts of dew point measurement are dew point detection and recognition. The present main dew point identification technologies include chilled mirror [7,8], and image recognition [9], quartz crystal microbalance (QCM) [10] and so on. The chilled mirror dew-point hygrometer, whose principle is based on the photoelectric detection of condensed water droplets on a cooled sensor surface. This method costs too much and the instrument is not easy to carry since it is only suitable for laboratory use. Image recognition has complicated systems. Compared with previous methods, the QCM has advantages of high accuracy and high sensitivity to mass change on the nanogram scale (1 ng/cm^2). As a sensor, the QCM has been widely used in monitoring change in mass loading by measuring the shift of its resonant frequency [11,12]. Since 2011 our team have focused on two types of quartz resonant dew point sensor. One type is without frequency measurement and it has achieved good results [13,14]. The second type is about frequency measurement sensors. In this type of research, we find that the temperature has a great influence on the results of the frequency measurement, and we must rely on the temperature compensation to obtain relatively accurate results. In the process of dynamic measurement, it is difficult to completely eliminate the influence of temperature on the frequency [15].

Therefore, this paper proposes a novel method based on the dual quartz crystal resonator (D-QCR) and this method can effectively eliminate the influence of temperature on the frequency in the dynamic measurement process. This sensor combined Peltier module with two QCRs of which one provides a reference frequency without gas contact and the other measures dew point with gas contact. The two QCRs were cooled by the same Peltier. Frequency difference was calculated by using the frequency difference of the

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D-QCR before refrigeration minus the frequency difference of the D-QCR after condensation. The frequency difference was only caused by condensation and the effect of temperature on the QCR was eliminated. Calibration and test results show that this method can not only identify the dew point but also eliminate the influence of temperature on the frequency and finally yield highly precise measurement of dew point.

2. Experimental set-up

As shown in Fig. 1, the sensing device includes: two QCRs, thermally conductive silica gels, a temperature sensor, a Peltier cooler and a heat sink. Each of the two AT-cut QCRs have gold electrodes on its surface with the resonant frequency of 6 MHz. Two PT100 platinum thermal resistances are attached to the cold surface of the Peltier cooler. The outer parts of the resistances are bonded with heat conductive silicone pads where the two QCRs are placed, in order to improve heat transfer uniformity and hence shorten the response time of the entire sensing device. The electrodes are fixed and are linked to the frequency sweep generation device. The hot surface of the Peltier cooler is attached to the heat sink for better cooling. Two QCRs are separated by a layer of tetrafluoroethylene to make sure that the tested QCR is connected with a gas channel while the reference QCR is separated with the gas. A complete measuring device is formed by sealing the main body of the device with an upper cover. The materials of the entire device are made up by tetrafluoroethylene which has properties of heat preservation and insulation and anti-vibration. A gas channel passes through the upper surface of the tested QCR. Considering there remains some gas on the upper surface of the reference QCR, the main body of the device has a hole where extremely dry gas (with humidity of 2% RH) from outside can pass into the upper part of the reference QCR before measurement in order to make sure that no condensation occurs on the reference QCR under a wide range of temperatures.

As shown in Fig. 2, the experimental system mainly includes the measuring device, the temperature controller, the temperature acquisition module, the frequency sweep generator, the frequency acquisition module, the standard dew point instrument and industrial control computer.

The sweep frequency generation device uses 4294A Agilent impedance analyzer. The frequency is collected through connecting the 4294A Agilent impedance analyzer and the computer by using the 82357AUSB/GPIB connector. The temperature controller uses data acquisition card to output adjustable analog voltage which is transferred through the power amplifier into analog current with the input and output ratio of 1:1. The adjustable current can be used to control cooling power of the semiconductor refrigerator. The temperature acquisition module collects temperature data by using four wire platinum thermal resistance PT100. The output resistance values are converted into digital signals by the ADAM-4015 and the digital signals after the ADAM-4520 conversion are obtained by the computer. The MICHELL S4000 dew point instrument is used to provide standard humidity parameters for the experimental environment. The air pipe and the measuring device are connected in parallel to ensure the same humidity environment. The PC software is developed by using LabVIEW.

3. Measurement principle

3.1. Mass-frequency effect

QCM is a very sensitive mass detection technology which can be used to detect the quality at the cashier level in certain conditions. This paper is to exploit high sensitivity of QCM for mass-frequency. As shown in Fig. 3, a Peltier cooler is used to cool the QCR to yield condensation on its surface. The condensation indicates mass increase and further results in frequency mutation due to mass change. The frequency mutation is measured to recognize the moment dew point occurs and hence recognize dew point temperature.

Fig. 3 presents a schematic diagram of recognition principle. We can see that QCR resonant frequency is affected not only by the condensation occurring on the QCR surface, but also by temperature change produced in the cooling process of the semiconductor refrigerator. Therefore, the factor of temperature must be filtered out in actual dew point measurement. The proposed dual QCR structure is aimed at highly precise measurement of dew point by eliminating the influence of temperature on the QCR frequency.

3.2. Frequency measurement method and implementation

In this paper, a test system is built by using the Agilent4294A impedance analyzer to monitor the D-QCR resonant frequency. The impedance analyzer has the characteristic of wide band sweep frequency, and the frequency resolution can reach 10^{-6}. The traditional frequency is calculated based on the electrical parameters of the QCR and the BVD equivalent circuit model of QCR, but the sweep frequency time is generally about 2–3 s. In order to obtain the resonant frequency of QCR more efficiently, this paper uses the admittance characteristics of QCR to calculate the resonance frequency. The admittance of QCR is expressed as Eq. (1):

$$Y(jw) = G + jB = \frac{1}{R_q + jwL_q + \frac{1}{jwC_q}} + jwC_0 \tag{1}$$

L_q, C_q, R_q are the equivalent inductance, capacitance and impedance, respectively. The real and imaginary part of admittance wrote as G and B respectively meet Eq. (2):

$$\left(G - \frac{1}{2R_q}\right)^2 + (B - wC_q)^2 = \left(\frac{1}{2R_q}\right)^2 \tag{2}$$

Where $\omega = 2\pi f$, G gets a peak when scanning frequency equals to f_0, f_0 represents series resonance frequency.

$$G_{max} = \frac{1}{R_q} \tag{3}$$

This method which used in this paper is to measure the impedance amplitude and the corresponding frequency in the vicinity of the resonance frequency of QCR within a certain range, the frequency corresponding to the minimum of the impedance is the series resonant frequency of QCR.

In this paper, the real time monitoring of QCR resonant frequency is realized by computer programming using impedance analyzer. In the measurement, the calculation formula of the frequency resolution γ is expressed as Eq. (4):

$$\gamma = \frac{\delta}{n} \tag{4}$$

Where δ represents the range of sweeping frequency, n stands for scanning points. The main factor affecting the single measurement time is the number of frequency measurement points. The more the number of frequency measuring points is, the more time it needs. We expect to make measurement time short. But if the number of frequency measurement points is reduced, the frequency resolution in a constant frequency sweep range will increase accordingly, so that the measurement accuracy is reduced. Therefore, it is needed to weigh the measuring time and the precision of frequency measurement.

The impedance analyzer has the function of broadband sweep. The most direct way to measure frequency is by broadband. The frequency sweep range can be set when the maximum range of frequency change is given. However, it is not easy to grasp the