Sensors and Actuators B 256 (2018) 1–6

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

journal homepage: www.elsevier.com/locate/snb

Short communication

Active temperature control of quartz resonant dew point sensors based on dual surface cooling

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ARTICLE INFO

Article history:
Received 8 June 2017
Received in revised form 8 October 2017
Accepted 12 October 2017
Available online 14 October 2017

Keywords:
Dew point sensor
Active temperature control
Dew point
Humidity
Dual-cooling

ABSTRACT

The combination of the Peltier cooler and quartz crystal resonator (QCR) is critical for temperature-controlled, quartz resonant dew point sensors. As the environmental parameters continuous to change, the cooling effects on the QCR surface will cause unstable vibration changes for dew point sensing applications. In order to achieve continuous and accurate dew point measurements in a dynamically changing atmosphere, this paper presents a new scheme based on the dual surface cooling by connecting two Peltier coolers to both sides of the QCR using elastic thermal materials. The heat transfer performance and vibration characteristics of the QCR are simulated and analyzed, respectively. Simulation results show optimal parameters of the elastic thermal pad have the dimension of the ring structure with inner diameter of 5.2 mm and outer diameter of 8.6 mm. The prototype sensor is subjected to a dew point measurement test in the external environment with fluctuating conditions and results show the relative error of less than 0.06 °C at a cooling rate of 0.02 °C/s, which are as good as the commercial products. Furthermore, these data have been theoretically verified to measure the dew point in dynamically changing environments.

1. Introduction

The dew point temperature characterization scheme has been utilized as the most accurate humidity measurement method in aerospace, industry, and laboratory applications [1–3]. The standard instrument has a cold mirror for the photoelectric dew point detection but it is not as sensitive as the dew point measurement by the QCM (Quartz Crystal Microbalance) method. Several research institutions have been investigating the QCM dew point measurement schemes [4,5], mostly in the laboratory environment. For example, our research team has been working on the active control of quartz resonant dew point sensor since 2011. The combination of QCR and Peltier cooler in our prior structure used a face-to-face rigid connection such that the temperature transfer efficiency is high but the vibrational stability is poor [6,7]. In practical applications, the environmental parameters fluctuate to affect the operations of the dew point sensor and a stable QCR system is desirable to ensure long-term operational stability in both temperature and vibration of the system with optimized automatic control.

In this paper, a new type of sensor structure is proposed by using two Peltier coolers on both surfaces of the QCR in its outer-ring region, while the rest of the inner-circle regions of the upper and lower surface are used as electrical electrodes. This arrangement ensures effective temperature transfer with improved stability and resolution for the humidity sensing. The elastic thermal materials are used to provide fixtures for good vibrational stability and good heat transfer paths for the Peltier coolers at the outer-ring regions of the QCR. In this work, a microprocessor-based dew point tracking control system is also implemented to achieve accurate measurements of dew points in the dynamically fluctuating environment.

2. Qualitative description of the sensor

2.1. Sensing mechanism and structure of the sensor

The sensing mechanism of the dew point sensor is based on the stoppage of the oscillating Colpitts drive circuit when water is condensed on the QCR electrode surface as reported previously

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https://doi.org/10.1016/j.snb.2017.10.062
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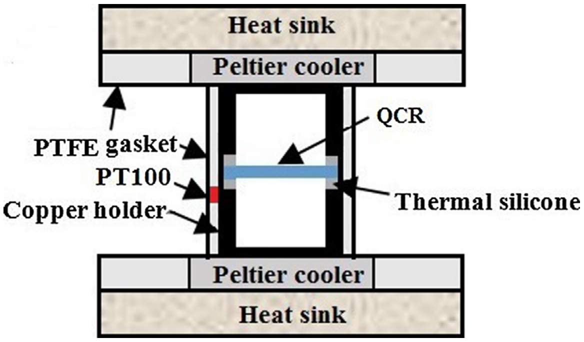

Fig. 1. The Schematic diagram of the sensor structure.

[8]. Fig. 1 illustrates the schematic diagram of the sensor, consisting of an AT cut QCR with a resonant frequency of 4 MHz and sliver electrodes, two Peltier coolers, two radiators, two thermal silicone rubber gaskets, a pair of cylindrical copper holders, and a resistive platinum thermal couple. The diameter of the quartz crystal is 8.6 mm, and that of the electrode is 5.2 mm. One side of the Peltier cooler (single-stage thermoelectric cooler, TEC1-3104) is connected to the heat sink for better cooling effects, while the other side of the cooler is connected to the flat surface of the copper holder as shown. The cylindrical copper holder has an annular groove at the other end in which the annular thermal silicone gasket can be aligned and placed to hold the outer ring-area of the QCR with good thermal conductivity and mechanical stability. Before the assembly process, the Peltier cooler and QCR are cleaned with alcohol. A PTFE holder is used to encapsulate the whole system in order to prevent the heat losses for better temperature control. The optical photos of the internal and external structure of the sensing device are shown in Fig. 2(a) and (b), respectively.

2.2. Structural optimizations

The size of the thermal gasket and the applied force between the thermal gasket and the QCR play important roles to prevent vibration and promote the heat transfer process. The finite element analysis (FEA- ANSYS 17.0) is used to simulate the model. Fig. 3(a) shows the schematic diagram of the model with two ring-shaped thermal pads at the non-electrode outer-ring regions of the upper and lower surfaces of the QCR. Fig. 3(b) is the geometry of the QCR used in the analysis with a thickness (t_q) of 0.416 mm, diameter (d_q) of 8.6 mm and the electrode diameter (d_e) is 5.2 mm, such that the lateral width of the non-electrode region is 1.7 mm, which is also the width of the outer-ring thermal cover region and a total of 17 points are used as the simulation data points. The thickness of the thermal gasket is simulated from 0.3 mm to 0.8 mm (with a step of 0.1 mm) and a total of 6 points are selected as the simulation data points. The thermal conductivity of the thermal conductive silica gel is 7 W/m K and its tensile strength is 55 kg/cm^2. Firstly, the effect of the heat transfer process is simulated with respect to different outer-ring size and thickness. The FEA simulation model for the thermal conduction analysis is shown as Fig. 3(c). The specific heat capacity, thermal conductivity and the density of the QCR are 800 J/(kg K), 6.8 W/(m K) and 2650 kg/m^3, respectively, and those of the gasket are 1700 J/(kg K), 7 W/(m K) and 1900 kg/m^3, respectively. The initial temperature of the thermal gaskets and the QCR are set as 22 °C and the convective heat transfer coefficient of the sections L1–L3, L10–L12 are set as 5 W/(m^2 °C), while those for the sections of L5–L8, L14 and L15 are set as 10 W/(m^2 °C). The temperature of the sections L0, L4, L9 and L13 are set as −20 °C as controlled by the Peltier coolers.

For different combinations of outer ring width and thickness, the time required for the temperature at the center regions of the QCR electrode to reach steady state is simulated to evaluate the effect of temperature transfer efficiency. In order to compare the temperature transfer efficiency of different structures, the simulation results for a device with the conventional single-surface cooling setup is also presented. The results in Fig. 4 show that the time required for the temperature at the center of the QCR electrode to reach steady state for the case of dual surface cooling is shorter than that of the single surface cooling system. Furthermore, it is found that the heat transfer efficiency depends more on the width of the outer-ring region as expected and large outer ring width will result in large contact area more effective cooling.

In order to select relatively balanced parameters, the mechanical structural simulation is carried out with a ring thickness of 0.5 mm and Fig. 3(d) illustrates the model for the QCR vibration analysis using hexahedral meshes with the quantity of 31488 points. The blue, yellow, and dark blue regions are the non-electrode region, electrode region, and constraining force applied region, respectively. In the simulation, the voltage applied to the electrode region is ±0.05 V. According to the tensile strength of the thermally conductive silica gel material, the constraining force range of 0.02 N to 0.1 N for the QCR non-electrode region can be calculated under different compression and deformation conditions. Therefore, the constraining force between 0.02 N and 0.1 N (every 0.02 N) is selected for the simulations and different combinations of the outer-ring widths are analyzed. The vibrational energy of the QCR electrode region is calculated accordingly and the vibrational energy (E) of the QCR surface is calculated as:

$$E = \int_{x=-\frac{1}{2}d_e}^{x=\frac{1}{2}d_e} |u_x| \Big/ \int_{x=-\frac{1}{2}d_q}^{x=\frac{1}{2}d_q} |u_x| \qquad (1)$$

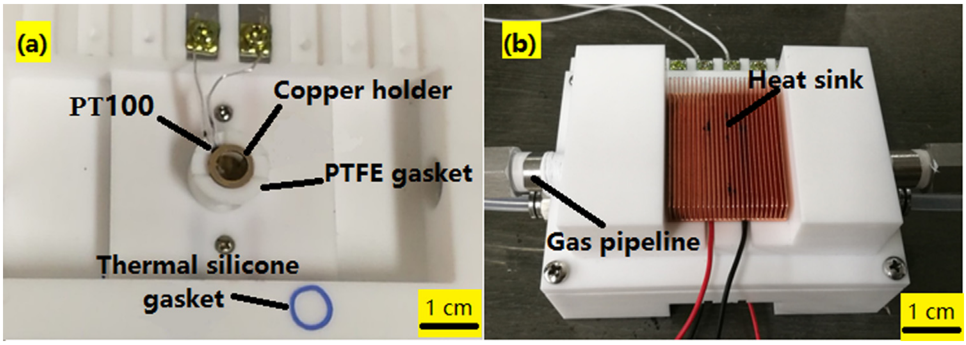

Fig. 2. Photograph of the sensor: (a) internal structure; (b) external structure.