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Novel humidity sensor using heat pipe: Phase transition thermally balanced sensor designed for measurement of high humidity at high temperature

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ABSTRACT

We developed a novel humidity sensor using a heat pipe on the basis of a new measurement principle. The sensor measures humidity using the condensation heat of water on the surface of the heat pipe. Theoretical equations describing the measurement principle using a simple model were derived. Comparison experiments were performed for dew points in the range of 50 °C to 80 °C using a humidity standard generator based on the International System of Units (SI). The standard value and the value calculated using the theoretical equations were in reasonable agreement with each other (with a difference within 0.5 °C). The difference was further decreased to within 0.2 °C by employing a calibration curve using multiple regression analysis. The sensor was also experimentally compared to a psychrometer, confirming that the two devices have similar performance. The sensor does not require the replacement of wicks or a water supply, and the measurement region is made of metal, making the sensor superior to the psychrometer in terms of low maintenance, and long lifetime and high durability at high temperatures and high humidities.

1. Introduction

Environmental test chambers are frequently used to examine the effect of environmental factors such as temperature and humidity on materials as well as the performance of electronic devices. They play an important role in evaluating the reliability and robustness of products. To appropriately perform various tests, the temperature and humidity in environmental test chambers should be accurately and precisely controlled at predetermined values. Therefore, accurate and precise thermometers and hygrometers usable in environmental test chambers are required. The demand for environmental testing of lightweight composite materials, materials used in in-vehicle equipment, and devices generating a large amount of heat [e.g., light-emitting diodes (LEDs), power devices] has recently been increasing. In particular, high-temperature and high-humidity bias tests, in which samples are subjected to a temperature of 85 °C and a relative humidity of 85 % for 1000 h, are considered to be important [1,2]. Psychrometers (wet-and-dry-bulb thermometers) [3] have long been used as hygrometers to control the humidity in environmental test chambers. However, they are not suitable for long-term tests, because regular replacement of wicks and the water supply are necessary. Although polymer film humidity sensors can be used for a relatively long periods without maintenance, they are not durable at high temperatures and high humidities, or under dew condensation. Based on the above discussion, hygrometers that can be stably used for a long period at high temperatures and high humidities are greatly needed. To meet this demand, we have developed a novel hygrometer, a phase transition thermally balanced (PTTB) sensor, using a heat pipe on the basis of a new measurement principle. The PTTB sensor, originally manufactured at ESPEC Corp., is similar to a psychrometer, in the sense that the latent heat of water is used for measuring humidity. However, whereas a psychrometer uses the heat of evaporation of water vapor on a wet bulb, the PTTB sensor uses the heat of condensation on a heat pipe, as schematically shown in Fig. 1. The sensing part of the psychrometers (wick) is made of gauze or paper, both of which are easily damaged or contaminated, and therefore, they must regularly be replaced. In contrast, the sensing part of the PTTB sensor is a heat pipe whose

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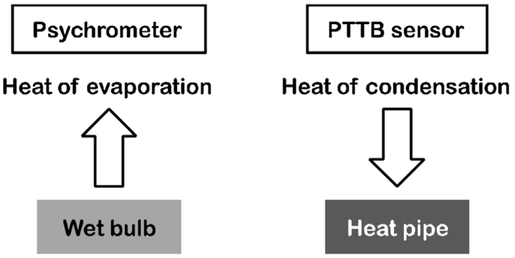

Fig. 1. Schematic diagram of the measurement principle of a PTTB sensor and a comparison with a psychrometer. Whereas the psychrometer uses the heat of evaporation on the wet bulb, the PTTB sensor uses the heat of condensation on the heat pipe.

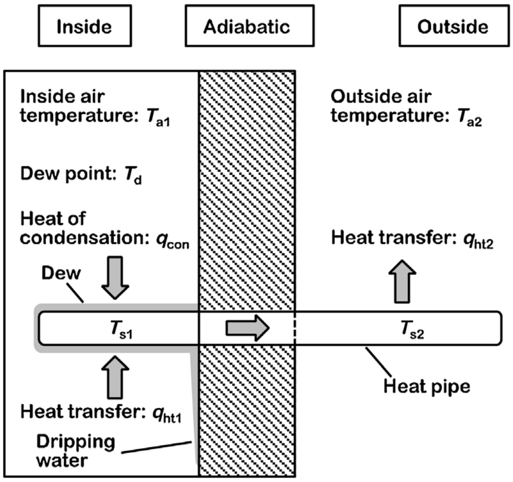

Fig. 2. Schematic diagram of the measurement principle of a PTTB sensor based on a simple model.

surface is covered with a metal, and therefore, it is much more robust, even at high temperatures and high humidities. In addition, unlike psychrometers, it is unnecessary for the PTTB sensor to be regularly supplied with water for measurement.

In this study, the humidified air generated using a humidity standard generator developed at the National Metrology Institute of Japan (NMIJ) was measured using the PTTB sensor. Then, the standard and measured values were compared for the purpose of confirming the measurement principle. Next, the PTTB sensor and a conventional psychrometer were placed in a commercially available environmental test chamber, and the performance of the sensor was compared to that of the conventional psychrometer.

2. Principle

Fig. 2 shows a schematic diagram of the proposed measurement principle based on a simple model. The PTTB sensor is divided into three regions: the inside of the chamber (the measurement region), the adiabatic region, and outside of the chamber (the heat release region). A heat pipe penetrates into the inside of a chamber from the outside through the adiabatic region. The temperature of the air and that of the surface of the heat pipe are given by T_a and T_s, respectively. The subscripts 1 and 2 used in the symbols in the figure represent the inside and outside of the chamber, respectively. The inside of the chamber is filled with humid air with a dew point of T_d and an air temperature of T_{a1}. If the surface temperature of the heat pipe inside the chamber, T_{s1}, is equal to or lower than T_d, condensation occurs on the surface; the heat pipe receives both condensation heat from water and other heat from the inside. If the surface temperature of the heat pipe outside the chamber, T_{s2}, is lower than T_{s1}, the heat received inside the chamber is conducted through the heat pipe to the outside of the chamber and is released to the outside air (provided that the temperature of the outside air, T_{a2}, is lower than T_{s2}, and the dew point of the outside air is lower than T_{s2}, and no condensation occurs on the surface of the heat pipe outside the chamber). Heat energy transferred per unit area and time (heat flux) on the surface of the heat pipe by water condensation, heat transfer from the inside, and heat release to the outside air are denoted as q_{con}, q_{ht1}, and q_{ht2}, respectively. The surface areas of the heat pipe inside and outside the chamber are denoted as S_1 and S_2, respectively. Here, we have the following relationship:

$$(q_{con} + q_{ht1})S_1 = q_{ht2}S_2. \tag{1}$$

In this model, we ignore the temperature gradient of the heat pipe and simply assume that there are two representative temperatures that represent the surface temperature of the heat pipe inside the chamber, T_{s1}, and that outside the chamber, T_{s2}.

The transport of water molecules from the inside air to the surface of the heat pipe is caused by the gradient in the concentration of water between these two regions. The amount of water condensed per unit time and unit area on the surface of the heat pipe, n_w, is given by [4]

$$n_w = \frac{D(T_{s1})}{\delta R T_{s1}}\left[e_s(T_d) - e_s(T_{s1})\right], \tag{2}$$

where $e_s(T_d)$ is the vapor pressure in the chamber, $e_s(T_{s1})$ is the saturated vapor pressure on the surface of the heat pipe, δ is the effective thickness of the diffusion layer, $D(T_{s1})$ is the diffusion coefficient of water in air, and R is the gas constant ($8.314\,\mathrm{J\,mol^{-1}\,K^{-1}}$). The water condensed on the surface will drip through the wall inside the chamber and re-evaporate on the wall or on the bottom of the chamber. Therefore, it is unnecessary to remove water from the chamber or to supply water. Denoting the latent heat of water as $L(T_{s1})$, q_{con} is given by

$$q_{con} = n_w L(T_{s1}) = \frac{D(T_{s1})L(T_{s1})}{\delta R T_{s1}}\left[e_s(T_d) - e_s(T_{s1})\right]. \tag{3}$$

Using the equation of heat transfer, q_{ht1} in Eq. (1) is expressed as

$$q_{ht1} = h_{ht1}(T_{a1} - T_{s1}), \tag{4}$$

where h_{ht1} is the heat transfer coefficient and T_{a1} is the temperature of the air in the chamber. Similarly, the heat flux released to outside the chamber, q_{ht2}, is given by

$$q_{ht2} = h_{ht2}(T_{s2} - T_{a2}). \tag{5}$$

From Eqs. (1) and (3)-(5), we obtain

$$e_s(T_d) = e_s(T_{s1}) - h_{ht1}(T_{a1} - T_{s1})\frac{\delta R T_{s1}}{D(T_{s1})L(T_{s1})} + h_{ht2}(T_{s2} - T_{a2})\frac{\delta R T_{s1}}{D(T_{s1})L(T_{s1})}\cdot\frac{S_2}{S_1}. \tag{6}$$

$e_s(T_d)$ can be calculated using Eq. (6) with the numerical values of T_{a1}, T_{s1}, T_{a2}, and T_{s2} measured in an experiment, assuming that the numerical values of h_{ht1}, h_{ht2}, $D(T_{s1})$, δ, $L(T_{s1})$, $e_s(T_{s1})$, S_1, and S_2 are available. Then, we can determine T_d from $e_s(T_d)$.

3. Experiment

A heat pipe made of copper with a working fluid of water was used in this study. The diameter and length of the heat pipe were 6 mm and 300 mm, respectively. A thermocouple was attached to the surface of the heat pipe to measure the surface temperature inside the chamber, T_{s1}. The heat pipe inside the chamber was sheathed in a stainless steel tube (a protective tube) with a length of 150 mm to protect the surface of the heat pipe and thermocouple from dew. In this study, T_{s2} was not measured, because T_{s2}