Short Note

Fabricating Thermocouple Micro Psychrometers

by the Bonding-Cellulose Method

by

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1. Introduction

Phase changes of water fulfill important roles in weather phenomenon related to our daily lives and in the atmospheric general circulation. For example, fog arises from water vapor condensation in the air and impairs traffic safety. Furthermore, latent heat flux is an important factor in surface heat budgets. In field observations, the latent heat flux is often obtained by the bulk method or the profile method. However, the vapor diffusive coefficient in the very stable thermally stratified layer remains uncertain in these methods (Sugita et al., 2001). Thus, it is important to conduct wind tunnel experiments with water phase changes for estimating the vapor diffusive coefficient, for developing forecasting techniques, and for measuring fog. The fog and the vertical vapor gradient are produced by cooling the test section floor below the dew point temperature of the airflow. However, the spatial resolution of the vapor measurement must be equivalent to that of the velocity measured by a hot-wire anemometer or by a laser Doppler velocimeter because the relative humidity (RH) changes rapidly with height from the surface. Only very small humidity sensors of millimeter order can make the high spatial resolution measurements. The sensors cannot be used with forced ventilation or air intakes because the ventilation and the air intake change the flow in the layer where the vertical humidity gradient is large. Capacitive polymer sensors are somewhat suitable because they are small. However, these sensors have slight temperature dependencies and hysteresis (Suzuki, 1996; Wiederhold, 1997). These features create measurement errors when the sensor is moved vertically in a layer with remarkable large gradients of humidity and temperature.

A thermocouple psychrometer is a possible solution because psychrometer does not have hysteresis either temperature dependency and because diameters of

thermocouple junctions can be made smaller than 1 mm by using appropriate diameter wires. Hanafusa et al. (1980) and Tsukamoto (1986) used thermocouple psychrometers for their field observations. The wet bulbs of their psychrometers were made by curling fine gauze thread around the thermocouple wires that the diameters were less than 120 μm . This method clearly requires manual dexterity. In the author's experiences of making similar wet bulbs and trial use, the thread had to be adjusted before use because the thread often sagged when it dried after the last use. The author thus proposes a new, effortless fabrication technique of constructing wet bulbs that does not need maintenance or dexterity. Water tanks are necessary for long-term continuous measurements by psychrometers. Unfortunately, water tanks near the sensor disturb the flow and prevent accurate measurement. A mechanism to supply water to the wet bulb through the thermocouple protection pipe was designed. This mechanism miniaturized the thermocouple psychrometer. The present paper describes the new wet-bulb fabrication technique and the water supply mechanism. Next, the performance of the thermocouple micro psychrometer produced by these inventions is surveyed, and an application example is presented.

2. Bonding-cellulose method for wet-bulb fabrication

The main features of this fabrication method are the use of cellulose powder instead of the fine gauze thread and bonding it to the thermocouple junction by a thermal conductive adhesive. The method is named the bonding-cellulose method after these features. Figure 1 shows the procedure of the bonding-cellulose method. Thermal conductive adhesive (CASTALL1520 made by CASTALL, Inc.) is applied to the thermocouple junction (Step 1). The thermal conductivity of this adhesive is $32.3 \times 10^{-4} \text{ cal s}^{-1} \text{ cm}^{-2} \text{ }^{\circ}\text{C}^{-1}$ (from its catalog). The thermocouple

Figure 1 Process of the bonding-cellulose method.

with the adhesive applied is inserted into the cellulose powder in the elastic tube with a closed end (Step 2). This powder is made by ADVANTEC for electrophoresis and has a fineness exceeding 300 mesh. The tube is pressed by the two fingers from the side (Step 3). The thermocouple is slowly drawn from the tube (Step 4). The superfluous powder is removed by shaking the thermocouple. It is possible to complete steps 1 to 4 within one minute. The cure time of the adhesive is 24 hours. After the cure, fine cotton yarn made in the first stage of the spinning process is linked with the root of the thermocouple junction (Step 5). Pulling the edges of the yarn after passing the thermocouple through the large yarn ring completes this easy step. The yarn grease is removed by alcohol rinse before the yarn is linked. The water is carried to the junction by the yarn capillary action. The above steps complete the wet bulb thermocouple. Figure 2 presents a micrograph of the wet bulb made by this method, and the wet bulb is moistened. The wire diameter of the wet bulb is $76\text{ }\mu\text{m}$, and the wet bulb diameter is 0.35 mm .

3. Structure of the thermocouple micro psychrometer

3.1 Connection

The thermocouples are made of cooper and constantan wires. Three thermocouples are necessary in the psychrometer, two for the wet bulb and the dry bulb temperature sensors, and the other for the ambient temperature sensor. The dry bulb and wet bulb sensors are connected in a differential mode for accurate measurements of the temperature difference between the dry bulb and the wet bulb thermometers.

Figure 2 Micrograph of the wet bulb made by the bonding-cellulose method.

3.2 Structure of the wet-bulb temperature sensor

Figure 3 shows the structure of the wet-bulb temperature sensor. The diameter of the thermocouple wire (2) is $76\text{ }\mu\text{m}$. The thermocouple is passed inside the protection pipe (5) in which the water absorption fibers (6) pulled from an aqueous felt-tip pen are crammed so straightly that the capillarity works well. A water absorption polymer (4) used in paper diapers is crammed into the tip to prevent the water from leaking superfluously. The water is injected into the protection pipe from the injector needle (7) and is carried through the gap of the absorption fibers and the yarn (3) to the wet bulb (1). The water is supplied to the needle from a tube pump (WP-1000 made by WELCO Co., Ltd.) that is linked with the needle in the silicon tube. The pump discharges 0.16 ml per revolution of the rotor and is operated intermittently by timer control. The water tank is put near the pump.

3.3 Structure of the dry-bulb and ambient-temperature sensors

Figure 4 shows the structure of the dry-bulb sensor and the ambient-temperature sensor. These sensors are included in one protection pipe. Psychrometer measurements made when the time constant of the dry-bulb sensor significantly differs from that of the wet-bulb sensor are unreliable when the ambient temperature is changing. The wet bulb is covered by the adhesive and cellulose powder with the water. Its time constant is therefore larger than that of the thermocouple with a bare junction. It is possible to use a wire of the same diameter as that used in the wet bulb if its time constant is adjusted by an adhesive coating. The result of the trial use of the coated ambient temperature sensor shows that the temperature measured by the sensor is 0.4°C lower at maximum than the actual temperature when the ambient humidity drops. Dust found on the junction surface by an

Figure 3 Structure of the wet-bulb sensor. (1. Wet bulb junction 2. Thermocouple wire 3. Fine cotton yarn 4. Water absorption polymer 5. Protection tube (3 mm outer diameter, 2 mm inside diameter and 6 cm length) 6. Water absorption fiber 7. Injector needle 8. Acrylic tube (3 mm inside diameter, 1 cm length) 9. Silicon elastic tube 10. Cork 11. Silicon tube)

Figure 4 Structure of the dry-bulb and ambient-temperature sensors. (1. Thermocouple for the dry-bulb sensor 2. Thermocouple for the ambient-temperature sensor 3. Cork 4. Protection tube (3 mm outer diameter, 2 mm inside diameter and 6 cm length) 5. Thermocouple connector)

electron micrograph seems to be hygroscopic and adheres while the adhesive is curing. Thus, bare thermocouples made of 125 μm diameter wire are used for the dry-bulb sensor and the ambient-temperature sensor.

3.4 Mount and measurement system

The wet-bulb sensor, the dry-bulb sensor and the ambient-temperature sensor are mounted as shown in Fig. 5 and are attached to a traverse member in the test section of the wind tunnel. The mount is composed of one stainless steel shaft for supporting the sensors and a sheet of vinyl chloride for inserting the sensors. The vinyl chloride sheet is used to minimize the effect of the conductive heat. The junctions are placed at identical levels and in a straight line. The thermoelectric voltages from the thermocouple are measured by a digital oscilloscope after being amplified 1000 times. A low-pass filter is employed for high-frequency noise rejection between the oscilloscope and the amplifier because the low-voltage signals are easily influenced by noise. The cut-off frequency of the low-pass filter is set at 40 Hz to reduce the noise from the 50 Hz power source. We use an ice-point reference chamber (ZC-114 made by Komatsu Electronics Inc.) to measure the ambient temperature. ZC-114's manual says that the reference chamber maintains its temperature between 0°C and 0.02°C for a long time when the surrounding air temperature is 20°C.

Figure 5 Mount for the thermocouple micro psychrometer. A 3 mm diameter stainless steel shaft supports the vinyl chloride sheet and the sensors.

4. Performance

4.1 Psychrometric constant, its wind velocity dependence and accuracy

Water vapor pressure is obtained from Sprung's psychrometric formula:

$$e = e_w - AP (T_a - T_w) \quad (1)$$

where e is the water vapor pressure, e_w is the saturation vapor pressure of water at the wet bulb temperature T_w , T_a is the dry-bulb temperature, P is the atmospheric pressure and A is the psychrometric constant. The values of A for Assman psychrometer (ASSMAN) and the Japan Meteorological Agency (JMA) type psychrometer are 0.000662 (Suzuki, 1996). These psychrometers consist of two mercury thermometers and are used with forced ventilation. The ventilation velocity of the ASSMAN model is 2.5 ms^{-1} and that of the JMA model is 4.0 ms^{-1} (Suzuki, 1996). Our thermocouple micro psychrometer is used without forced ventilation, and the velocity of the flow around the sensors varies every moment and from place-to-place. The wet bulb and the dry bulb are much smaller than the ASSMAN and JMA models. Therefore, the value of A for the micro psychrometer is decided from calibration at various ventilation velocities. The psychrometers are calibrated in the constant humidity and temperature tank (LH-40-03PRG-La made by Nagano Science Co., Ltd.). The micro psychrometer is set in a ventilation pipe to survey wind velocity dependence of A . The air is taken in through the net installed at the tip of the pipe. The net removes the turbulence caused by the circulation in the constant humidity and temperature tank. The ventilation velocity in the pipe can be changed from 0.1 ms^{-1} to 0.6 ms^{-1} by controlling the voltage applied to the fan. The relation between the applied voltage and the ventilation velocity was determined by measurements using a hot-wire velocimeter. The range of the ventilation velocity is wide enough because the wind

tunnel experiments with the water vapor condensation are often carried out at low wind velocities. The standards of water vapor pressure are obtained from a JMA model psychrometer. The atmospheric pressure P is measured by an aneroid barometer. The ambient-temperature sensor was compared with a platinum resistance thermometer in the constant-temperature liquid tank of the JMA Meteorological Instruments Center. The root mean square error in the temperature measured by the ambient-temperature sensor was 0.03°C .

The value of A is determined from regression analysis:

$$y = C(x - B) \quad (2)$$

where, C and B are constants, y is $e - e_w$ and x is $T_a - T_w$. The temperatures T_a and T_w are obtained by sampling the thermoelectric voltages at the rate of 100 Hz and averaging for 20 seconds. The value of e is obtained from the measurement by the JMA type psychrometer, and e_w is the saturation water vapor pressure at T_w of the thermocouple micro psychrometer. Since P can be considered as a constant because of its small change during calibration, A is given by $-C/P$. The constant B is the compensation for the temperature difference. This compensation is added because the thermoelectric voltage is not zero due to the specific quality difference in the thermocouple junctions even if the wet-bulb temperature is equal to the dry-bulb temperature and because it is very difficult to measure near-zero voltage accurately. As shown in Fig. 6, A and B are almost constant for ventilation velocities from 0.1 ms^{-1} to 0.6 ms^{-1} . The average of A is 0.00141 and that of B is 0.5841. The relative humidities measured by the thermocouple micro psychrometer are compared with the standards measured by the JMA type psychrometer from 30%RH to 98%RH at about 10%RH interval. The psychrometric constant A and the temperature difference compensation B are taken to be 0.00141 and 0.5841 for all ventilation velocities. The measured values are almost equal to those measured by the JMA type psychrometer, and the root mean square error in RH is 0.9%.

4.2 Response

Sano and Mitsuta (1968) studied the dynamic response of thermocouple psychrometer theoretically because it was difficult to make rapid artificial changes of humidity at that time. In the present paper, the response is surveyed by humidity impact experiments. The experiment setup is shown in Fig. 7. Dry air of 41%RH and 25.9°C flows out from one tube, and moist air of 63%RH and 23.1°C flows out from the other tube. The velocities of the two airflows are adjusted to 0.5 ms^{-1} . The

Figure 6 Wind velocity dependence of the thermocouple micro psychrometer's psychrometric constant A and the temperature difference compensation B .

Figure 7 Setup of the response experiments for the thermocouple micro psychrometer.

(1. Thermocouple micro psychrometer. 2. Ultrasonic humidifier 3. Dehumidifier 4. Fan)

flow from the tube of one side is applied to the sensor. The humidity impact is then applied by moving the two tubes as quickly as possible with both hands so that the flow from the other tube may hit the sensor. The stoppers, not shown in Fig. 7, limit the moving range of the tubes on the table. The distance between the tube centers is only 5.5 cm, so it is possible to make the humidity impact. When the temperature difference between the wet bulb and the dry bulb ΔT changes from ΔT_0 (the value before the humidity impact) to the terminal value ΔT_E , the normalized temperature difference deviation D is defined as:

$$D = |(\Delta T - \Delta T_0) / (\Delta T_E - \Delta T_0)|. \quad (3)$$

The time constant is given by the elapsed time until D becomes 0.632. The results show that the thermocouple micro psychrometer has a time constant of 0.4 s. This value is comparable to Sano and Mitsuta (1968)'s estimation for the wet bulb made of 120 μm diameter thermocouple wire. The effective diameter of their wet bulb is 0.31 mm, which is close to that of ours.

4.3 Long-term stability

Our thermocouple micro psychrometer could be used for two months without maintenance. It was stored for four months after the last use in a plastic box and was recalibrated. The wet-bulb sensor completely dried during the storage period. We injected water into the water absorption fibers before the calibration. There was no sag nor was any adjustment necessary. The result shows that the error increases to 2.9%RH when the constants in the first calibration (see 4.1) are used and that A and B become 0.00114 and 0.2658. The capacitive humidity sensor (HMP 12 3B made by VAISALA) in the constant humidity and temperature tank is also calibrated. The error increased from 0.5%RH to 3.2%RH in six months. The long-term stability of the thermocouple micro psychrometer is thus comparable to that of the capacitive humidity sensor.

5. Application Example

We measured the spatial distribution of humidity in the

test section of the Meteorological Research Institute's large meteorological wind tunnel using the thermocouple micro psychrometer. This wind tunnel is an indoor cycloid type with an open rear end in the test section. The test section of the wind tunnel is 18.0 m long, 3.0 m wide and 2.0 m high. The floor of the test section consists of six 3-m-long panels whose surface temperature can be controlled. Figure 8 shows the experiment setup in the test section. The x-direction is taken along the flow, and the z-direction is taken as upward. The upwind end of the cooled floor is chosen to be $x=0$. The airflow into the test section is moisturized by dry-fog humidifiers (AD-T sets made by H. Ikeuchi & Co., Ltd.). A 3cm-deep water pond is made in the first 3 m of the test section to further moisturize the lowest layer. The boundary layer is developed by mesh attached to the floor. The airflow temperature is lowered by cooling the floor panels to 3°C. The water vapor is condensed on the floor. The measurement locations are $x = -0.1, 0.1, 0.2, 0.4, 1.0, 2.0$ and 4.0 m at the center of the width of the test section, and the measurement heights are 0.3, 0.5, 0.7, 1.0, 2.0, 4.0 and 6.0 cm. The sampling rate is 100 Hz and the averaging period is 20 seconds. The measurements are made twice at each point and averaged.

Figure 8 Experiment setup in the test section of MRI large meteorological wind tunnel.

Figure 9 Vertical section of the relative humidity distribution measured by the thermocouple micro psychrometer.

Figure 9 shows the vertical section of the relative-humidity distribution. The relative humidity gradually increases downstream after a rapid increase at $x=0$ m, and the layer to the 2 cm height is saturated near $x=4$ m. Fog generation is confirmed in the saturated layer by visualization using a light sheet. Figure 9 clearly shows the high spatial resolution of the thermocouple micro psychrometer.

6. Summary

Using the bonding-cellulose method, it is quite easy to make very small thermocouple wet bulbs without special dexterity. The thermocouple micro psychrometer made by this method has a high accuracy of 0.9%RH and a fast response due to its 0.4 s time constant. The psychrometric constant is almost constant at 0.00141 for ventilation velocities from 0.1 ms^{-1} to 0.6 ms^{-1} . Its high spatial resolution for humidity measurements in wind tunnel experiments is achieved by a mechanism that supplies water to the wet bulb through a thermocouple protection pipe. The long-term stability of the sensor is very good; it exhibited only a slight increase of error from 0.9%RH to 2.9%RH after two months use and four months storage. Furthermore, it is not necessary to adjust the yarn after the sensor is dried. The thermocouple micro psychrometers will enable wind tunnel experiments with water phase changes for investigating water vapor transfer.

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