Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

Psychrometer based on a contactless infrared thermometer with a predictive model for water evaporation

Chien Lee [a,b,*], *Yu-Jen Wang* [a]

[a] *Department of Mechanical and Electromechanical Engineering, National Sun Yat-sen University, No. 70 Lienhai Rd., Kaohsiung, Taiwan*

[b] *Tainan District Agriculture Research and Extension Station, Council of Agriculture, No. 70 Mu Chang, Sin Hua District, Tainan, Taiwan*

ARTICLE INFO

Article history:
Received 14 June 2016
Received in revised form
4 March 2017
Accepted 27 May 2017

Keywords:
Psychrometer
Wet bulb
Relative humidity
Saturation vapour pressure
Infrared thermometer

This study developed a novel psychrometer design in which air is pumped by a 0.35-W minifan through a chamber with a hanging wet wick and a single-packaged contactless infrared thermometer aimed at the wick. The thermometer is small sized, low cost, commercially available, and comes factory calibrated with a digital I^2C communication port. It can measure the temperatures of the package itself (dry bulb) and the wick surface (wet bulb).

For the fast conversions of relative humidity (RH) and vapour pressure deficit Δe from both dry- and wet-bulb temperatures in a low-end microcontroller, a method for deriving a fifth-order polynomial approximation equation for saturation vapour pressure e_s is presented. This equation enables the calculation to be rapidly executed on the microcontroller. An error analysis of conversion conducted taking the Goff–Gratch equations as a standard indicates that at temperatures ranging from 0 °C to 55 °C, the computational accuracy for RH reading is within +0.02 to −0.005, compared with ±0.1 derived for the Magnus form; in addition, the accuracy for Δe is within +0.002 to −0.0013 hPa, compared with +0.23 to −0.024 hPa derived for the Magnus form.

For predicting the water evaporation of the psychrometer according to its own climate parameters, a model based on the simplified Penman Equation was constructed; the predictive error for water mass loss is within ±2 g for a 325-g evaporation.

1. Introduction

Water is omnipresent, and the quantity of water vapour in the air (i.e., humidity) has many crucial consequences, affecting the suitability of living environments for plants and animals, storage conditions for matter, and the appropriateness of factories for manufacturing products such as foods and semiconductors. Reliable and accurate humidity sensors are therefore very important for monitoring and controlling the humidity of environments. The most common type of humidity sensor is based on humidity-sensitive materials (Chen

* *Corresponding author*. Tainan DARES, COA, No. 70 Mu Chang, Sin Hua District, Tainan, Taiwan.
E-mail addresses: clee@mail.tndais.gov.tw (C. Lee), yjwang@mail.nsysu.edu.tw (Y.-J. Wang).

http://dx.doi.org/10.1016/j.biosystemseng.2017.05.010

Nomenclature

T	(°C) temperature
T_{dry}	(°C) dry-bulb temperature or air temperature
T_{wet}	(°C) wet-bulb temperature
e	(hPa) vapour pressure of water in air
e_s	(hPa) saturation vapour pressure of water in air
$\bar{e}_s$	(hPa) approximation of e_s
$\Delta e = e_s - e$	(hPa) vapour pressure deficit
$RH = e/e_s$	(%) relative humidity
α	(°C^{-1}) psychrometric coefficient
P_{atm}	(hPa) atmospheric pressure
$\widehat{\frac{dE}{dt}}$	(mm day^{-1}) evaporation rate of Penman equation
Δt	(sec) time interval of psychrometer measurements
λ_v	latent heat of vaporisation (=2.265 MJ kg^{-1} for water)
R_n	(MJ m^{-2} day^{-1}) solar radiation
V	(m s^{-1}) wind speed
E	(g) cumulative evaporative mass of water
G	(g s^{-1} °C^{-1}) instrument's constant for the predictive model of water evaporation

& Chi, 2005; Rittersma, 2002) and involves the materials' properties (i.e., capacity, resistance, or mechanical strain) changing depending upon the degree of humidity. Because of the necessity of being exposed to air, the sensing materials age particularly quickly in hot and humid atmospheres (Matsuguchi et al., 2000; Nahar, 2000). Agricultural environments are even harsher for this type of sensor owing to the chemical contaminants from fertilisers and pesticides clinging to the sensing materials. Hence, an accurate and robust method of measuring humidity is necessary in order to reduce the cost of refurbishment and recalibration.

The dry- and wet-bulb psychrometer and chilled-mirror dew-point hygrometer (Wiederhold, 1997) measure humidity based on temperatures; both alternative methods enable the immunity to ageing and degradation because of the hermetic encapsulation of temperature sensors. However, both need ventilation by a fan and regular maintenance; the psychrometer needs water to be refilled and the wick for the wet-bulb to be replaced, and the mirror for dew-point hygrometer needs cleaning.

The chilled-mirror hygrometer (Jachowicz & Makulski, 1993) must precisely control the cooling power of the mirror based on an optical feedback signal. However, this is too expensive to be widely applicable to agriculture, although it attains the highest accuracy of the various types due to the direct physical measurements of humidity.

Measuring humidity based on the evaporative cooling of wet bulb has a long history that can be traced back to the aspiration psychrometer (Assmann, 1892). This device used a clockwork fan to draw air past the bulbs, which were shielded from radiation by polished metal casings. With technological advancements, the original mercury thermometers were replaced by thermocouples (Powell, 1936), and it was noticed that the wet-bulb depression $T_{dry}-T_{wet}$ depends on the degree of ventilation, the diameter of the wire, the thickness and length of the water film covering the junction of the wet thermocouple, and the relative positions of the wet and dry thermocouples. Subsequently, a specially designed psychrometer was proposed (De Wit, 1953) that achieved sufficient ventilation by oscillating the dry- and wet-bulb thermocouples. However, this technique has never been practically applied. Except for the requirement for refilling water, it has been demonstrated that the psychrometer requires few repairs and that dust accumulation has a negligible effect on accuracy (Barber & Gu, 1989). By contrast, dust contamination on the chilled mirror for dew-point hygrometer can severely affect the reflected optical signal and cause the calculated relative humidity (RH) to appear to be higher (Costello, Berry, & Benz, 1991).

Figure 1 shows a common psychrometer that has a fan with a cross-section of 80 × 80 mm^2 and a 3.5-W power rating; it is used in a greenhouse with a climate that is controlled precisely for agricultural production. Currently, psychrometers appear to be the best type of sensor for humidity measurement in

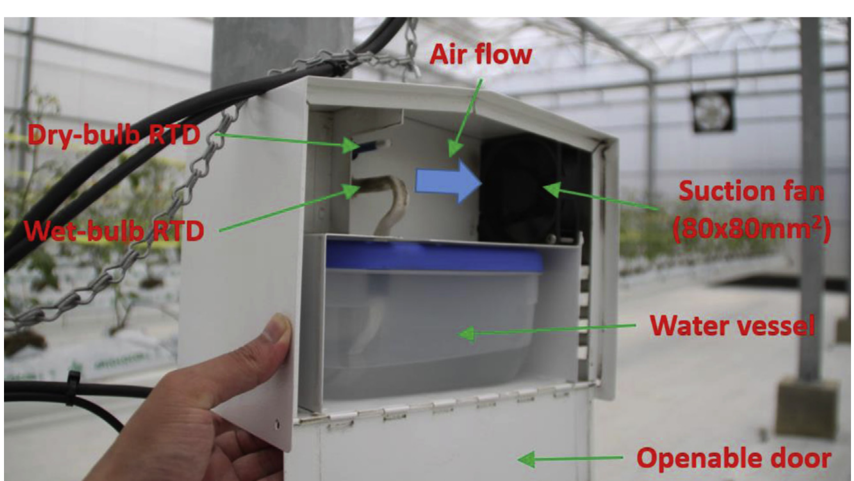

Fig. 1 – Common type of psychrometer produced for use in greenhouses by Priva B.V., Netherlands (http://www.priva.ca/en).