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A Diode Sensor for Air Temperature and Humidity Profile Measurements

Josefina C. Argete
Department of Meteorology and Oceanography
College of Science

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ABSTRACT

An instrument package was developed for measuring four-level dry-bulb and wet-bulb temperature profiles. Germanium diodes (1N270) incorporated into a constant current circuit were used as sensing heads. Laboratory calibrations were referenced against a factory-calibrated thermistor with an accuracy of 0.25 deg C. The diodes showed a linear response over normal atmospheric temperature range and a sensitivity of about 1.8 mV/deg C. Field performance gave the following spread of values among the four psychrometers: 0.15 deg C for T_d, .05 deg C for T_w and 0.15 hPa for vapor pressure.

The diode psychrometers allow air temperature and humidity profile analyses over the earth-atmosphere interface wherein accuracy, flexibility in field use, and remote reading are required.

INTRODUCTION

The temperature and concentration of water vapor are two parameters that define the state of the atmosphere at the earth's surface. Measurements may be crude for climatological purposes, but they must necessarily be precise for micrometeorological profile analyses that seek to evaluate the transfer of energy at the earth-atmosphere interface.

Wet-bulb psychrometry has remained the most common technique for evaluating atmospheric moisture. A thermometric pair, one measuring the air temperature (henceforth the dry-bulb tmperature T_d) and the other the temperature of an evaporating water surface (henceforth the wet-bulb temperature T_w) is used to determine the partial pressure of water vapor from known T_d/T_w-humidity thermodynamic relation. In the meteorological service, the sling (fast becoming obsolete), the Assman, and the August psychrometers, all using mercury-in-glass thermometers and hence manually read, are conventionally accepted as standards. However, for profile analyses over various surfaces (e.g., smooth such as agricultural areas or rough such as over forests) wherein accuracy, flexibility in field use, and remote reading are required, alternative temperature sensors like thermocouples, thermistors, and diodes are used.

The use of diodes for temperature measurement is based on the dependencies of reverse current on temperature and of the forward current on junction voltage, interacting to produce a linear junction voltage versus temperature relation (Sargeant 1965). The strong points for their use as temperature sensors are the large sensitivity (about 2 mV/deg C), do not require reference temperature junctions, and within the atmospheric temperature range their temperature dependence is almost linear. All of these requirements were met by the 1N270 Germanium diode[*] (Argete and Wilson 1989; McCaughey and Walker 1977) selected for use in the present study. Several researchers have documented the use of diodes in the field (Sargeant and Tanner 1967; Hinshaw and Fritchen 1970; Black and McNaughton 1972).

EXPERIMENTAL

A. Pre-grading of 1N270 diodes for the purpose of diode pair selection

The 1N270 diode is cylindrical in shape, approximately 0.0025m in diameter and 0.008m long, with axial leads. Twenty such diodes were pre-graded. Using a Fluke 75 digital multimeter set at 0.47mA, a mean junction voltage of 226.1mV with a standard deviation of 5mV was found. The diodes were ranked in order of deviation from the mean junction voltage. The eight with the smallest deviations were used in the temperature array. Diode pairs with readings closest to each other were selected.

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[*] One of the evaluators suggested the use of an inexpensive precision temperature sensor currently in the market, the LM 335/334, which has a sensitivity of 10mgV/deg C. We will consider this in our future designs.

B. Assembly of the temperature measurement circuitry

The basic measurement circuit (Figure 1) consisted of a constant current supplied to the 1N270 diodes by the MC1466L integrated circuit. The diodes were connected in series. The voltage drop V_{dry} across the dry-bulb diode and the total voltage drop across the two diodes V_{total} were measured; V_{wet} was obtained by subtraction.

A simple bridge rectifier with filters was constructed to supply 24V-DC to the integrated circuit, in lieu of store-bought variable-voltage power supply.

Details of the mounting of the 1N270 diodes are shown in Figure 2. The diode was first mounted on one end of a 1.5 cm matchstick. The diode terminals were soldered to a pair of fine twisted copper wires (32 AWG). The wood-end of the wood-diode assembly was inserted into an arm of a polyurethane-T (actually catheters) and the whole assembly was sealed with epoxy resin. The other arm of the poly-T was cut close to the junction, the signal wires were led out and the whole unit finally sealed with epoxy from the junction. Four diode pairs were mounted.

C. Laboratory calibration

The four diode pairs were calibrated in the laboratory against a reference temperature T_{ref} measured with a factory-calibrated thermistor with an accuracy of 0.25°C.

The laboratory set-up is shown in Figure 3. Calibration consisted of two parts. In the $T > T_{room}$ portion, the diodes and the thermistors were placed inside a Bosch mini-freezer. As T dropped from room temperature to 4°C, T_{ref} and the voltage drop across the diodes were logged. In the $T > T_{room}$ portion, a miniature wind tunnel (recycled from used carton spool, 1.5m x 10 cm ID) fitted with a hair dryer was used. The heating rate was regulated by a speed controller, and temperatures up to 65°C were logged.

The diodes and the thermistors were wired to the data logger (Omnidata International, Logam, Utah)* in a single-ended configuration, i.e. the signal wire (hi) was connected to the input channel while the signal common (lo) was connected to one of the analog ground terminals. Sampling time was set

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at 1-minute intervals. The data logger was programmed through a RS-232 cable connected to a serial port of an IBM-PC. Data consisting of V_{wet}, V_{dry} for each diode pair, T_{ref} and the actual sampling time were logged and stored in floppy diskettes for subsequent analysis.

D. Assembly of the psychrometer units

A schematic diagram and the actual photograph of the psychrometer assembly are given in Figures 4a and 4b, respectively. The sensor pair was housed in a PVC pipe 40 cm long and 2.54 cm ID. A section of the pipe served as trapdoor by making a longitudinal slice through half the pipe's length. The cut section was attached by masking tape on one side to serve as hinge. Three holes were drilled in the pipe below the trapdoor to mount the two diodes and the T-plastic tubing for the wick. When mounted, the dry-bulb diode was about 7 cm from the air intake end, the tip of the wet-bulb diode 4 cm behind the dry-bulb diode, and the wick tubing 3 cm further back. The wick tubing connected through the snap-on type lid of a 5-cc plastic water reservoir placed outside the pipe and held securely by epoxy resin unto the PVC. The wick consisted of a previously boiled hollow shoelace (100% cotton). The wick passed from the reservoir through the plastic T tubing onto the wet-bulb diode. The end of the wick was sewn by cotton thread for a close fit around the diode. The PC-board for the constant current circuit was made to sit securely inside the uncut portion of the PVC pipe.

The PVC pipe housing the sensors was covered with a layer of polyurethane (tubular foam insulation) 1.0 cm thick and adhesive aluminium foil (K-foil vapor barrier) to minimize radiant heating.

It was necessary to ventilate the wet-bulb diode ventilated at a certain windspeed (3-4 ms^{-1}) to be assured of an adiabatic heat transfer consistent with the wet-bulb theory. In fabricating miniature suction fans, the motor of a pocketsize portable fan (powered by two 1.5V dry cells) was used. The blade (2.54 cm dia) was made from discarded biscuit tin cans, and the fan housing from tin spools for wiring materials. In the field set-up, the fans of the four psychrometer units were connected in series and powered by a 12-V DC car battery.

E. In-situ evaluation of psychrometer performance

The psychrometers, spaced 10 cm apart, were mounted on a horizontal bar 1.5 m high. The thermistor measuring T_{ref} was inserted inside the housing of psychrometer #2 to avoid radiant heating. The data logger wiring configuration was the same as in the laboratory calibrations, except that the calibration equations were inputted into the data logging program to acquire directly the equivalent wet- and dry-bulb temperatures. Unlike that in laboratory calibrations, the cotton wicks were in place and took distilled water from the reservoirs, the suction fans were on, the foam insulations were in place and data were remotely read through long field cables. As an independent check, an Assman psychrometer was mounted with the psychrometers and manually read every 10 minutes. The experiment was performed on an open field at the back of the National Institute of Geological Science (NIGS) building, U.P. Diliman.

F. Calculation of atmospheric humidity

The vapor pressure of the air e (in mb or hPa) was calculated from T_d and T_w using the psychrometric equation:

$$e = e_s - \gamma\,(T_d - T_w) \qquad (1)$$

where e_s = saturation vapor pressure over water

γ = psychrometric constant given as:

$$\gamma = c_p\,P/\varepsilon L_v \qquad (2)$$

where c_p = specific heat of air at constant pressure

= 1005 J kg^{-1} K^{-1}

P = atmospheric pressure, 1013 hPa

ε = ratio of molecular weight of water to dry air

= 18/29

L_v = latent heat of vaporization of liquid water

= 2.5×10^6 J kg^{-1}

The saturation vapor pressure was determined using (i) the Clausius-Clapeyron equation and (ii) Teten's empirical power formula. The former is written as:

$$\frac{d \ln e_s}{dT} = \frac{L_v}{R_v T^2} \tag{3}$$

which upon integration gives:

$$e_s = e_0 \exp\left[\frac{L_v}{R_v}\left(\frac{1}{T_o} - \frac{1}{T_w}\right)\right] \tag{4}$$

where e_o = vapor pressure over ice, 6.108 hPa

T_o = 273.16 deg K

R_v = specific gas constant, 461.51 J $kg^{-1}K^{-1}$

(Teten's formula below is faster and adequately accurate on a computer)

$$e_s = 6.108 \exp\left[a\left(T_w - 273.16\right) / \left(T_w - b\right)\right] \tag{5}$$

$$a = 17.269388,\ b = 35.86,\ T_w \text{ in deg } K$$

RESULTS AND DISCUSSION

A plot of voltage drop versus temperature for the first diode, and the corresponding regression equation are presented in Figure 5. **DW1** is the designated wet-bulb diode of the first diode pair. These are but name assignments to identify diode pairs. It should be noted that laboratory calibrations measure dry-bulb temperatures.

The temperature dependence is clearly linear. The sensitivity of the 1N270 diode as reported in the literature is about 2.0 mV/deg C. This is the reciprocal of the slope of the regression equation in Figure 5, summarized for all diodes in tabular form in Table 1. It is evident that the reported sensitivity was closely reproduced in the calibrations.

For psychrometers intended to measure vertical gradients of vapor pressure, such as in moisture and heat flux determinations, the philosophy adopted in calibration is that the differences between instruments are more important than the absolute values. In other words, sensitivity is of more importance than is absolute accuracy. This is important because such factors as cables, connectors and junction offsets all introduce bias into the data. The measured differences between instruments will not be affected, however, if the same bias is applied to all of them.

While laboratory calibration of the diodes is relatively straightforward, vapor pressure calibration is not as convenient, because observations must be made with the psychrometers under aspiration. The aspiration requirement makes it difficult to obtain a suitable source of air with uniform temperature and water properties to make relative comparisons of one instrument against another. Furthermore, standard instruments required to assess absolute accuracy are unavailable. The Assman psychrometer is rather crude; its general acceptance as a standard appears related more to the ease in standardizing construction than to the accuracy of its readings (Brown and Van Haveren 1972). For these reasons, detailed and rigid laboratory calibrations of humidity designed to determine the absolute values were not done. The emphasis of the field performance evaluation centered on removing the bias among the sensors which for this case is extremely important for vertical gradient measurements. The Assman data were taken mainly to spot-check on the wicking system and aspiration.

The bias on the psychrometers as discussed above is evident in the raw data obtained in the 30-min run field performance experiment shown in Figures 6(a) and 6(b). Because the psychrometers are intended to be mounted at different levels of a meteorological tower, the lengths of their field cables vary. Sensors 1 and 3 have cables of the same length, sensor 4 the longest and sensor 2 the shortest, since the junction box for succeeding experiments will be placed close to the level of sensor 2. The temperature readings of the thermistor (T_{ref}) and T_d of the Assman closely followed that of sensor 2. The same trend is seen for the wet-bulb temperatures as checked by the Assman T_w.

Using sensor 2 as reference, the offsets are removed. For instance, for the dry-bulb temperature of psychrometer 1 (TD1), the mean deviation from TD2, (TD1–TD2), is subtracted from each 1-minute TD1 value. This is equivalent to subtracting the bias from the intercept of the laboratory calibration equations. Results of this procedure are shown in Figures 7(a) and (b). There is a mean spread of values (among sensors) of about 0.15 deg C for T_d and 0.05 for T_w.

With the corrected temperature readings, the corresponding vapor pressures calculated from Teten's formula are plotted as in Figure 8. A Mean spread of values of about 0.15 hPa is obtained.

COMMENTS

It is claimed that the use of germanium semiconductors as temperature sensors is subject to certain limitations: (a) a relatively poor long-term stability especially in the use of leakage current as indication of temperature change, and (b) a linear response only at a certain narrow range, i.e., not very reliable at temperatures greater than 30°C. While the laboratory calibration curves regarding non-linearity of response show otherwise, we intend to continue monitoring and evaluating the sensor's long-term stability and performance in the field. A follow-on experiment which uses the psychrometers for heat flux determination over agricultural surfaces is in progress.

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Table 1. Summary of the temperature-voltage drop calibration of 1N270 diodes

Diode No.	Calibration equation	Sensitivity	R-square
DW1	Y = −0.5549X + 167.3393	1.802	0.9951
DD1	Y = −0.5653X + 170.7453	1.769	0.9964
DW2	Y = −0.5370X + 145.3531	1.862	0.9963
DD2	Y = −0.5791X + 155.6444	1.727	0.9983
DW3	Y = −0.5271X + 140.8266	1.897	0.9943
DD3	Y = −0.5228X + 140.2339	1.913	0.9944
DW4	Y = −0.5173X + 140.5527	1.933	0.9954
DD4	Y = −0.5248X + 142.6313	1.905	0.9965

Units:

Y = temperature, deg C
X = voltage drop, mV

Sensitivity, mV/deg C

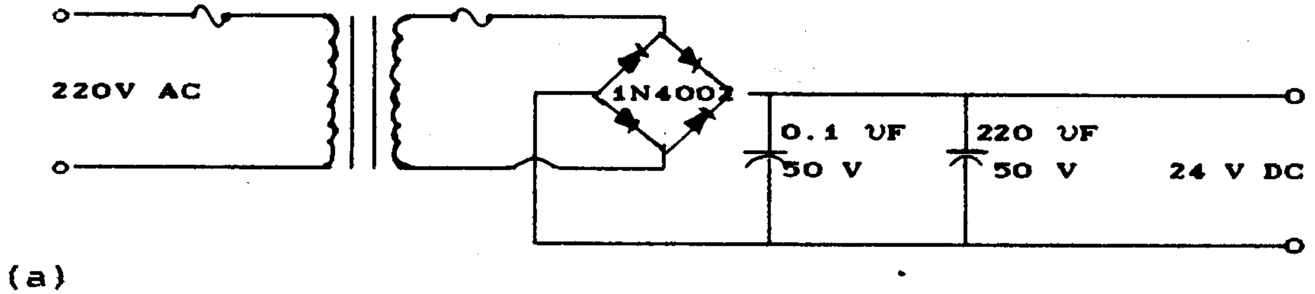

Fig. 1. (a) 24V DC power supply for MC1466L integrated circuit.

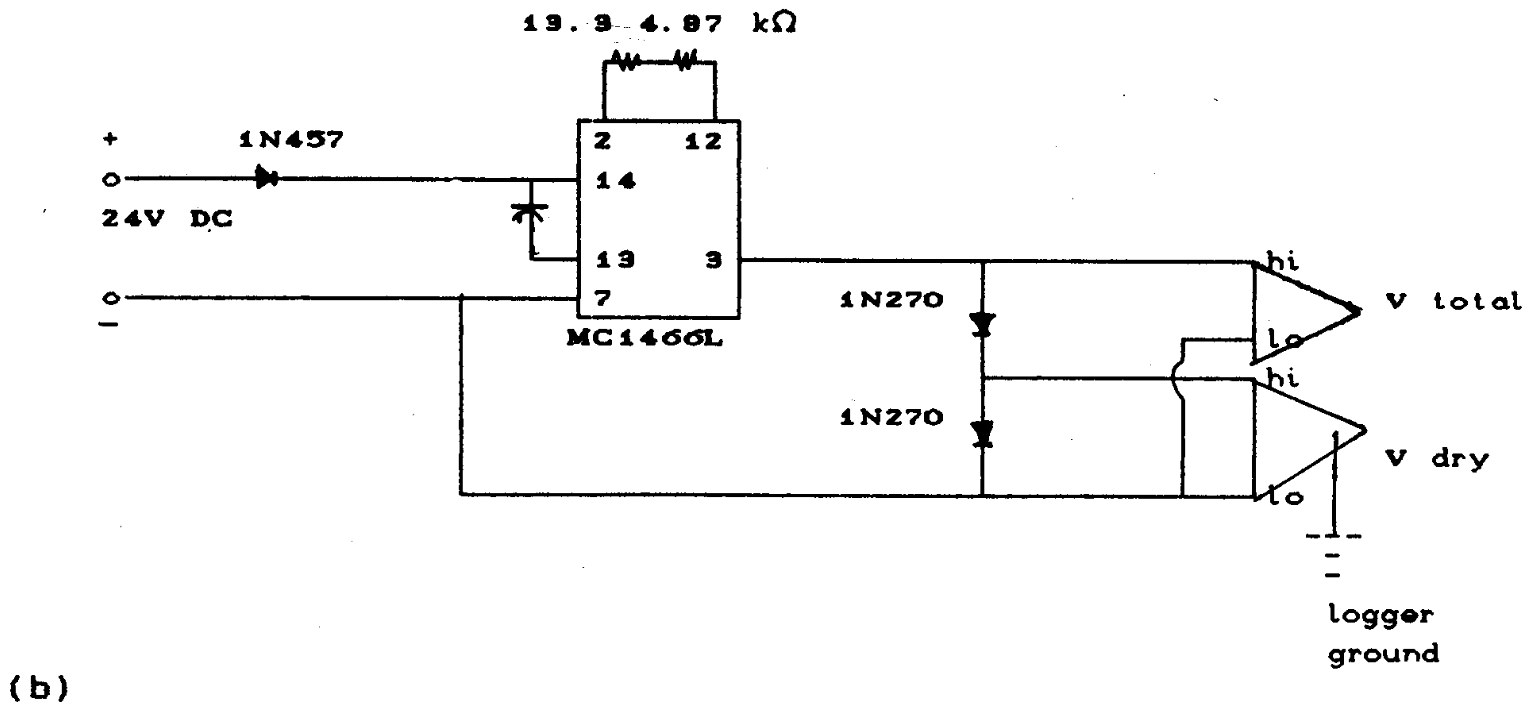

Fig. 1. (b) Schematic diagram of the psychrometric measurement system.
V_{total} = total voltage drop across the two diodes
V_{dry} = voltage drop across the dry-bulb diode
$V_{wet} = V_{total} - V_{dry}$.

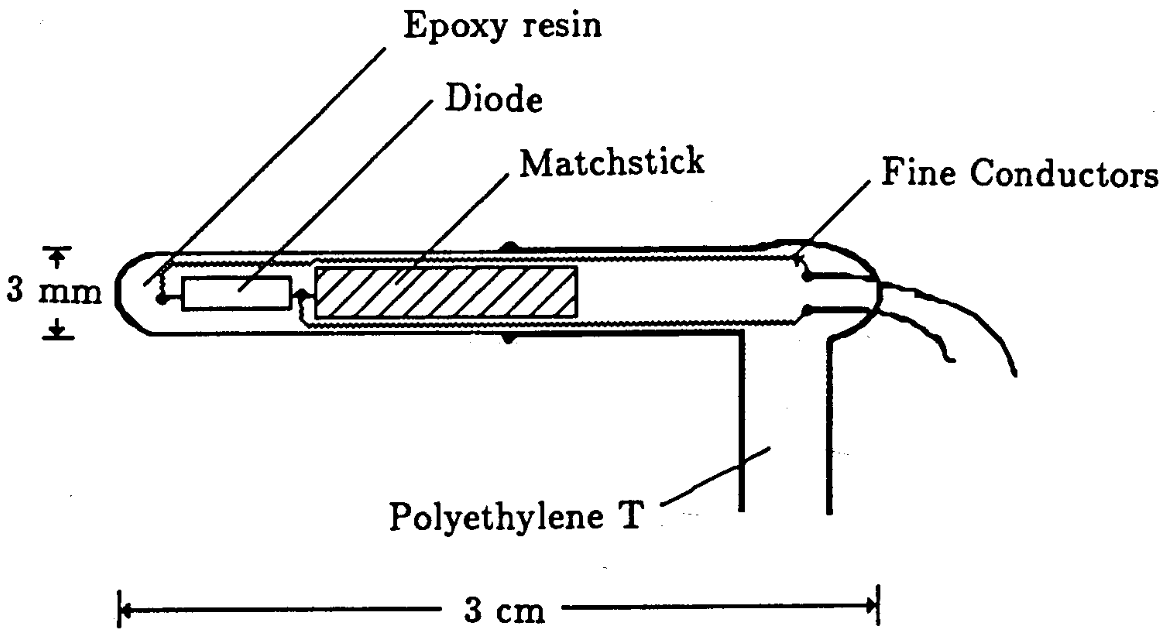

Fig. 2. The IN270 germanium diode was mounted on wood and polyethylene T and sealed with epoxy resin

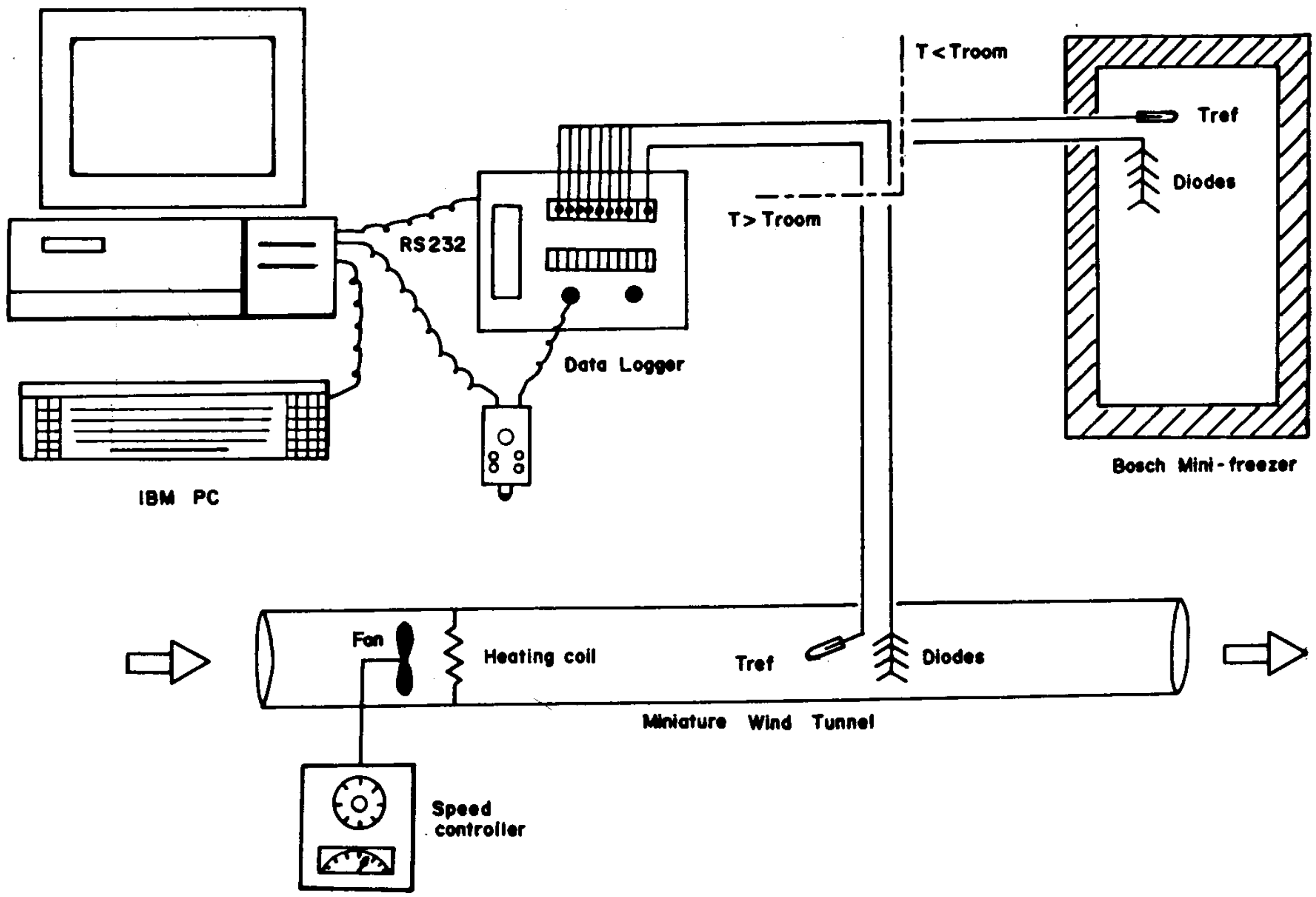

Fig. 3. Diode calibration set-up.

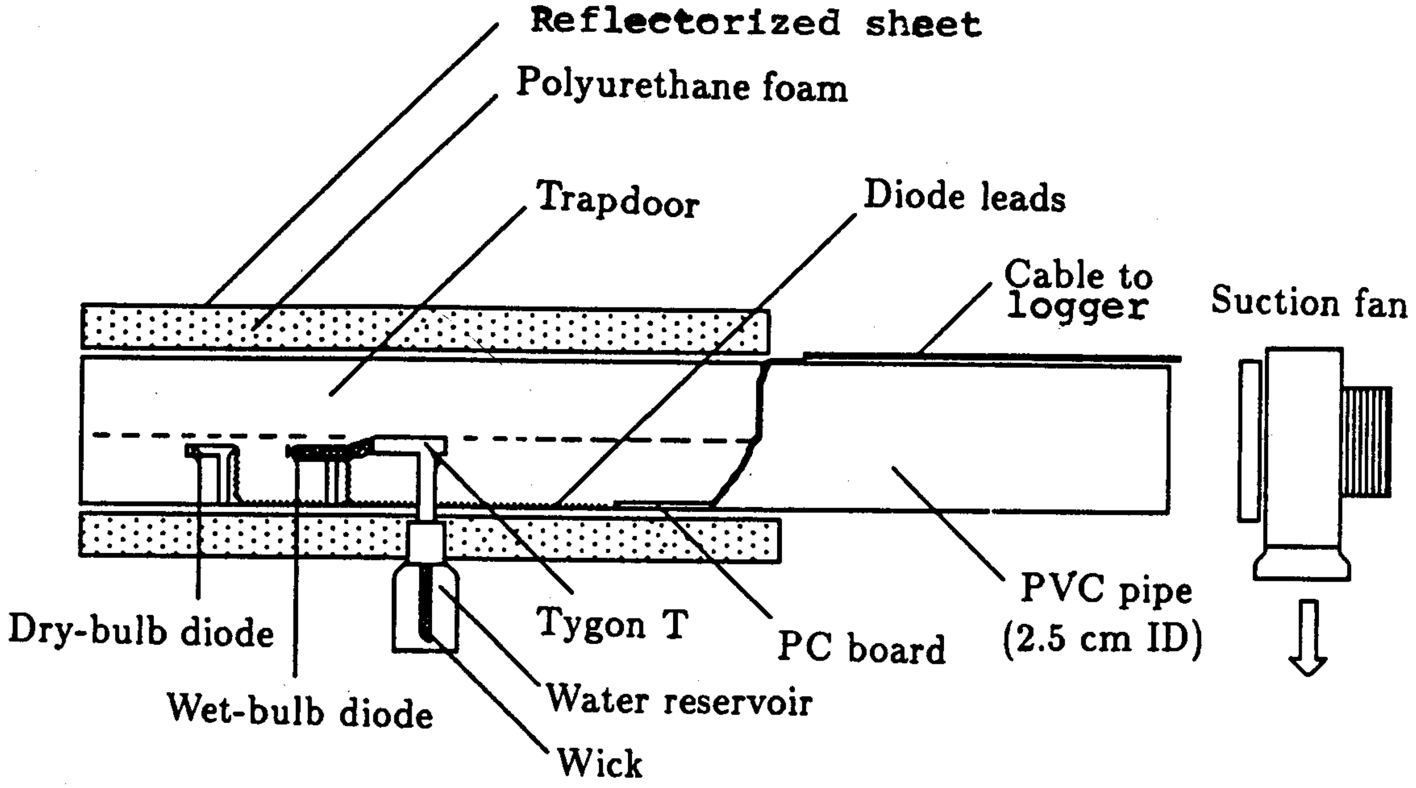

Fig. 4(a). Cross-section of the diode psychrometer assembly
(not drawn to scale)

Fig. 4(b). Photograph of the diode psychrometer assembly

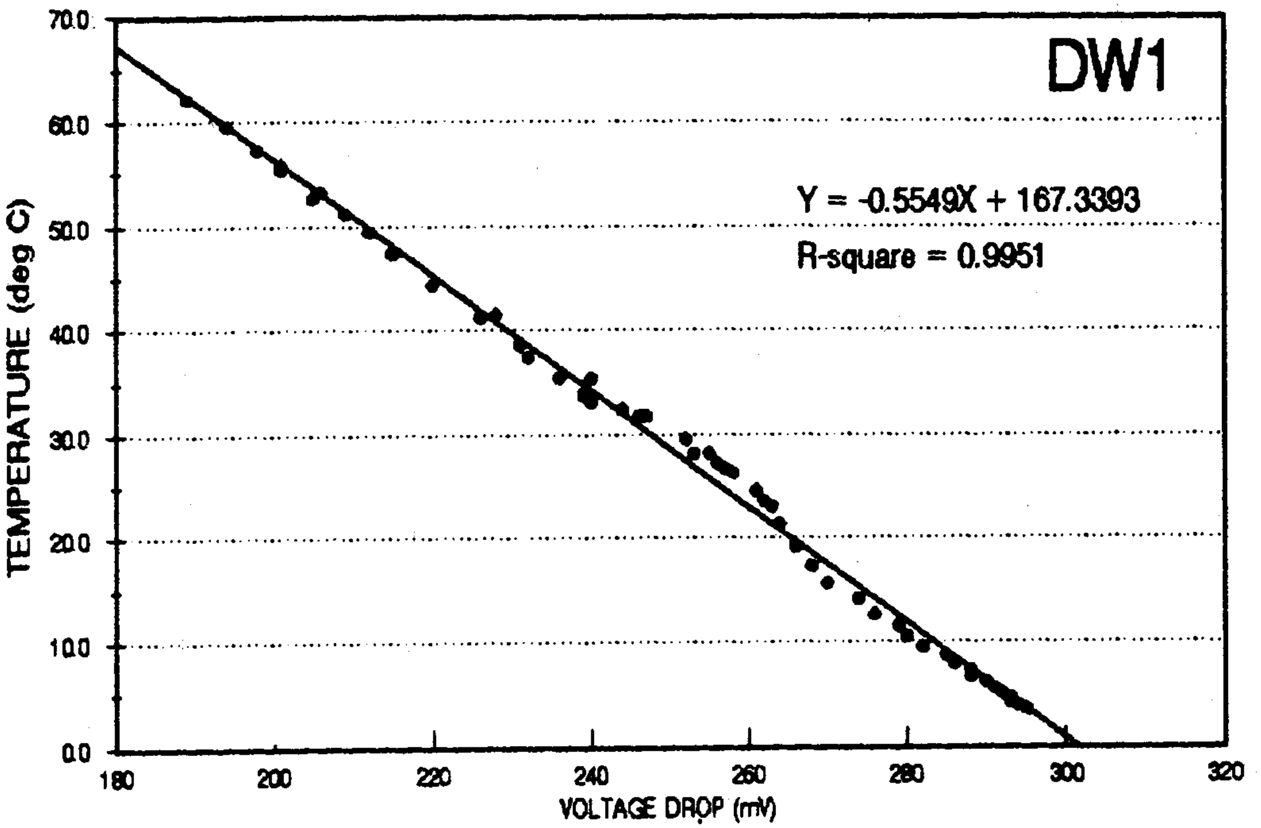

Fig. 5. Laboratory calibration curves

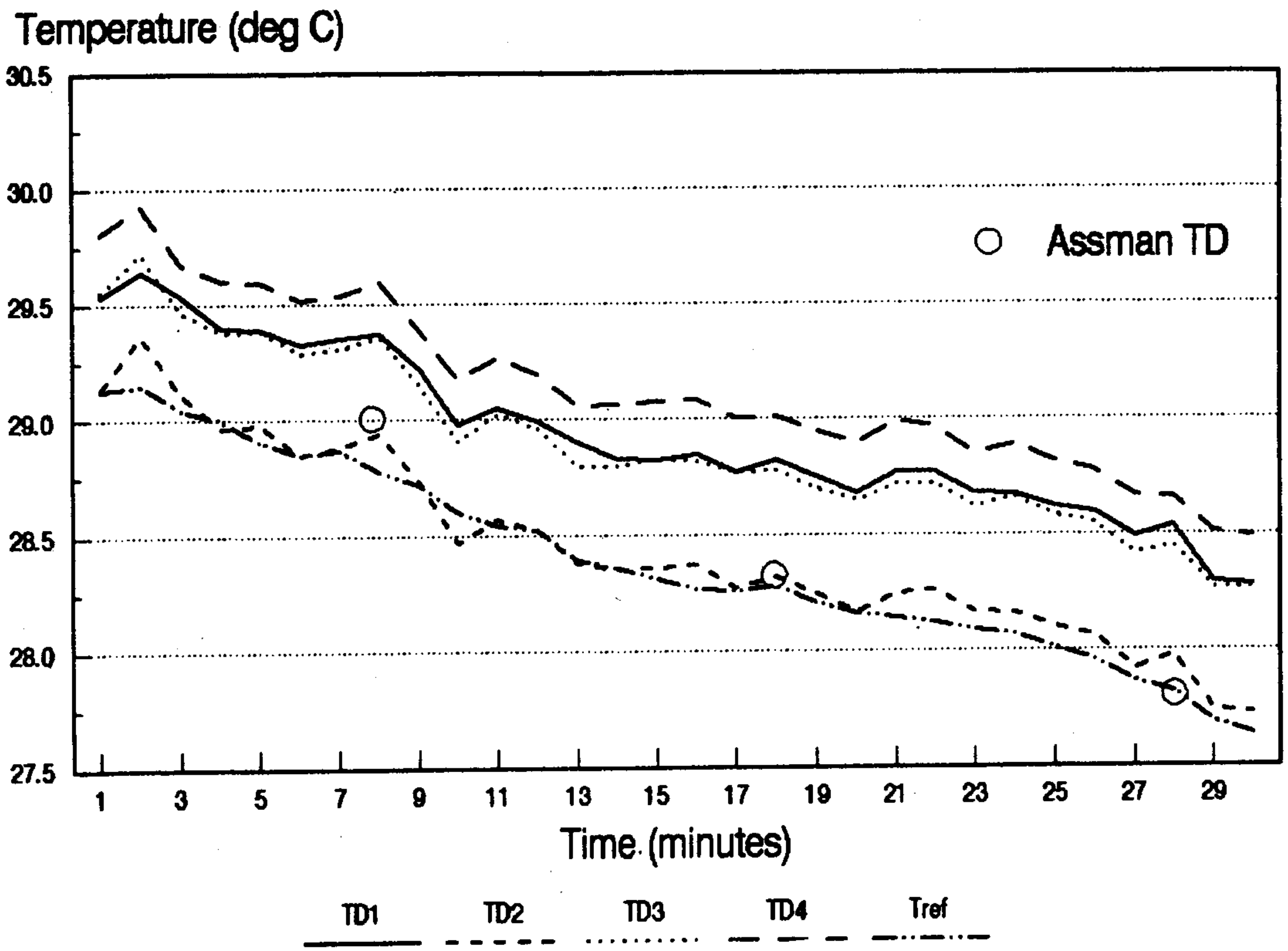

Fig. 6(a). Dry-bulb temperatures uncorrected for offset

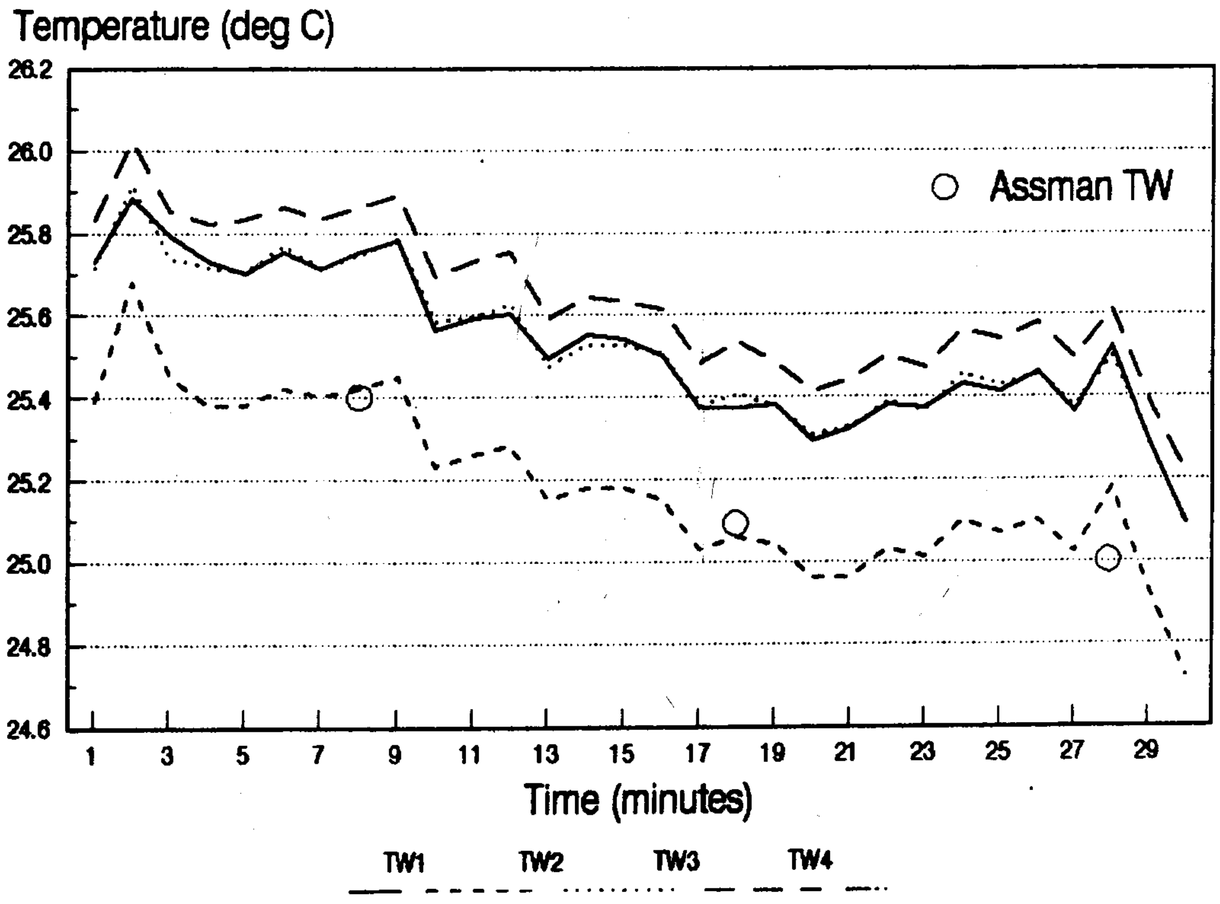

Fig. 6(b). Wet-bulb temperatures uncorrected for offset

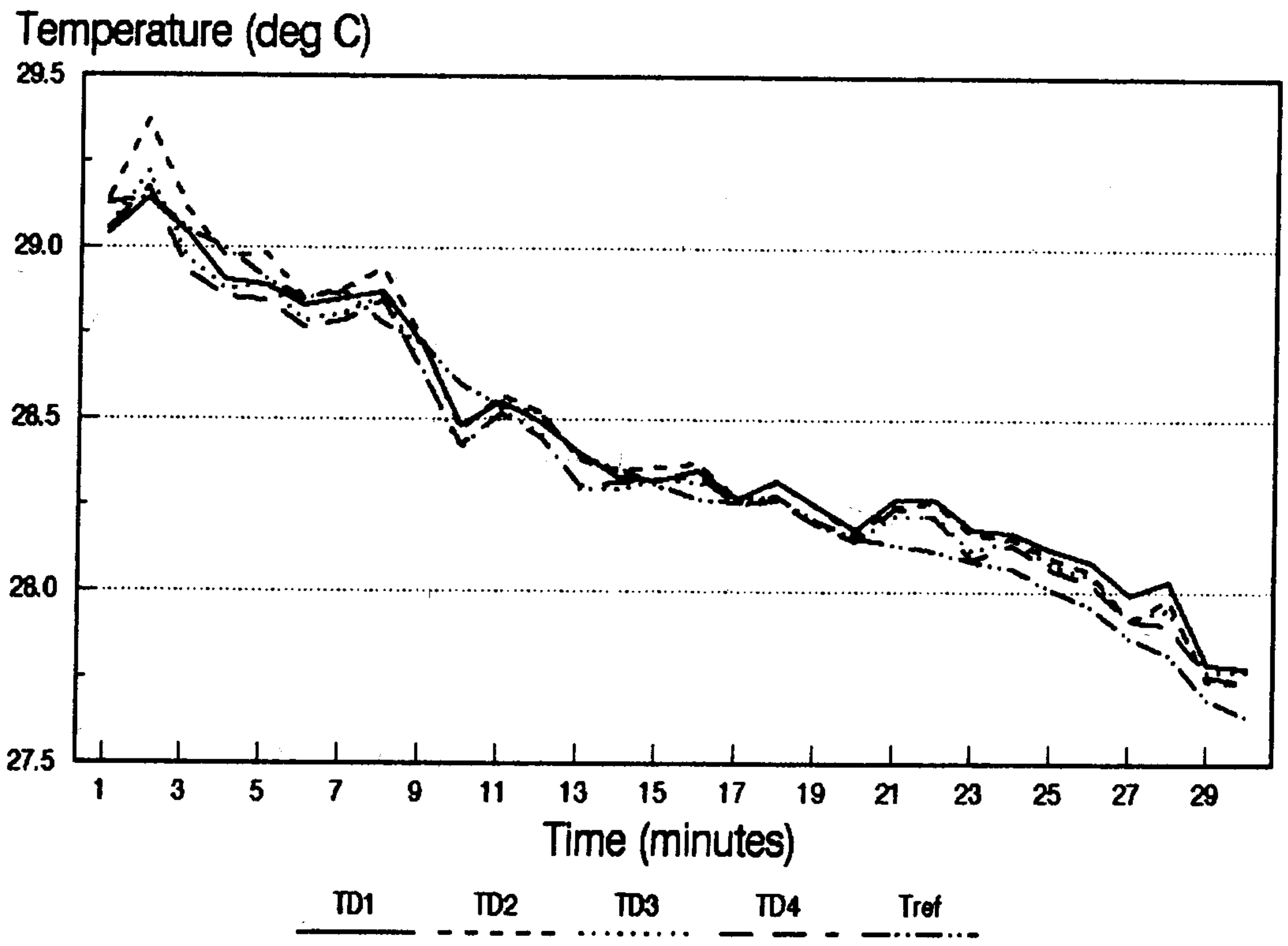

Fig. 7(a). Dry-bulb temperatures corrected for offset

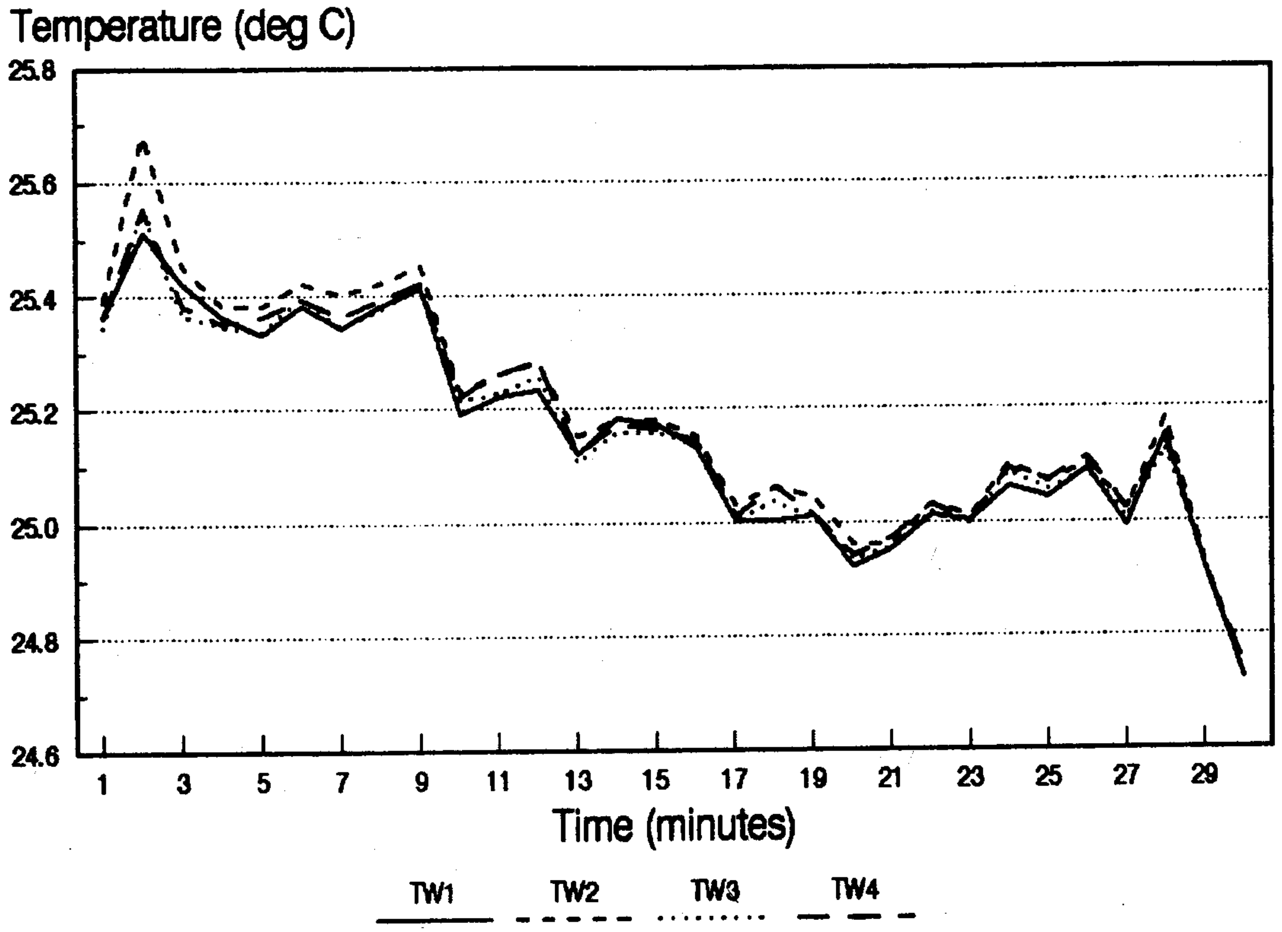

Fig. 7(b). Wet-bulb temperatures corrected for offset

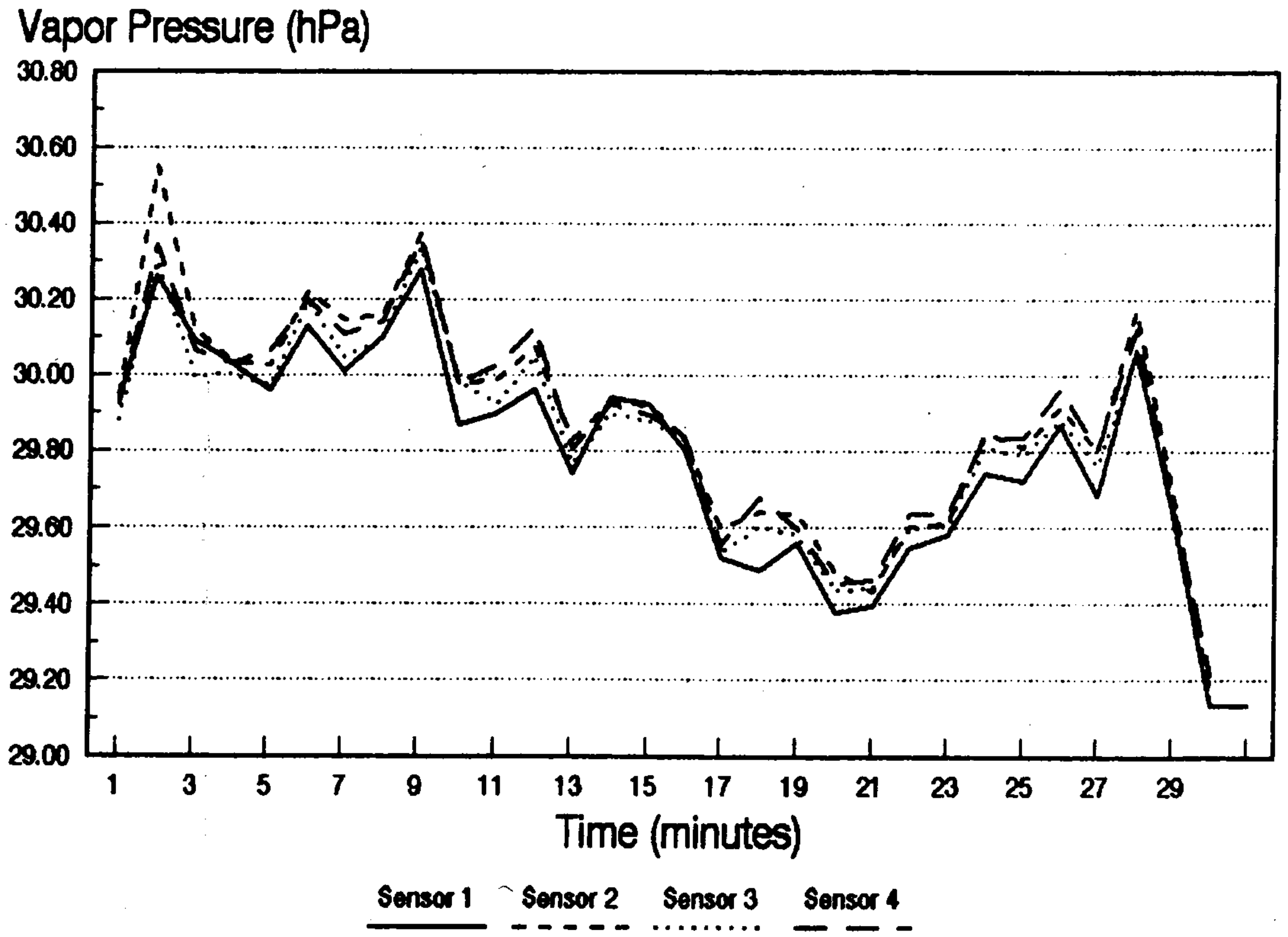

Fig. 8. Calculated vapor pressure of the air from corrected T_d and T_w