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Calibration of Psychrometers at Spring Singapore

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Abstract To assess the uniformity of the psychrometer coefficient of psychrometers commercially available in the market, results of calibrations of aspirated psychrometers and whirling (or sling) psychrometers performed by our laboratory at about 23°C and 55% rh over a period of six years are analyzed. It is found that although the psychrometer coefficient of a particular psychrometer can be quite consistent with long-term stability typically within the range of ±1% rh equivalent, there are larger variations (up to 4% rh equivalent) among different psychrometers even of the same type. The psychrometer coefficient variations in other temperature and humidity conditions are also studied through experiment using a randomly chosen aspirated psychrometer.

Keywords Aspirated psychrometer · Psychrometer coefficient · Whirling psychrometer

1 Introduction

SPRING Singapore calibrates about 25 psychrometers each year. Almost all the calibrated psychrometers use liquid-in-glass thermometers to measure dry and wet bulb temperatures. The liquid-in-glass thermometers used are generally of 0.2°C graduation and 0.5/1.0°C graduation for aspirated psychrometers and whirling (sling) psychrometers, respectively. The psychrometers are calibrated in terms of both temperature and relative humidity. The calibration reports include a temperature correction table for the liquid-in-glass thermometers from about 10 to 45°C and a psychrometer coefficient

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obtained by measuring the wet and dry bulb temperatures at one known temperature and relative humidity, normally 23°C and 55% rh.

From 2000 to 2006, about 160 calibrations were performed, with half of them being aspirated psychrometers and the others whirling psychrometers. A statistical study was conducted to understand the distribution of the measured psychrometer coefficient values by type of psychrometer. Among these calibrations, many were regular calibrations at different periods of time and therefore it was possible to study the consistency of the psychrometer coefficients over several years. The calibration results of a regularly calibrated psychrometer are given as an example to show the consistency of the psychrometer coefficient.

To verify the variation of the psychrometer coefficient under various relative humidity and air-temperature conditions, a randomly chosen aspirated psychrometer was calibrated. The psychrometer coefficient values were then computed and analyzed.

2 Method of Calibration

Before calibrating a psychrometer in terms of the psychrometer coefficient, the liquid-in-glass thermometers of the psychrometer were removed and calibrated in a liquid bath against a reference thermometer from about 10 to 45°C. The readings of the liquid-in-glass thermometers were taken by a CCD camera through a computerized data acquisition system and, as a result, the resolution of the liquid-in-glass thermometer was increased by a factor of 10. As such, the calibration uncertainty was significantly reduced (typically 0.03 for 0.2°C graduation liquid-in-glass thermometers). A table showing the thermometer corrections at the tested temperatures was tabulated at the end of the calibration. All the subsequent liquid-in-glass thermometer readings were corrected according to this table. The liquid-in-glass thermometers were then re-installed into the psychrometer. It is worth noting that the liquid-in-glass thermometer calibration result in a temperature-controlled chamber does not differ significantly from the calibration result using a liquid bath.

Prior to calibration, the wick of the psychrometer was cleaned in an ultrasonic bath, or replaced, depending on its condition. The wick was then soaked in distilled water before it was placed back onto the wet bulb. Five to ten minutes were allowed to let the wet bulb attain equilibrium with the surrounding environment before the commencement of the calibration.

The aspirated psychrometers and the whirling psychrometers were usually arranged differently during the calibration to determine the psychrometer coefficient. In the case of the aspirated psychrometer, it was placed in a temperature- and humidity-controlled chamber together with a standard chilled mirror dew-point hygrometer and its thermometer, which was placed in the vicinity of the wet bulb of the psychrometer, to measure the relative humidity and temperature. Another two or three reference thermometers were placed in the vicinity of the dry bulb of the psychrometer to check for any possible temperature non-uniformity in the chamber (see Fig. 1 for the calibration layout). The chamber temperature and relative humidity were set to about 23°C and 55% rh, respectively, and the motor of the psychrometer was switched on only after the chamber conditions had stabilized. The readings of the reference dew-point meter,

Fig. 1 Layout of aspirated psychrometer calibration

reference thermometers, and wet and dry bulb thermometers were taken at least 5 min after the motor was switched on. In the case of the whirling psychrometer, the psychrometer was placed in a stable ambient environment. Instead of manually whirling the psychrometer, a fan was placed in front of its wet bulb to provide the required airflow while the psychrometer was kept stationary (see Fig. 2 for the calibration layout). Verification was performed to ensure that the airflow provided by the fan was equivalent to that produced by manual whirling. Similarly to the calibration of the aspirated psychrometer, a standard chilled mirror dew-point meter, and its thermometer were placed in the vicinity of the wet bulb of the psychrometer to measure the temperature and relative humidity of the environment (generally about 23°C and 55% rh). The fan was left to run for at least 10 min before the commencement of the calibration. In both cases, the readings of the dew-point meter and its thermometer were captured using computer software while the readings of the wet and dry bulb liquid-in-glass thermometers were taken manually. A barometer was used to measure the atmospheric pressure in the chamber and under ambient conditions for the aspirated and whirling psychrometers, respectively.

To calculate the psychrometer coefficient based on the various measured parameters, a psychrometer equation was needed. Several psychrometer equations have been reported by various authors [1–3]. The simple one recommended by the ASHRAE Standard [1] was adopted:

$$p = p_{\text{wb}} - AP(t_{\text{db}} - t_{\text{wb}}) \tag{1}$$

Fig. 2 Layout of whirling psychrometer calibration

where:

p = partial water vapor pressure in the atmosphere
p_{wb} = saturation vapor pressure at the wet-bulb temperature
t_{db} = dry-bulb temperature
t_{wb} = wet-bulb temperature
P = atmospheric pressure
A = psychrometer coefficient (°C^{-1}), where p, p_{wb}, and P are expressed in the same units.

The relative humidity is given by

$$rh\% = (p/p_{db})100 \quad (2)$$

where
p_{db} = saturation vapor pressure at the dry-bulb temperature

Combining Eqs. 1 and 2, the following equation is obtained:

$$rh\% = \frac{P_{wb} - A\,(t_{db} - t_{wb})\,P}{P_{db}}100 \quad (3)$$

Using Eq. 3, the psychrometer coefficient (A) can be computed when all the other parameters in the equation are known. Among these parameters, the wet and dry bulb temperatures, relative humidity, and atmospheric pressure were measured while the water saturation vapor pressures at the wet and dry bulb temperatures were calculated using the Hardy ITS-90 saturation-vapor formulation [4].

3 Calibration Results and Discussion

To study the variation of the psychrometer coefficient, the computed psychrometer coefficients were divided into two groups based on the type of psychrometer—aspirated or whirling psychrometer—and each group included about 80 calibration results. The majority of the calibrated aspirated psychrometers were axially ventilated, and only a few were transversely ventilated. There was no significant difference found between the two types of ventilation, although this could be due to sampling only a small number of transversely ventilated psychrometers. Therefore, the calibration results of the transversely ventilated psychrometers were statistically grouped together with the axially ventilated psychrometers. The results show that the psychrometer coefficient values vary from about $6.0 \times 10^{-4\circ}\text{C}^{-1}$ to $7.9 \times 10^{-4\circ}\text{C}^{-1}$ for the aspirated psychrometers and from about $6.2 \times 10^{-4\circ}\text{C}^{-1}$ to $8.4 \times 10^{-4\circ}\text{C}^{-1}$ for the whirling psychrometers. At 23°C and 55% rh, these variations corresponded to a relative humidity variation of 4% and 4.6% rh for the aspirated and whirling psychrometers, respectively. The slightly greater dispersion in the results for the whirling psychrometer could be caused by the larger graduation of the liquid-in-glass thermometers used in this type of psychrometer and by the larger variation of the relative humidity and temperature in the ambient conditions of the laboratory as opposed to the temperature- and humidity-controlled chamber used for the aspirated psychrometers.

The expanded uncertainties of the measured psychrometer coefficient were estimated to be equivalent to 1.4% rh for aspirated psychrometers and 1.9% rh for whirling psychrometers with a level of confidence of approximately 95% and $k = 2$ according to the "Guide to the expression of uncertainty in measurement" [5]. The uncertainty budget for an aspirated psychrometer with 0.2°C graduation liquid-in-glass thermometers is summarized in Table 1 as an example. In the table, the uncertainty in the wet bulb temperature measurement is slightly higher than that of the dry bulb. This is because, the possible effect of additional heat transfer by radiation or conduction, which is estimated to be equivalent to 2% in A, has been considered [6]. The uncertainty in the relative-humidity measurement is mainly from the dew-point hygrometer that was used, a very old instrument lacking good reproducibility. Application of a more accurate dew-point hygrometer would improve the humidity measurement uncertainty by a factor of two and then the expanded uncertainty in the psychrometer coefficient, A, would be less than 1.0% rh equivalent at the current temperature and humidity.

Among the 160 calibrations, there were 59 individual psychrometers from 13 different manufacturers. Some of the units were calibrated regularly once or twice a year. Therefore, it was possible to study the consistency of the psychrometer coefficient

Table 1 Uncertainty budget table of aspirated psychrometer calibration

	t_{wb}	t_{db}	rh	P	p_{wb}	p_{db}
$u(x_i)$	0.09 (°C)	0.06 (°C)	0.61 (% rh)	1 (mb)	Negligible	Negligible
$u(A)$ (Equivalent in % rh)	0.23	0.15	0.61	0.01	Negligible	Negligible
$u_c(A)$ (Equivalent in % rh)	0.67					
U (Equivalent in % rh)	1.4 ($k = 2$, level of confidence approx. 95%)					

over a certain period of time. An example of the calibration results of an aspirated psychrometer over a six-year period is given in Fig. 3. It can be seen that the results are quite consistent—ranging from $6.42 \times 10^{-4}{}^{\circ}\mathrm{C}^{-1}$ to $7.34 \times 10^{-4}{}^{\circ}\mathrm{C}^{-1}$. This variation is equivalent to a difference in relative humidity of about 1.9% rh, at 23°C and 55% rh, which is well within the expanded measurement uncertainty. It is worth noting that similar behavior has been observed for other psychrometers, including whirling psychrometers.

As the psychrometer coefficient for a specific psychrometer seems to be quite consistent, the large variations found in the calibration results are likely due to the differences among different units. To verify this, the calibration results for each unique psychrometer were averaged for those units that had been calibrated more than once, so that each psychrometer had only one psychrometer coefficient. The psychrometer coefficient for each type was then plotted as a histogram, as shown in Fig. 4a and b. The histograms show that, although the variations are somewhat smaller when compared to the overall results for both types of psychrometer, the variations are still quite large and clearly wider than that given in the ASHRAE standard [1] and in "A Guide to the Measurement of Humidity" [7], where the variation ranges from $6.5 \times 10^{-4}{}^{\circ}\mathrm{C}^{-1}$ to $6.9 \times 10^{-4}{}^{\circ}\mathrm{C}^{-1}$ and $6.4 \times 10^{-4}{}^{\circ}\mathrm{C}^{-1}$ to $6.8 \times 10^{-4}{}^{\circ}\mathrm{C}^{-1}$, respectively. If we were to take the lowest and the highest among these values to form a range, i.e., from $6.4 \times 10^{-4}{}^{\circ}\mathrm{C}^{-1}$ to $6.9 \times 10^{-4}{}^{\circ}\mathrm{C}^{-1}$ (as indicated by the two lines in Fig. 4), only about 62% and 43% of the calibration results would fall within the given range, for the aspirated psychrometer and whirling psychrometer, respectively. Lastly, the computed psychrometer coefficients of the whirling psychrometer seem to be higher than that of the aspirated psychrometer, as can be concluded from Fig. 4. This observation

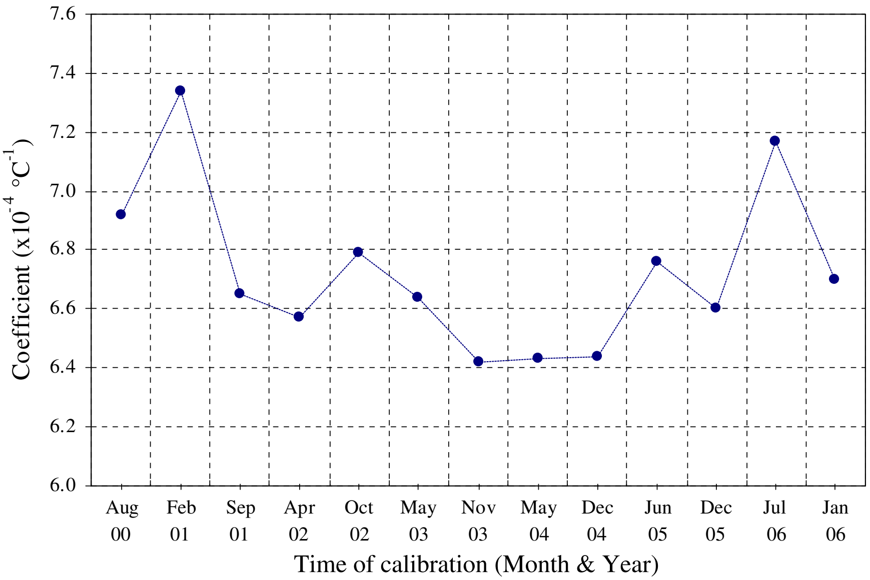

Fig. 3 Consistency of psychrometer coefficient of an aspirated psychrometer over a period of six years

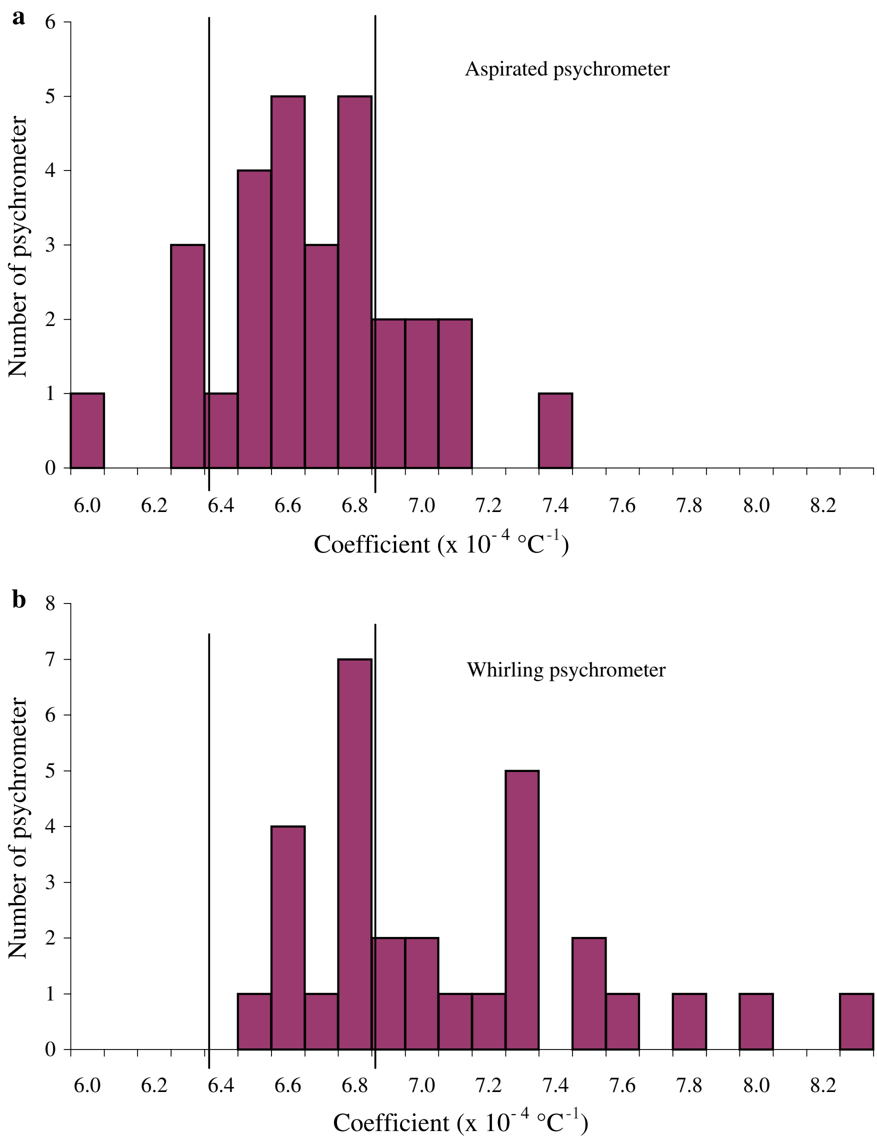

Fig. 4 Histogram of computed psychrometer coefficient

was also confirmed by averaging the psychrometer coefficients of all psychrometers of a given type, resulting in 7.15×10^{-4}°C^{-1} for the whirling psychrometers and 6.73×10^{-4}°C^{-1} for the aspirated psychrometers, with the former evidently slightly higher. However, the behaviors of the two types of psychrometer were very similar and there was no clear distinction between them. It was found that the computed

Table 2 Computed psychrometer coefficients under various relative humidity and temperature conditions ($\times 10^{-4}$°C^{-1})

	Nominal temperature (°C)			
Nominal RH (% rh)	15	23	30	40
30	6.44	6.48	6.44	6.90
55	7.19	6.59	6.58	6.91
75	7.77	6.86	7.30	7.10

average psychrometer coefficient for the aspirated psychrometers was quite close to the commonly used value of 6.66×10^{-4}°C^{-1} [7].

Based on the results and discussions above, it is clear that, although the psychrometer coefficient can be quite consistent for a specific psychrometer, there are variations in the psychrometer coefficient among different psychrometers even if they are of the same type. This implies that the psychrometer coefficient could be affected by the different physical characteristics of the psychrometers, such as thermometer size, radiant shield, air ventilation direction and speed, etc. [8]. The study of these effects will be included in future research of the laboratory.

So far, in our study, all the calibrations were performed at about 23°C and 55% rh. One might have concerns as to whether the computed psychrometer coefficient at 23°C and 55% rh would still be valid at other temperature and humidity conditions, and what kind of uncertainty could be expected if this coefficient were used under other environmental conditions. To address these concerns, a randomly chosen aspirated psychrometer was calibrated at various relative humidity and air temperatures using the same calibration method as described in Sect. 2. The results are presented in Table 2.

It can be seen that there were indeed some variations in the psychrometer coefficient under different temperature and relative humidity conditions. To verify the effect of these variations, the computed coefficient value at 23°C and 55% rh, i.e., 6.59×10^{-4}°C^{-1}, was used as the psychrometer coefficient and, together with the wet and dry bulb readings, the corresponding relative humidity at each test condition was calculated. The calculated relative humidity value was then compared with the relative humidity in the chamber, which was measured by the same dew-point meter as specified in Sect. 2. The differences of the two values were within the range from −1.6% rh to 1.0% rh, with the largest discrepancies happening at 15°C, 55% rh and 15°C, 75% rh. These discrepancies were at about the same level as the expanded uncertainty of the psychrometer coefficient, which was estimated to be equivalent to about 1.9% rh at a level of confidence of about 95% with $k = 2$. Therefore, the calibration of psychrometers at 23°C and 55% rh is sufficient for applications where the accuracy is not demanding.

Lastly, to evaluate the effect of the enhancement factor, the saturation vapor pressure used in the above calculation was corrected by the enhancement factor. The enhancement factor was calculated based on the Greenspan formulation [9] using coefficients updated to ITS-90 by R. Hardy [4]. The results of the study showed that the effect was less than ±0.1% rh equivalent under the various environmental conditions.

4 Conclusion

Calibrations of aspirated psychrometers and whirling psychrometers at 23°C and 55% rh over a period of 6 years were analyzed. Quite a large variation in the psychrometer coefficient was observed for both psychrometer types. On the other hand, the calibration results of a particular aspirated psychrometer showed good consistency over a 6-year period. The results imply that, while the psychrometer coefficient of a specific psychrometer may be consistent, there are variations among different psychrometers, even of the same type, and these variations are larger than indicated by the published data. It was also found that, although there was some difference between aspirated psychrometers and whirling psychrometers, there was no clear distinction between the two. The average of the computed psychrometer coefficients for aspirated psychrometers was found to be very close to the published and commonly used psychrometer coefficient. Therefore, the study confirmed that the published psychrometer coefficient is quite representative.

An aspirated psychrometer was tested at various temperature and humidity levels. The computed psychrometer coefficients varied at about the same level as the measurement uncertainty. Therefore, calibration at 23°C and 55% rh is sufficient for applications where the accuracy is not very demanding. Finally, the effect of the enhancement factor was evaluated and the results confirmed that the effect was not significant.

The purpose of this article is to indicate the performance of psychrometers available in the marketplace by analyzing data from routine calibrations. Due to such an opportunistic means of data collection, the calibration results may not represent the optimal performance that can be achieved under more carefully controlled conditions. As a matter of fact, the calibration uncertainties of these psychrometers are somewhat limited by the reference dew-point hygrometer used (as discussed in Sect. 3), so the uncertainty in the psychrometer coefficient is a bit too large to derive more detail from the data. For example, as discussed in Sect. 3, the large variations found among different psychrometers are likely due to the different physical characteristics of the psychrometers. But, with the current data, we are unable to reveal this information. Measurements with a more accurate humidity reference are planned so that more detailed effects can be studied. Lastly, in the present study, the psychrometer coefficient variations under moderately different temperature and humidity conditions were evaluated. Evaluation under extreme temperature and humidity conditions will be carried out in the near future.

References

1. Method for Measurement of Moist Air Properties, ASHRAE Standard (U.S.), *ANSI/ASHRAE 41.6-1994* (1994)
2. D. Sonntag, Zeitschrift für Meteorologie **40**, 340 (1990)
3. P.R. Wiederhold, *Water Vapor Measurement* (Marcel Dekker, Inc., 1997), ISBN 0-8247-9316-6
4. R. Hardy, in *Papers and Abstracts from the Third Int. Symp. on Humidity and Moisture*, vol. 1 (NPL, London, 1998), pp. 214–222
5. *Guide to the expression of uncertainty in measurement*, International Organization of Standardization (ISO, Geneva, 1993), ISBN 92-67-10188-9

6. I.C. Kemp, S. Bell, C.G. Berg, in *Papers from the 4th Int. Symp. on Humidity and Moisture* (CMS/ITRI, Taipei, 2002), pp. 198–205
7. A Guide to the Measurement of Humidity, *the Institute of Measurement and Control* (1996), ISBN 0-904457-24-9
8. A. Actis, A. Carotenuto, M. Dell'Isola, in *Papers and Abstracts from the Third Int. Symp. on Humidity and Moisture*, vol. 1 (NPL, London, 1998), pp. 262–270
9. L. Greenspan, J. Res. Natl. Bur. Stand. (U.S.) **80A**, 41 (1976)