Report 2

Humidity measurement and psychrometers in environmental testing equipment

Hirokazu Nakahama*

The use of psychrometers to measure humidity in environmental testing equipment is practically universal. No other thermometers are available that can stand up as well to the severe usage conditions of environmental testing equipment. While some features need to be improved, the construction of the psychrometers is simpler and more reliable than any other type of humidity sensor. Because of this, we discuss features of psychrometers such as construction, working principles, precision, factors of error, reliability, and points for caution in use. We also mention various related standards. Finally, we also examine functions required for humidity measurement in environmental equipment and future trends.

1. Introduction

Temperature and humidity equipment is used quite commonly in environmental testing equipment. Temperature and humidity are combined as environmental conditions used in testing, and many types of equipment, such as the Temperature/Humidity Cycle Testing Chamber and the Stability Testing Chamber, are geared to this type of test application.

Methods for measuring temperature are comparatively easy to understand, but humidity is unexpectedly troublesome. Humidity fluctuates according to temperature and pressure, and must be considered in conjunction with those phenomena.

Because of this, we would like to examine humidity measurement methods, and psychrometers in particular, used in environmental testing equipment.

2. Indicating performance in environmental testing equipment

2-1. Standards for environmental testing equipment

Within environmental testing equipment, performance standards (JTM standards) for Temperature and Humidity Chambers and Temperature and Humidity Rooms are set independently by the industry group the Japan Testing Machinery Association (JTMA).1), 2)

To enact JTM standards, the JTMA has performed a broad range of investigative research.3), 4), 5) Within this research, in cooperation with the Electrotechnical Laboratory of the Agency of Industrial Science and Technology, experiments were performed on thermometers used to evaluate chamber performance. Foreign standards were also consulted, BS in particular.6), 7), 8) These BS standards have now been abolished. Moreover, to adopt developments in the latest peripheral technology, JTM K-01 was revised in 1998 based on international investigations.9), 10) These revisions included changing the title.

The purpose of JTM standards is not to standardize the test equipment, but rather to provide a reasonable basis for consultations between equipment manufacturers and users and to provide a fair basis for evaluating test results. The main items are concerned with methods of indicating and evaluating performance in relation to temperature and humidity fluctuation and temperature and humidity uniformity. Fig. 1 shows a thermometer for evaluating the chamber performance adopted in JTM standards. The JTM standards do not establish any specifics concerning the construction of thermometers for evaluating chamber performance. Rather, they establish the use of the psychrometer and the psychrometric formula and the wind speed when using the psychrometer.

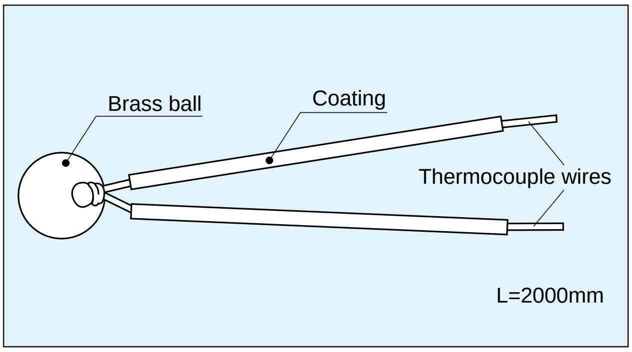

Fig. 1 Thermometer for evaluating equipment performance, JTM K-01, 03

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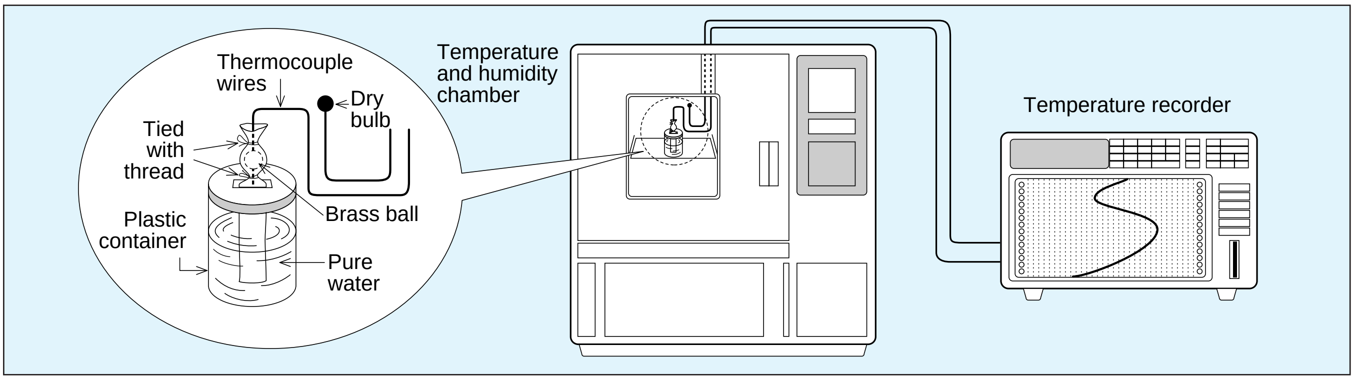


Fig. 2 Measuring temperature and humidity to evaluate equipment performance

Fig. 2 shows an outline of the humidity measurement for the evaluation method used at Tabai Espec. A plastic container (such as an empty 35 mm film canister) is used as a water pot, and a sleeve cloth (called a wick) is put over a thermocouple (type T) to detect wet-bulb temperature. To improve adherence between the wick and the thermocouple and the time constant adjustment, a 5 mm diameter brass ball is soldered to the temperature measuring junction of the thermocouple (type T). Therefore, as a thermometer, this device is the same as the one shown in Fig.1.

Equipment is nothing more than a means to attain functions and environmental conditions required for environmental testing, so each manufacturer should be continually adding improvements to the equipment design constant and the equipment construction depending on the users' requirements.

2-2 Performance indication of temperature and humidity

The temperature and humidity performance items specified in the catalogs and specifications differ depending on the type of equipment. The main items include temperature and humidity control range, temperature and humidity fluctuation, temperature and humidity uniformity, and the temperature heat-up/pull-down rate. These definitions and measurement conditions are established in the JTM standards.

The fluctuation and uniformity performance of temperature and humidity shows performance in a stable condition. The area of equipment performance in which a disparity tends to occur is performance in transitional conditions. This includes such matters as the smallness of the amount of overshooting and undershooting when attaining temperature and humidity settings, and the smallness of the disparity from the setting gradient when operating in ramp mode. Stability of performance is also crucial when defrosting refrigeration circuits and in poor surrounding conditions. Manufacturers are constantly striving for quality in dynamically controlled performance in these areas. However, these are not normally written in the specifications. It is difficult to specify them as standard performance items, and there seems to be no good means of displaying them as performance data.

2-3 Hygrometers and the range of temperature and humidity

One of the main products in the Tabai Espec line-up is the line of temperature and humidity chambers called the Platinous Series, which has achieved sales of approximately 30,000 units since being put on the market in 1969. Fig. 3 shows the basic construction, and Fig.4 shows an example (for PDR and PDL) of the temperature and humidity control range.

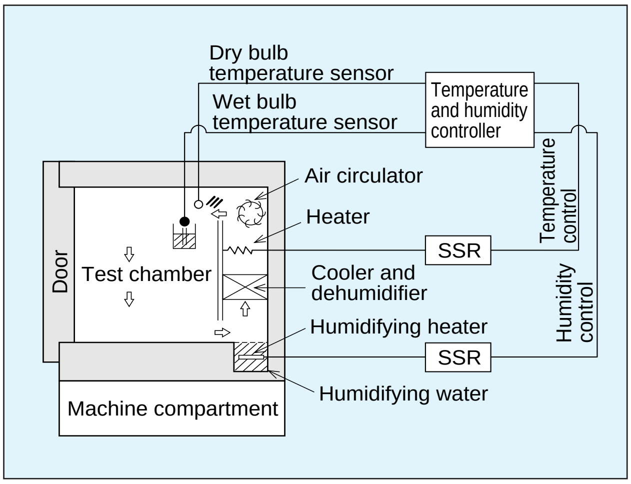
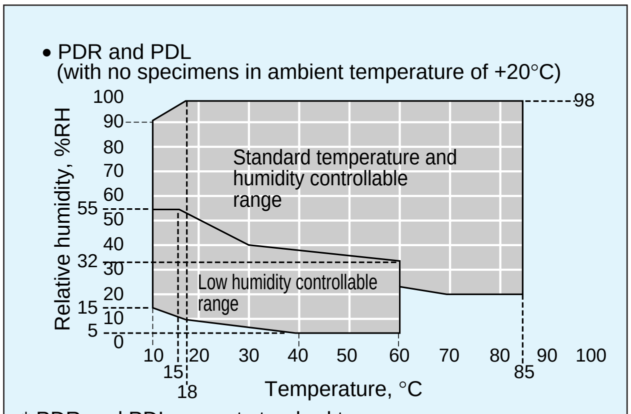


Fig. 3 One type of temperature and humidity chamber



* PDR and PDL are not standard types.
They are low humidity types.

Fig. 4 Example of the temperature and humidity control range in temperature and humidity chambers

The range in which temperature and humidity can be controlled simultaneously is from 10°C at 15% RH to 85°C at 98% RH. The range of operation for temperature alone depends on the machine type, but in general extends from –70°C to +150°C. Therefore, in psychrometers for measurement control, wet- and dry-bulb thermometers and hygrometers have been used from the outset. Even today, a better means of measuring temperature and humidity has still not been devised.

Some companies, foreign companies in particular, are using lithium chloride dew-point hygrometers and chilled mirror dew-point hygrometers for measurement control.[9), 10)]

Also, so-called electronic humidity sensors can be used if the temperature and humidity conditions and the usage atmosphere are limited, but the writers of this report do not believe that such devices provide a requisite level of reliability to make it possible to mount them as standard equipment on the Platinous Series. For example, even at normal temperature and humidity the humidity sensor could fail due to the effect of volatile matter unexpectedly coming from the specimen, so this presents a major risk for use as standard equipment.

Actually, a humidity sensor can be mounted as an option in the walk-in type H-Series temperature and humidity chambers, because the humidity sensor is easier to use for control in the low-temperature and low-humidity region of 5°C and 5 percent relative humidity. Also, in the environmental chamber used for analyzing the physiology and ecology of the human body, use of a humidity sensor is now standard. Even in the temperature and humidity chamber, the conditions of user applications must be fully considered for selecting optional mounting technology.

Next, let’s look at psychrometers.

3. The psychrometer as a weather gauge

3-1 Construction of the psychrometer

The psychrometer has been used for over 100 years as a weather gauge. The Assmann psychrometer, designed in 1887 by R. Assmann, is a typical psychrometer. Fig. 5 shows an external diagram of this type of psychrometer.

Two identical glass thermometers are placed inside a metal ventilation tube that protects from surrounding radiation, and a fan is used to circulate the surrounding air over the thermometers. A gauze wick covers the temperature-sensing area of one thermometer, and this wick is dampened with water for taking measurements. The thermometer covered with the wick is called a wet-bulb thermometer, and its temperature-sensing area is called a wet bulb. The other thermometer is a dry-bulb thermometer, and its temperature-sensing area is called a dry bulb.

Even today the basic construction of this type of psychrometer has not changed, with only the spring-wound ventilation fan having been changed to a motor-driven type. Depending on the type of equipment, a wick and water pot are devised that can be used for electrical output from the thermometer.

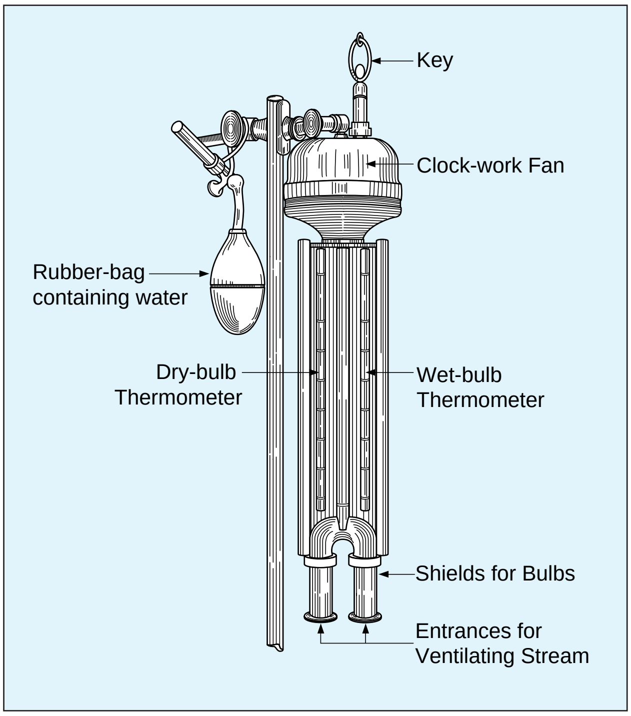


Fig. 5 Assmann psychrometer

3-2 Principle of the psychrometer

In the psychrometer, moisture evaporates from the wet bulb in response to the dryness of the surrounding air and the temperature displayed on the wet-bulb thermometer drops and reaches the equilibrium temperature, which is the temperature displayed on the wet-bulb thermometer. The corresponding air temperature is called the dry-bulb temperature.

According to the boundary-layer theory, evaporation from the water surface can be shown approximately with the following formula. When this is applied to the evaporation of water in the wet bulb, it becomes:

$$Ga = Dp\,(e_{sw} - e)\,/\delta \qquad (1)$$

Where:

Ga = the flow mass per unit of surface area of evaporating water vapor,

Dp = the pressure-base diffusion constant,

e_{sw} = water vapor pressure in contact with the surface of the water (i.e., saturation water vapor pressure in wet bulb temperature),

e = water vapor pressure in areas well away from the surface of the water (i.e., water vapor pressure in the desired atmosphere), and

δ = the thickness of the boundary layer.

The value of δ, the thickness of the boundary layer, varies according to wind speed. Therefore, the formula for ϕ, the quantity of heat cooled by water evaporation, is as follows.

$$\phi = Ga \cdot L_H \qquad (2)$$

Where:

ϕ = the quantity of heat cooled by water evaporation,

Ga = flow mass per unit of surface area of evaporating water vapor, and

L_H = evaporation latent heat of the water

The quantity of heat cooled by this evaporation matches the quantity of heat transmitted to the wet bulb from the surrounding area, providing balance. Items such as the following can be given as sources of the quantity of heat transmitted from the surrounding area.

- Heat transmitted from the air
- Radiated heat
- Heat transmitted from the thermometer
- Heat transmitted from the supply water

We have presented above a very approximate outline. For a detail theoretical analysis of the psychrometer, please refer to the books and literature in the references. 13), 14), 15)

3-3 Formulas for psychrometers

The psychrometer does not give humidity as an absolute value, but rather gives the wet- and dry-bulb temperatures from which wet- and dry-bulb formulas can be used to find the partial water vapor pressure in the air.

The following Sprung formula is very widely used as a formula for psychrometers. Sprung came up with it in 1888 using the Assmann psychrometer.[16)]

$f = f' - A\,(t - t')\,b/755$ (3)

Where:
t = dry-bulb temperature
t' = wet-bulb temperature
f = water vapor pressure in the air to be obtained
f' = saturated water vapor pressure in wet-bulb temperature t'
b = atmospheric pressure
A = the psychrometer constant

Sprung used the following two values of standard humidity to perform experiments to determine constant A.

[1] Dew point found using an ether-cooled dew-point gauge
[2] Gravimetric method causing absorption of water vapor in a U-shaped tube filled with phosphates

Table 1 shows the results of those experiments

Table 1 Results of Sprung's experiment

*	*	b	t	t'	f'	f		f'—f		t—t'	A	
						durch Absorp.	*durch Taup.*	*durch Absorp.*	*durch Taup.*		*durch Absorp.*	*durch Taup.*
		mm	°C.	°C.	mm	mm	mm	mm	mm	°C.	mm	mm
1887	27. XI	757	16.6	11.0	9.7		6.6		3.1	5.6		0.55
	28. XI	760	21.1	12.9	11.1		6.8		4.3	8.2		0.52
	bo.	760	21.2	12.9	11.1		7.3		3.8	8.3		0.46
	1. XII	764	21.3	12.5	10.8		6.7		4.1	8.8		0.46
1888	11. II	748	18.9	11.9	10.4	6.8	6.5	3.6	3.9	7.0	0.52	0.56
	18. II	746	8.6	6.2	7.1		5.7		1.4	2.6		0.54
	21. II	754	8.3	5.3	6.6	5.2	5.0	1.4	1.6	3.0	0.47	0.53
	25. II	762	7.6	4.6	6.3	4.9	4.8	1.4	1.5	3.0	0.47	0.50
	29. II	767	7.5	4.0	6.1	4.3	4.4	1.8	1.7	3.5	0.51	0.48
	6. III	757	16.3	8.6	8.3	4.3	4.5	4.0	3.8	7.7	0.52	0.49
										Mittel:	0.498	0.509

*Date of experiment

Measurements were made 10 times using the dew-point method in [1] and five times using the gravimetric method in [2]. A varied from 0.46 to 0.56. A = 0.5 was used as an average.

At JIS, Sprung's formula was transcribed in the following way, and is used as a standard.

$e = e_{sw} - A \cdot p\,(t - t_w)$ (4)

Where:
A = 0.000662 (when the wet bulb is not frozen)
A = 0.000583 (when the wet bulb is frozen)

The symbols in formula (3) can be replaced with $f = e$, $f' = e_{sw}$, $b = p$, and $t' = t_w$. A becomes 0.5/755 = 0.000662, and is the same number. Nothing is written in the reference literature[16)] about when the wet bulb is frozen.

Saturated water vapor pressure e_s, at dry bulb temperature t, is found using the formula (or table) for saturated water vapor pressure.

The formula for relative humidity U (%) is thus:

$U = (e/e_s) \times 100$ (5)

A number of formulas besides the Sprung formula are used as formulas for psychrometers, which is explained in the JIS[17)] commentary. All formulas used are based on the fundamental characteristic of having the temperature differential between the wet- and dry-bulb temperatures $(t - t_w)$ proportional to the water vapor pressure differential $(e_{sw} - e)$. Also, the psychrometer theoretically is affected by the wind speed. The Assmann psychrometer requires a wind speed of from 2 to 5 meters per second.

4. The psychrometer in environmental testing equipment

4-1 The structure of the psychrometer

The basic structure of environmental testing equipment (the temperature and humidity chamber), as shown in Fig. 3, consists of an arrangement for regulating the temperature and humidity of air, which is then circulated from the air-conditioner to a hermetically sealed, comparatively narrow test area. Most wet- and dry-bulb thermometers are mounted near the port for the air to enter the chamber from the air conditioner. Feedback control is employed to maintain the temperature and humidity settings inside the chamber.

Because of this, ventilation tubes, such as those on the Assmann psychrometers, are not used. There are many types of environmental testing equipment, so the structure of the psychrometer will depend on the manufacturer, and will even be different on different types of equipment built by the same manufacturer. Differences are particularly seen in wind direction, wick shape, and supply water mechanisms, and even intellectual property rights may be involved. Fig.6 shows typical constructions that are presented in JIS[17)] commentary. Of the three examples shown in Fig. 6, the one on the left corresponds to one type of construction used at Tabai Espec. The examples in the center and on the right are used by other companies.

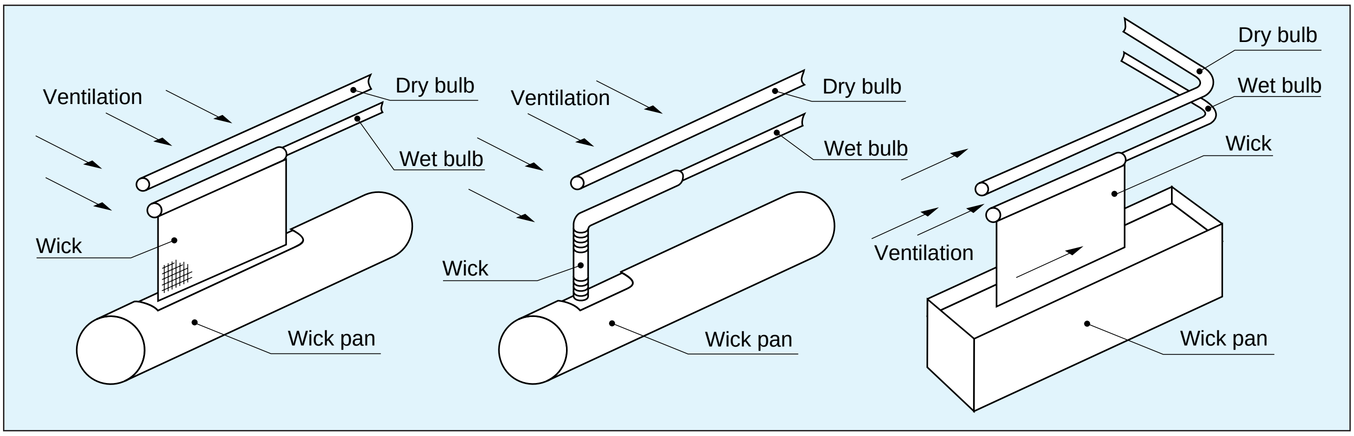


Fig. 6 Typical psychrometers used in environmental testing equipment

4-2 Formulas for psychrometers

When the wind speed is at least 2.5 m/s, the JTM standards use the Sprung formula as the formula for the psychrometer used to evaluate performance of the temperature and humidity chamber. When a wind speed of at least 2.5 m/s cannot be maintained, the Pernter formula is used. The Pernter formula and its constants are as follows.

$$e = e_{sw} - a \cdot p\,(t - t_w)\,(1 + t_w/b) \qquad (6)$$

Table 2 Pernter formula constants

Wind speed around the wet bulb	When the wet bulb is not frozen		When the wet bulb is frozen	
	a	b	a	b
0 – 0.5	0.0012	610	0.00106	689
1.0 – 1.5	0.0008	610	0.000706	689
Min.2.5	0.000656	610	0.000579	689

The JTM standards do not prescribe anything about the psychrometer used to measure and control the equipment. In actual practice, the Sprung formula and the Pernter formula are used without modification for the psychrometers used in the equipment.

The JIS[17)] commentary concerning the psychrometers used for the equipment states, "Formulas for psychrometers suited to the conditions of usage and to specifications such as the relationship between the wind speed and the direction of the wind current vis-a-vis the wet bulb must be scrutinized and clarified." Strictly speaking, the optimum formula exists for the specific construction of the psychrometer.

However, the authors of this report believe that in environmental testing equipment, scrutinizing the formula itself in regard to usage conditions is not very practical. The four major reasons are as follows.

(1) In environmental testing equipment, many different types of equipment construction are used depending on the aims and applications of the test, and the construction of the psychrometer mounted on the equipment will vary. Scrutinizing the formula for psychrometers itself in regard to usage conditions for each machine type is not practical. It would be better to unify the formulas in one all-purpose formula.

(2) With ventilated psychrometers, even in the widely-used Sprung formula the value of the constant A is not uniform in the standards of all countries. In the ISO[18)] and the ANSI/ASHRAE[19)] the value is 6.5 to 6.9×10^{-4}, while in ASTM[20)], the value is 6.2 to 6.9×10^{-4}.

(3) The life of the wick is crucial to the performance of the psychrometer mounted on environmental testing equipment. Required environmental testing cannot be carried out with a wick that has a short life, so both life and precision must be considered in the construction.

(4) Important points for gauges include resistance to being affected by error-producing factors, minimal dispersion, and ability to maintain stable measurement. Furthermore, since the measurement values are used to control the equipment, performance in controlling the equipment and responsiveness must be considered together.

5. Error-producing factors in humidity measurement

5-1 Saturated water vapor pressure

Various units and indication methods are used for humidity, and they must be converted. The basis for calculating humidity is the saturated water vapor pressure formula (or the table). The JTM standards refer to JIS[17)]. The formula used is the Sonntag formula, based on the International Temperature Scale-90. Before the revised edition (JTM K $01^{-1985,\ 1991}$), the Goff-Gratch formula was followed according to the pre-revision JIS[21)].

Fig. 7 shows a saturated water vapor pressure line and constant relative humidity line.

Vapor pressure increases exponentially in response to temperature. Therefore, temperature measurement errors in the high and low temperature regions will cause large errors in humidity measurement. Also, even at any one temperature, the size of the error will differ in high and low humidity regions. The following section, 5-2, shows specific values.

Looking at the psychrometric chart, always given in air conditioning handbooks, gives a good understanding of the matter.

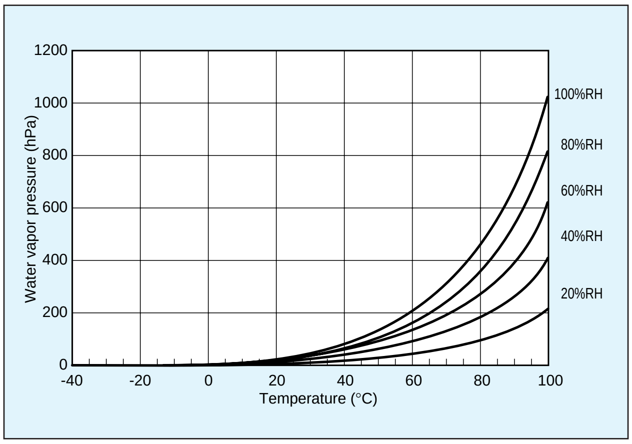


Fig. 7 Constant relative humidity line graph and water vapor pressure

5-2 Temperature

The psychrometer can theoretically provide accurate humidity levels if the wet- and dry-bulb temperature differential ($t - t_w$) is accurate. Even a 0.1°C error in the same direction in both dry-bulb temperature t and wet-bulb temperature t_w, will have little effect on the relative humidity. Table 3 shows the effect of errors in measuring the wet- and dry-bulb temperature differential.

Table 3 Level of relative humidity error due to errors in the wet- and dry-bulb temperature differential

■ 85°C 85%RH

Units: %RH

		Dry bulb temperature t (°C)		
		84.9	85.0	85.1
Wet bulb temperature t_w (°C)	81.1	85.6	85.2	84.9
	81.0	85.2	84.9	84.5
	80.9	84.9	84.5	84.2

■ 10°C 95%RH

Units: %RH

		Dry bulb temperature t (°C)		
		9.9	10.0	10.1
Wet bulb temperature t_w (°C)	9.7	97.6	96.4	95.2
	9.6	96.4	95.2	94.0
	9.5	95.1	94.0	92.8

■ 10°C 5%RH

Units: %RH

		Dry bulb temperature t (°C)		
		9.9	10.0	10.1
Wet bulb temperature t_w (°C)	1.2	6.7	6.2	5.6
	1.1	5.8	5.2	4.6
	1.0	4.9	4.3	3.7

Because of this, with the psychrometer, rather than independently measuring the dry bulb temperature and the wet bulb temperature and accumulating error dispersion for each temperature measurement, it would be better to measure accurately the differential between the dry bulb temperature and the wet- and dry-bulb temperature.

5-3 Atmospheric pressure

As seen in formula (4) and formula (6), the formulas for the psychrometer include the atmospheric pressure. The impact on relative humidity can be ignored if the variation is in the range of 1 to 2 percent from standard atmospheric pressure. However, when the variation reaches 3 percent, the differential in the low-temperature, low-humidity region cannot be ignored. Table 4 shows an example of calculating relative humidity at the standard atmospheric pressure of 1013hPa, and at the low atmospheric pressure of 980hPa. Normally, when atmospheric pressure is given as meteorological information it has first undergone sea-level correction (e.g., reference[22]), so the value must be thought of as the atmospheric pressure for the altitude of that location.

Table 4 Variations in relative humidity due to variations in atmospheric pressure

Units: %RH

Dry bulb temperature t (°C)	**Wet bulb temperature t_w (°C)**	**Standard atmospheric pressure 1013hPa**	**Low atmospheric pressure 980hPa**
10.0	9.6	95.2	95.2
	5.6	50.0	50.8
	1.1	5.2	6.8
30.0	29.3	94.9	95.0
	22.1	50.2	50.6
	12.1	4.9	5.9
50.0	49.1	95.1	95.1
	38.8	50.0	50.2
	21.3	4.9	5.4

5-4 Wind speed

The psychrometer is theoretically influenced by wind speed. Experiments[23] have shown the dependence of wind speed in the psychrometer constant A in Sprung's formula. According to the experiments:

$$A = 9.90 \times 10^{-4} \left(\frac{1 + 0.69\sqrt{V}}{1 + 1.35\sqrt{V}} \right) \qquad (7)$$

V: wind speed (m/s)

When V = 1.5 (m/s), $A = 6.9 \times 10^{-4}$. When V = 2.5, $A = 6.6 \times 10^{-4}$. When V = 5.5, $A = 6.2 \times 10^{-4}$. The JIS[17] commentary presents detailed calculations of the differences in relative humidity due to differences in constant A. In the low-temperature, low-humidity regions, the difference is greater than ±1 percent relative humidity.

Pernter's formula conveniently can be used even at low wind speed, but at 0 to 0.5 m/s, it becomes the same as the simple unventilated psychrometer, and precision suffers. Therefore, JTM K 01:^{1998} states that when using the psychrometer at low wind speed, calibration is desirable according to a higher level humidity gauge. A higher level humidity gauge corresponds to a traceability system, based on the Japanese measurement law. Specifically, this means a chilled mirror surface dew-point hygrometer with an automatic equilibrium function built in.

As seen in Fig. 3, most psychrometers for measurement control in environmental testing equipment are installed near the port where the wind enters the chamber from the air conditioning unit, and a minimum 2.5 m/s wind speed is maintained. Therefore, when desiring to lower the wind speed so that the wind doesn't hit the specimens, special countermeasures must be taken such as using a chamber within specially designed precision, or the wind may be directed at the entire surface of the ceiling of the temperature and humidity chamber.

5-5 Wet bulb water and wick

The purity of the water supplied to the wet bulb is a vital factor. Tap water or other impure water causes measurement error of the wet bulb temperature, and impurities in the wick shorten the promoted life[24]. Also, the life of the wick varies according to the temperature and humidity region of use. At Tabai Espec, we encourage the use of pure water with maximum conductivity of 10μ S/cm. As a rule of thumb, the wick should be changed once a month.

The wick covering the wet-bulb thermometer should be of a length that isn't affected by heat conducted from the thermometer, and requires a certain amount of length. The shape of the wick and the materials used are known to be intimately related to the life of the wick. At Tabai Espec, other than the long (flag-shaped) wick shown in Fig.6, we also use a long wick with three sides of a square cut into it (the left side not cut). This wick shape is called a self-cleaning wick, and the water that is wicked up very gradually naturally flows away. Because the water is constantly flowing, impurities do not tend to accumulate, and the wick has a particularly good life in high-temperature, low-humidity regions with a large amount of moisture evaporation[25].

6. In conclusion

As hygrometers for environmental testing equipment, electronic humidity sensors and other types of humidity gauges are not likely to completely replace psychrometers any time soon. The psychrometer combines simple construction and high reliability. However, at low-temperature, low-humidity regions, precision is theoretically lower, so some equipment types have humidity sensors installed. In some cases, equipment performance indication is classified as being different in low-temperature, low-humidity regions. The psychrometer still has a lot of room for improvement in wick life and in maintenance, but the question of whether it will be replaced by another type of hygrometer depends on the combination of cost, precision, and reliability.

In the final analysis, equipment performance will be evaluated by the user who is actually performing the environmental testing. At Tabai Espec, we are doing everything in our power to provide products that meet user needs.

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