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Relative humidity measurement for fire danger rating in Canada

M.D. Flannigan and P.J. Litwin

Information Report PI-X-93
Petawawa National Forestry Institute

PETAWAWA NATIONAL FORESTRY INSTITUTE

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RELATIVE HUMIDITY MEASUREMENT FOR FIRE DANGER RATING IN CANADA

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Information Report PI-X-93
Petawawa National Forestry Institute
Forestry Canada
Chalk River, Ontario
1989

Catalogue No. Fo46-11/93-1989E
ISBN 0-662-17216-7
ISSN 0706-1854
Printed in Canada

Copies of this publication may be obtained free of charge from the following address:

Forestry Canada
Publications Distribution Centre
Petawawa National Forestry Institute
Chalk River, Ontario
K0J 1J0

Telephone: 613-589-2880

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Mesures de l'humidité relative pour l'évaluation des risques d'incendie

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Abstract

Wet and dry bulb temperatures from ventilated and non-ventilated screens can be used to obtain realistic values of relative humidity provided the appropriate psychometric coefficient is used. However, relative humidity from non-ventilated screens are subject to significant error when the weather is sunny or calm.

Our investigations revealed that thermohygrometers are poor for field measurement of RH whereas the PCRC-11 sensor and Vaisala humicap performed well.

There is a need for a sensitivity study of the Fire Weather Index with respect to relative humidity. We would also suggest the relative humidity lookup table be replaced by the Goff-Gratch equation. Finally, alternatives like using dewpoint temperature to obtain relative humidity or automating the system should be investigated.

Résumé

Les températures des thermomètres secs et mouillés, installés dans des abris ventilés et non ventilés, peuvent servir à obtenir des valeurs réalistes de l'humidité relative à condition que le coefficient psychrométrique indiqué soit utilisé. Toutefois, les valeurs obtenues dans le cas des abris non ventilés peuvent être considérablement erronées lorsque le temps est ensoleillé ou calme.

Nos recherches ont permis de constater que, pour mesurer l'humidité relative sur le terrain, les thermohygromètres ne donnaient pas de bons résultats, au contraire du bon fonctionnement du détecteur PCRC-11 et du dispositif Vaisala.

Il faudrait effectuer une étude sur la sensibilité de l'indice forêt-météo en ce qui concerne l'humidité relative. Nous proposons également de remplacer le tables des valeurs de l'humidité relative par l'équation Goff-Gratch. Enfin, d'autres solutions devraient être étudiées comme l'application de la température du point de rosée pour obtenir l'humidité relative ou bien l'automatisation du système.

Introduction

Relative humidity is one of many variables used to describe the amount of moisture in the atmosphere. Relative humidity (RH) is the ratio expressed as a percentage of the partial pressure (e) of water vapour in the air to the saturation pressure $e_s(T)$ of water vapour for a particular air temperature (T).

$$RH = \frac{e}{e_s(T)} \times 100 \qquad [1]$$

Relative humidity along with temperature, wind speed, and 24-h precipitation are the inputs for the Canadian Forest Fire Weather Index* (FWI) System (Canadian Forestry Service 1984, Van Wagner and Pickett 1985, Van Wagner 1987). The FWI is in use across Canada and, as a result, most provinces have established a network of meteorological stations to collect data. The instruments measuring these variables are not standardized across the country, particularly so in the case of RH.

Traditionally, RH was calculated by measuring the wet- and dry-bulb temperatures** inside a Stevenson screen. Some provincial fire control agencies use non-ventilated screens to calculate RH instead of ventilated screens. The initial impetus for this investigation was to compare RHs calculated within ventilated and non-ventilated screens. The study was eventually broadened to compare various instruments and procedures that are in common use by Canadian fire control agencies to measure or calculate RH.

Method

The study was conducted at the Petawawa National Forestry Institute (46°01'N, 75°27'W) within a forest clearing called Branstead Field. The cleared area is about 3 ha, has a gentle slope and 30° aspect, and is surrounded by trees up to 25 m in height. This clearing does not meet specifications laid down by the World Meteorological Organization (WMO) (1968) for a forest meteorological station. WMO guidelines are for clearings to have diameters of at least 10 times the surrounding tree heights. However, the authors feel that the clearing is of sufficient size to obtain representative values of RH.

Two Stevenson screens were placed in Branstead Field, one ventilated (Figure 1) with an electric fan and the other not ventilated (Figure 2). Inside both screens were wet and dry bulb mercury thermometers. Also within both screens were thermistors connected to a Campbell Scientific CR21 datalogger. A portable Vaisala humicap HMI31 measured temperature and RH in both screens. The Vaisala humicap is a capacitive polymer sensor and operates under the principle that the capacitance of the solid polymer changes with adsorbed moisture (RH). In the ventilated screen there was a thermohygrometer made by Enercorp. The thermohygrometer operates on the principle that human hair stretches and shrinks according to RH. The change in length is indicated by the deflection of the needle. In the non-ventilated screen there were two thermohygrometers and a RH and temperature sensor (Campbell Scientific model 201 PCRC-11). The PCRC-11 is an electrolyte impedance sensor using the principle that the impedance of the liquid electrolyte or processed plastic wafer changes with adsorbed moisture (RH). For the thermohygrometer and humid ap RH was read directly off the instrument and for the PCRC-11 it was off the datalogger.

Other sensors used in the study included a Kipp and Zonen CM5 Moll-Gorczynski type pyranometer, and two R.M. Young, Model 1202 Gill 3-cup anemometers, one at 10 m and the other at screen height (1.5 m). A wind vane (R.M. Young, Gill Microvane, model 12305) was also placed at 10 m above ground. All the above sensors were connected to the CR21 datalogger. Solar insolation and wind speed were measured to see how they might impact the measurement of RH by the non-ventilated screen. The size of clearing would affect wind speed and direction at 10 m; indeed, the authors have observed swirling winds at Branstead Field.

All instruments had been factory calibrated. We checked the calibration of every unit prior to the study, beginning in early May. The RH sensors were checked in chemical solution chambers

*The FWI is comprised of three moisture codes and two intermediate indexes. The three moisture codes represent the moisture content of fine fuels (Fine Fuel Moisture Code, FFMC), loosely compacted decomposing organic matter (Duff Moisture Code, DMC), and the deep layer of compact organic matter (Drought Code, DC). The two intermediate indexes, which are derived from the moisture codes and the surface wind, indicate the rate of initial fire spread (Initial Spread Index, ISI) and total available fuel (Build Up Index, BUI). The two intermediate indices are combined to obtain the FWI which represents the intensity of the spreading fire.

**The wet bulb temperature is the lowest temperature to which the air is cooled by evaporating water at a constant atmospheric pressure. The wet bulb temperature is obtained by covering the temperature sensor with a moist jacket of clean muslin and then ventilating it by means of a fan or sling.

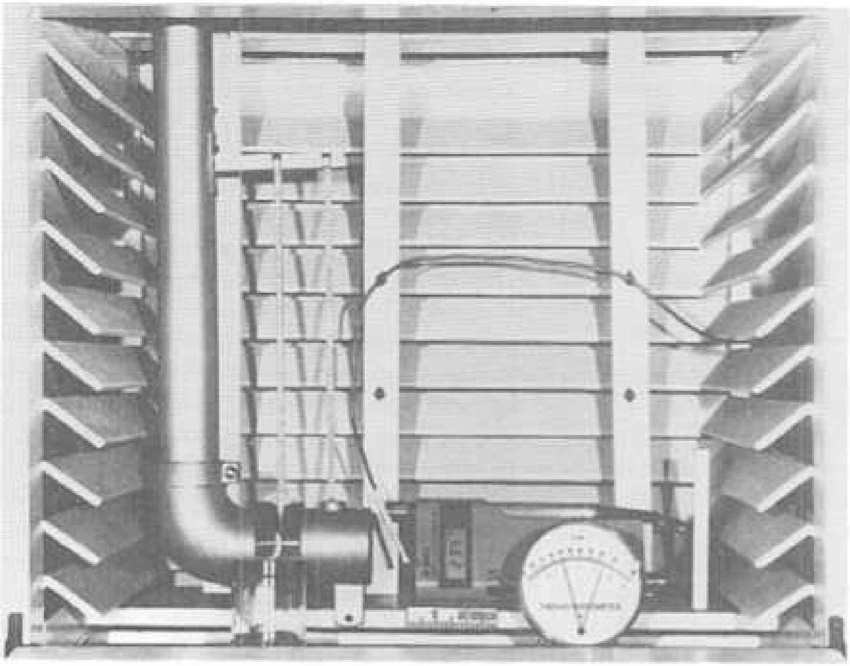

Figure 1. The instruments used in this study within the ventilated screen.

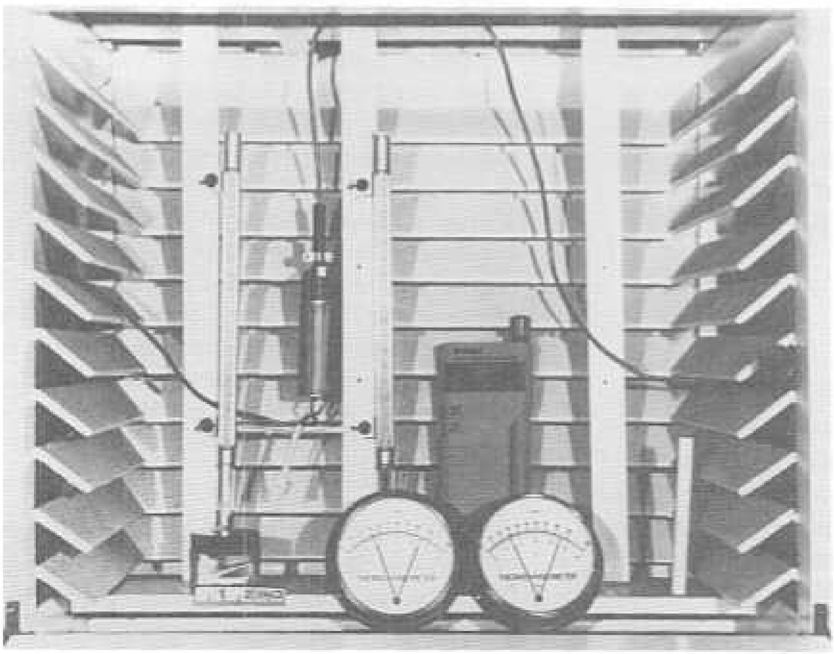

Figure 2. Instruments used within the non-ventilated screen.

using LiCl at 25°C, which yields 12% RH, and K_2SO_4 at 25°C, which yields 96.9% RH.

Observations were made at 0800, 1000, 1200, and 1400 EST every Monday through Friday starting May 2, 1988 and ending on September 13, 1988 for the wet and dry bulb temperatures and the RHs. The CR21 datalogger stored 10 min averages of temperature, RH (PCRC-11), solar insolation, wind speeds, and direction from 1 min. samples. We used the observational procedures established by the WMO (1983) for measurement of RH. A total of 242 observations were made during the course of the study. The study period corresponds roughly to the forest fire season in most of Canada. The RH was either read off directly from a sensor or calculated from wet and dry bulb observations.

The calculation of RH from observing the wet and dry bulb temperature is done by substituting the Regnault equation

$$e = e_S(T_W) - Ap\,(T - T_W) \qquad [2]$$

into equation [1] where e is the vapour pressure, $e_S(T_W)$ the saturation vapour pressure at the wet bulb temperature (°K), T the dry bulb temperature, T_W the wet bulb temperature, p is atmospheric pressure, and A the psychrometer coefficient.

The calculation of the saturation vapour pressure (e_S) is the most difficult aspect of this equation. The saturation vapour pressure is related to temperature by integrating the Clausius-Clapeyron equation

$$\frac{1}{e_S}\frac{de_S}{dt} = \frac{\varepsilon L}{RT^2} \qquad [3]$$

where L is the latent heat of vaporization of water, R the gas constant for dry air, and ε is the ratio of the molecular weight of water vapour to that of dry air. The integration of equation 3 is complicated by departures from the ideal gas law and by the fact that L, the latent heat, varies with temperature. Empirical formulas were developed by Goff and Gratch (1945) and Goff (1965) to calculate e_S. The calculation has been refined by Wexler (1976, 1977) and Hyland (1985). A number of researchers have developed simpler equations to calculate e_S (eg. Blackadar 1983, Fan and Whiting 1987, Magnus 1844, Revfeim and Jordan 1976, Tabata 1973). However, we chose not to examine these simpler equations for the following reasons:

(i) the simpler equations are not quite as accurate as the more complex formula, and

(ii) Abbott and Tabony (1985) have already examined a number of these simpler equations.

Fire control agencies in Canada use psychrometric tables produced in 1976 by Canada's Atmospheric Environment Service. These tables are based on the Goff-Gratch equations. We did not use tables in our study but employed the equations as outlined in Appendix 1. However, we did apply values for the psychrometric coefficient used for the tables, namely 6.4309×10^{-4} $(°K)^{-1}$ for a ventilated screen and 7.7170×10^{-4} $(°K)^{-1}$ for a non-ventilated screen. We caution the reader that these values are subject to change, as research still continues on the value of the psychrometric coefficient (Fan 1987; Wylie and Lalas 1981). But it should be noted that the impact of a revised psychrometric coefficient in the calculation of RH would be minimal from an operational perspective.

Results

The RH, as can be seen in Appendix 1, is strongly influenced by temperature and to a lesser extent by atmospheric pressure. Atmospheric pressure was not measured at our Branstead Field site but both screens were subjected to the same pressure. The pressure was set to 1000 mb in the Regnault equation, which introduced some error (less than 1%). The temperature of both screens was closely monitored. In the non-ventilated screen temperatures were significantly higher than within the ventilated screen. The ambient (dry bulb) temperature was an average of 0.2°C warmer in the non-ventilated screen compared with the ventilated screen. The wet-bulb temperature was an average of ~0.6°C warmer within the non-ventilated screen. These differences are statistically significant at the 1% level ($p \leq .01$) using a t test. The net effect of the higher dry and wet bulb temperatures was to obtain a higher RH in the non-ventilated screen if the incorrect psychrometer coefficient (6.4309×10^{-4}) was used (Figure 3). We include this graph because a number of stations across Canada have occasionally used the incorrect psychrometric coefficient. When the proper coefficient ($A = 7.7170 \times 10^{-4}$) is used for the non-ventilated case there is a very good agreement between the two RHs (Figure 4).

Using the RH calculated by the wet and dry bulb readings in the ventilated screen as a standard we plotted the performance of all the other instruments. Figures 5-7 show differences between thermohygrometer readings and the standard RH. All three units, regardless of which screen they were in, read significantly higher than the standard RH. Figures 8 and 9 show standard RH versus the humicap readings inside both ventilated and non-ventilated screens. Both plots are similar with relatively good fits. There is a departure in relative humidities in the high RH range (70-100%). Also, there are some outliers that are probably artefacts of the physical movement of the sensor from one screen to another. The RHs from the PCRC-11 sensor appears to have a non-linear trend, with marked departures at high RHs (Figure 10).

The mean square error (MSE) as shown in equation (4) was calculated for every measured RH.

$$MSE = \frac{1}{N}\Sigma | RH - E |^2 \qquad [4]$$

where N is the number of cases, RH is the true value (in this case as calculated by the Goff-Gratch equations using the wet and dry bulb temperatures from the ventilated screen), and E is the estimated value read directly off the instrument or calculated by the Goff-Gratch equation using wet and dry bulb temperatures from the non-ventilated screen. Table 1 shows MSE. The bias is also listed in this table and is defined as follows.

$$Bias = \frac{1}{N}\sum_{i=1}^{N} (E - RH) \qquad [5]$$

A negative bias would mean that the estimated value on average is lower than the actual value. The MSE can be used as a relative measure to rank the various instruments according to reliability. We divided the instruments into three general groups based on results in the first row of Table 1. The first is the RH calculated from the wet and dry bulb temperature in the non-ventilated screen that has the lowest MSE. The second group includes the humicap and the PCRC-11 sensor which perform reasonably well (moderate MSE). The last group consists of the thermohygrometers, which perform poorly (high MSE). The second row in Table 1 is for low RH cases (RH < 60%). We did this classification because the days with low RH are active days from a fire control viewpoint. These results show that the MSE dropped for the instruments in groups 1 and 2, whereas the MSE rose for the thermohygrometers (group 3).

Table 2 shows the effect of solar radiation and wind on the measurement of RH within the non-ventilated screen. There are four broad classifications used for Table 2, namely: windy, calm, sunny, and cloudy. 'Windy' was defined as wind speed 7 over km/h while 'calm' was for wind speeds of 3 km/h or less. Wind speeds of 3-7 km/h were not used in this classification. 'Sunny' was a pyranometer reading of 700 W/m^2 or above, while 'cloudy' was for reading of 300 W/m^2 or less. Pyranometer readings of 300-700 W/m^2 were not used in this classification. Figures 11-14 show how RHs within the two screens changed with the conditions.

Discussion

Tables 1 and 2 have shown that RH calculated from wet and dry bulb temperatures in a non-ventilated screen is generally acceptable. From Table 2 and Figures 11-14 we see that there is some change in performance according to environmental conditions. For example, when it was windy there was general agreement between the screens, although values from the non-ventilated screen were on average too low (bias = -.71). Agreement was good for cloudy days though the bulk of the data is above 60% RH, which is of little concern for fire control personnel. The MSE for sunny conditions is comparable to results under cloud except that the bias is different. RHs from the non-ventilated screen for sunny conditions were on the average .41% too low but this was not unexpected as temperatures within the non-ventilated screen were higher. Sparks (1972) points out that Stevenson screens overheat in bright sunshine. But what is disturbing is the fact there is significant scatter of the results in Figure 11, with differences in RHs of 5% or more at several points. The worst fit is for calm conditions; when winds speed are low there will be not enough natural ventilation and the result will be higher wet bulb temperatures in the non-ventilated screen. During calm conditions

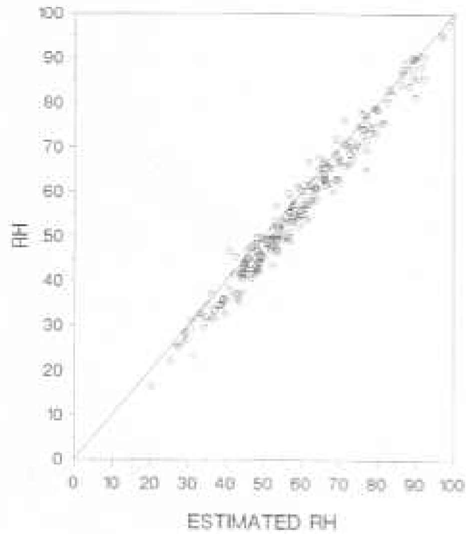

Figure 3. The RH calculated from wet and dry bulb temperatures in a non-ventilated screen versus a ventilated screen using the psychrometric coefficient $A = 6.4309 \times 10^{-4}$ $(^{o}C)^{-1}$. The line indicates a perfect fit.

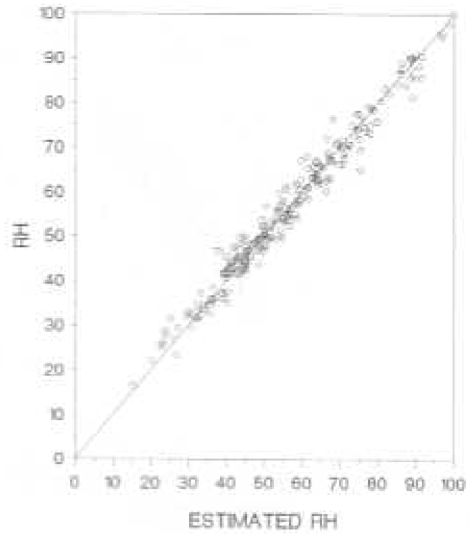

Figure 4. The RH calculated from wet and dry bulb temperatures in a non-ventilated screen versus a ventilated screen using the correct psychrometirc coefficients: $A = 7.7170 \times 10^{-4}$ $(^{o}C)^{-1}$ for the non-ventilated screen and $A = 6.4309 \times 10^{-4}$ $(^{o}C)^{-1}$ for the ventilated screen.

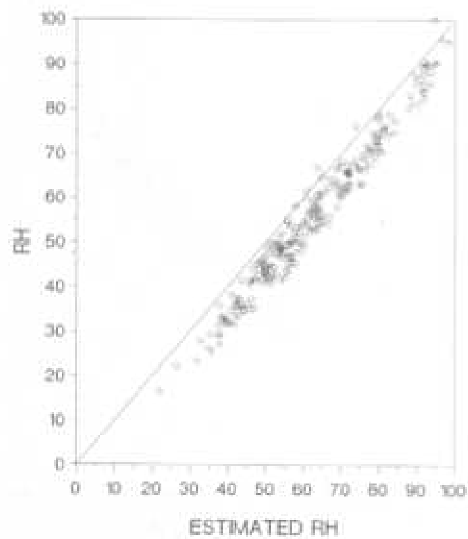

Figure 5. The RH measured by a thermohygrometer in the ventilated screen versus the reference RH.

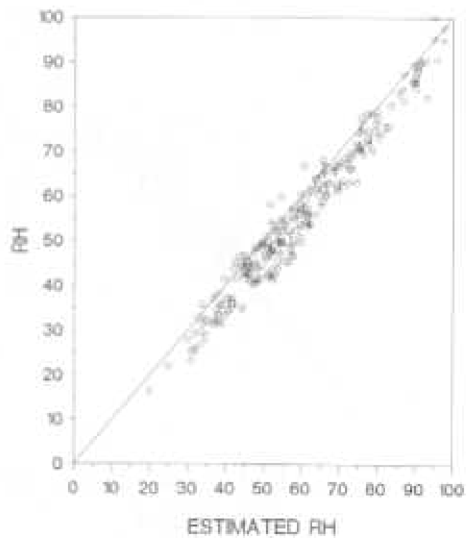

Figure 6. The RH measured by thermohygrometer #1 in the non-ventilated screen versus the reference RH.

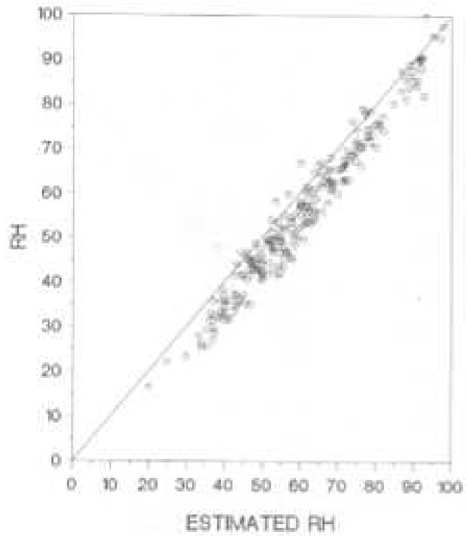

Figure 7. The RH measured by thermohygrometer #2 in the non-ventilated screen versus the reference RH.

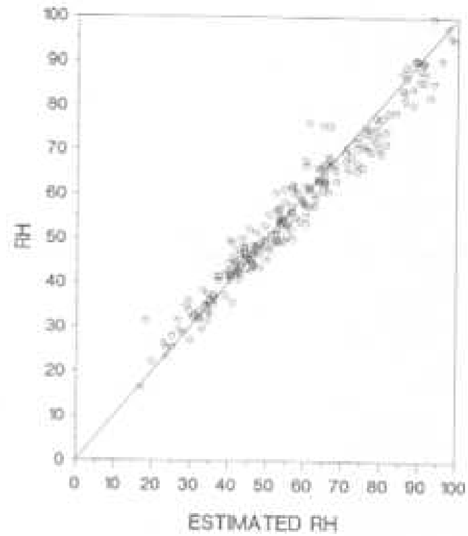

Figure 8. The RH readings from the Vaisala humicap in the ventilated screen versus the reference RH.

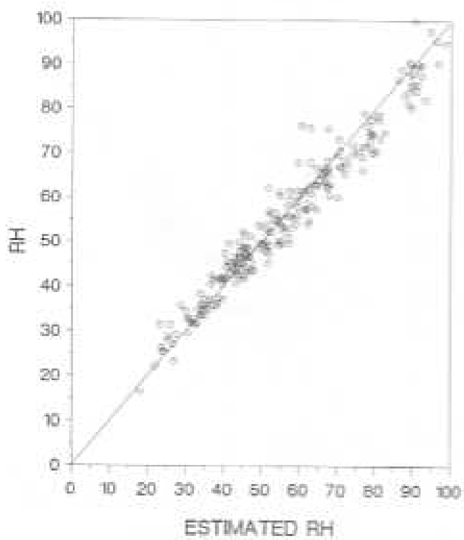

Figure 9. Relative humidity readings from the humicap within the non-ventilated screen versus the reference RH.

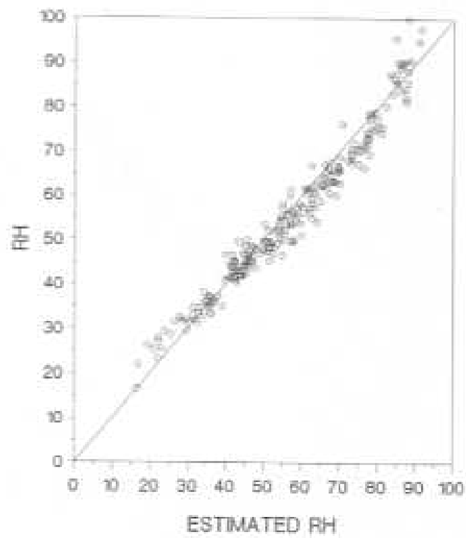

Figure 10. Relative humidity from the PCRC-11 sensor in the non-ventilated screen versus the reference RH.

Table 1. The Mean Square Error (MSE) and bias for various methods of relative humidity calculation for all cases and for low relative humidity (RH < 60%).

	Observations	RH Non-ventilated		Humicap ventilated		Thermohy-grometer ventilated		PCRC-11		Thermohy-grometer#1 non-ventilated		Thermohy-grometer #2 non-ventilated		Humicap non-ventilated	
		MSE	BIAS	MSE	BIAS	MSE	BIAS	MSE	BIAS	MSE	BIAS	MSE	BIAS	MSE	BIAS
All cases	242	8.11	-.04	15.51	.45	50.46	6.41	14.66	1.20	26.47	3.91	36.99	4.99	17.74	.75
Low RH*	149	6.85	-.37	9.73	-.28	55.56	6.88	11.72	.74	29.42	4.19	44.36	5.76	11.22	.00

* RH < 60%

Table 2. The MSE and bias for relative humidity calculated from the wet and dry bulb temperatures measured within the non-ventilated screen for various conditions

	Observations	Relative Humidity non-ventilated	
		MSE	BIAS
All cases	242	8.11	-.04
Low RH (RH<60%)	149	6.85	-.37
Sunny	77	7.59	-.54
Cloudy	93	7.81	.41
Calm	135	8.91	.68
Windy	46	5.12	-.71

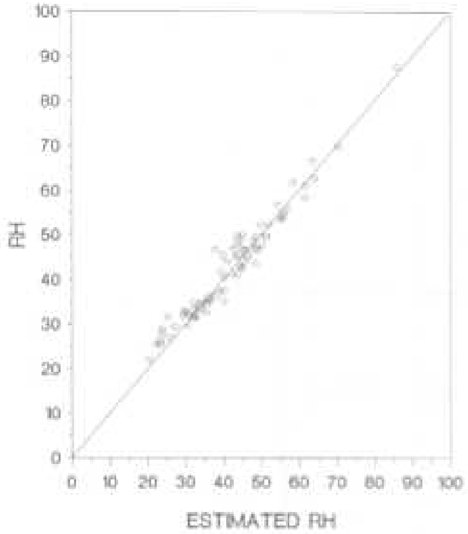

Figure 11. Relative humidity calculated from wet and dry bulb temperatures within the non-ventilated screen versus the reference RH for sunny conditions.

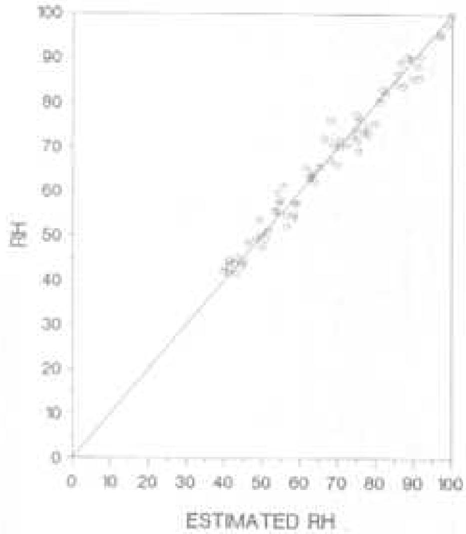

Figure 12. Relative humidity calculated from wet and dry bulb temperatures in the non-ventilated screen versus the reference RH for cloudy conditions.

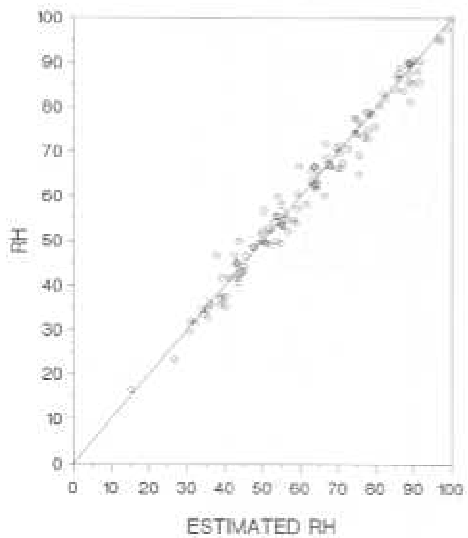

Figure 13. Relative humidity calculated from wet and dry bulb temperatures within the non-ventilated screen versus the reference RH for calm conditions.

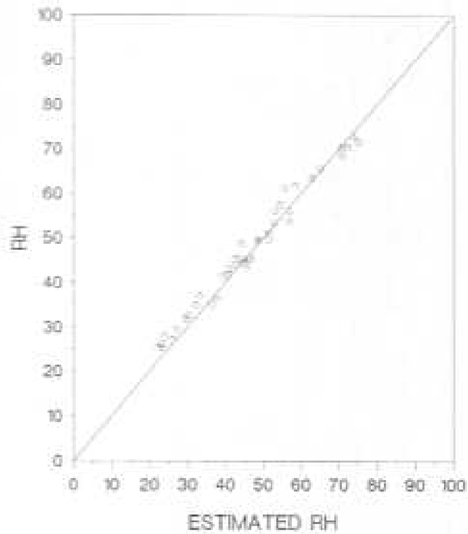

Figure 14. Relative humidity calculated from wet and dry bulb temperatures within the non-ventilated screen versus the reference RH for windy conditions.

RH from the non-ventilated screen was on average 0.68% too high and there is also significant variation, as seen in Figure 13. Such readings demonstrate that even with good results in terms of the statistics (Table 1) the use of non-ventilated screens can give significant individual errors under calm or sunny conditions. Conversely, when conditions are windy we can have confidence in results from the non-ventilated screen. No combinations of the four conditions (e.g. sunny and calm) are presented here as the number data points were too low.

Thermohygrometers do not accurately measure RH. On the other hand, the humicap and the PCRC-11 sensor appear to give accurate measurements. We advise readers, however, that we only used one humicap and one PCRC-11. In other tests (Muller and Beekman 1987) the Vaisala humicap did not fare well due to hysteresis.

We also did not account for the response times of the various RH sensors. The response time can vary significantly and could be responsible for part of the MSE. A thorough comparison among sensors will need to consider response time.

The impact of RH errors in calculating the FWI has to be studied. Indeed, a sensitivity study of the FWI with regards to all four weather inputs is required. Turner and Lawson (1978) have a short discussion on FWI sensitivity but more needs to be done. Although we did not address the issue it is intuitively obvious that errors in RH data can lead to errors in the FWI. Moreover, the errors may be cumulative due to the built-in lag of the FWI system.

There can be many sources of error when measuring or calculating RH. There are inherent mechanical errors associated with the equipment; routine calibration can reduce such errors. There can also be methodological errors. For example, RH measurement via wet and dry bulb temperatures is a function of atmospheric pressure and, because most fire weather stations do not measure atmospheric pressure, some error is introduced. Also, tables (Can. For. Serv. 1984) used to calculate RH when using wet and dry bulb temperatures contain large steps (0.5°C) and the rounding of RH values can introduce errors of over 3%. We would like to see the tables replaced by the Goff-Gratch equations. Human error introducing inaccuracies is, of course, a constant probability. Thus, it is more accurate to read RH directly from a reliable instrument than to calculate it via the multi-step of the wet and dry bulb temperature method. A more complete discussion of errors associated with RH measurement can be found in Wylie and Lalas (1981).

Finally, there are other ways of obtaining RH. For example, we can observe dry-bulb temperature and the dewpoint temperature and then compute RH. The equation relating dewpoint and relative humidity is subject to the same assumptions and problems as those for the psychometric equation. But the advantages of measuring dewpoint are that there are a number of instruments available that will accurately record dewpoint, and dewpoint is conservative, i.e. the RH is a strong function of temperature whereas this is not the case with the dewpoint. RH can vary rapidly over a few hours whereas dewpoint remains relatively steady. Another alternative is to automate the system completely, eliminating human error. However, the workings of the psychrometer are better understood relative to an automated system. This makes it easier to detect problems if something unusual happens. Observations could be fed into a computer with the outputs being components of the FWI. Indeed, some provinces have already automated all or parts of their fire weather network.

Acknowledgments

We greatly appreciate the careful reviews by Dr. R. Silversides and D.J. McKay. Thanks are also due to B.M. Wotton, E. Andersen, L. Roy, and S. Handke for their dedicated work in various capacities.

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Appendix 1

We can determine relative humidity using equations [1], [2], and an equation calculating saturated vapour pressure, e_S.

$$RH = \frac{e}{e_S(T)} \times 100 \qquad [1]$$

$$e = e_S(T_W) - Ap\,(T-T_W) \qquad [2]$$

The Goff-Gratch formula for calculating e_S (List 1984) is:

For T = 273.16 to 373.16 °K

$$\log e_S = -7.90298\,(373.16/T - 1) + 5.2808\,\log_{10}(373.16/T)$$

$$-\,1.3816 \times 10^{-7}\,(10^{11.344[1-(T/373.16)]} - 1) + 8.1328 \times 10^{-3}\,(10^{-3.49149[(373.16/T) - 1]} - 1)$$

$$+\log_{10} 1013.246 \qquad [6]$$

Now, by substituting equation [2] into equation [1], we have

$$RH = \frac{e_S(T_W) - Ap\,(T-T_W)}{e_S(T)} \,.\, (100) \qquad [7]$$

where A is known (6.4309×10^{-4} $(^oK)^{-1}$ for ventilated screens), p is the pressure in hPa, and T, T_W are in °K and must be measured. The saturated vapour pressures $e_S\,(T_W)$ and $e_S\,(T)$ can be obtained by solving the Goff-Gratch equation (eqn [6]) above. The RH can then be calculated.