




AUTOMATIC SYSTEM FOR PSYCHROMETRIC CALCULATIONS

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ABSTRACT

Air psychrometric properties are important in several areas of agricultural engineering, such as calculation of evaluation of the animal environment and air control in grain storage units. Due to their relevance and the complexity and the uncertainties in the use of psychrometric charts, the objective of this paper was to develop the software, *PsyCalculator*, which stands out for the automated function that allows presenting the data acquired through sensors and the respective psychrometric properties of the air, either in graph or tables. The automatic data acquisition system consists of a microcontroller that performs readings of sensors that measure the dry bulb temperature and another variable, which may be: wet bulb temperature, relative air humidity or dew point temperature. Then, the values are sent to the *PsyCalculator* software system. In addition to the values of dry bulb temperature, the software system presents wet bulb temperature and dew point temperature, values of saturation vapor pressure, vapor pressure, mixing ratio, specific volume, enthalpy and degree of saturation. Among the psychrometric variables analyzed, the software developed in the study presented a maximum error of 2.14% for the calculation of dew point temperature. The developed software allows the automation of systems that depend on the psychrometric parameters in a friendly and precise fashion.

Palavras-Chave:

Aquisição de dados
Software
Propriedades físicas do ar

SISTEMA AUTOMÁTICO PARA REALIZAÇÃO DE CÁLCULOS PSICROMÉTRICOS

RESUMO

As propriedades psicrométricas do ar são importantes em diversas áreas da Engenharia Agrícola, dentre elas: avaliação da ambiência animal e controle do ar das unidades armazenadoras. Devido a essa importância e à complexidade da utilização de gráficos psicrométricos, o objetivo deste trabalho foi desenvolver um software, o *PsyCalculator*, cujo diferencial é uma função automatizada que apresenta os dados adquiridos por meio de sensores e suas respectivas propriedades psicrométricas do ar, em gráfico ou em tabelas. O sistema automático para a aquisição de dados é composto por um microcontrolador que realiza leituras dos valores de sensores que medem a temperatura de bulbo seco e uma outra variável que pode ser: temperatura de bulbo úmido ou umidade relativa ou temperatura de ponto de orvalho. Posteriormente, os valores são enviados ao *PsyCalculator*. O *software* apresenta além dos valores de temperatura de bulbo seco, e de bulbo úmido, umidade relativa e temperatura de ponto de orvalho, valores de pressão de vapor de saturação, pressão de vapor, razão de mistura, volume específico, entalpia e grau de saturação. Dentre as variáveis analisadas, o *software* desenvolvido apresentou um erro máximo de 2,14% para o cálculo da temperatura de ponto de orvalho. O sistema desenvolvido permite a automação de sistemas que dependem de parâmetros psicrométricos de forma amigável e precisa.

INTRODUCTION

Psychrometry is the study of the thermodynamic properties of the vapor-gas mixtures. It is an indispensable science for the calculation of energy in the drying and cooling of agricultural products, humidity and temperature control in storage units, evaluation of animal environments, meteorological calculations, cooling towers, human comfort and evapotranspiration calculations among others. It is also necessary in processes that use air conditioning, since the air is not dry; it is a mixture of dry air and water vapor (BELTRÁN-PRIETO *et al.*, 2016; GUPTA & PATEL, 2017; JESUS & SILVA, 2002; ROGDAKIS, 2014; SENAY, 2018)

The following properties of humid air may be related to the amount of water vapor: vapor pressure, mixing ratio, absolute humidity, relative air humidity, specific humidity and degree of saturation. Those directly related to temperature are the dry bulb temperature, wet bulb temperature and dew point temperature. In addition, the air properties may also be related to thermal energy and specific volume (LOPES *et al.*, 2000). In general, the dry bulb temperature (T_{db}) is known, and together with another parameter, such as relative air humidity (H_r), dew point temperature (T_d), or wet bulb temperature (T_{wb}), it allows obtaining all the other psychrometric values. Over the years, many formulas to obtain psychrometric air properties, with different levels of complexity and precision, have been proposed (BELL *et al.*, 2017). As an alternative to the traditional methods, such as the table, the psychrometric chart and semi-empirical mathematical models (AGRAWAL & RAO, 1974), researchers have been developing computer programs and even web pages (ASHRAH, 2018), where it is possible to calculate the psychrometric properties of air. They were developed to help determining the air properties, since the psychrometric graph, which is the most complete description of parameters in the analysis of humid air (SCHIAVON *et al.*, 2014), brings a great deal of information. Thus, it may be confusing and lead to reading errors. Therefore, the automated methods allow calculating the psychrometric values with greater precision.

Several programs, with and without graphical interfaces, have been developed to calculate the psychrometric properties of air, including Grapsi and Psicro 2009 (COMPAGNON *et al.*, 2009; MELO *et al.*, 2004; PELLANDA, 2016). However, these available programs are not integrated into an automatic data acquisition system for real-time calculation of the desired psychrometric parameters. Thus, in the existing programs, users must input the data and save the results later. The software system developed in this study, *PsyCalculator*, allows users to calculate and present all the psychrometric properties of the environment, both in graphs and tables, using the data of the measured parameters by the sensors and in real time. Basic functionalities were also implemented, such as saving measured parameters and calculating individually or in the form of database. This research aims to present the *PsyCalculator* software system, valid for temperatures between -40°C and 110°C , as well as the equations used and the error rate when compared to the ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers), the most commonly used psychrometric calculation system (ROGDAKIS, 2014), presented in Wilhelm (1976). The software was registered in July, 2018 at the National Institute of Industrial Property (INPI) from Brazil with process number: BR 51 2018 001063-6.

MATERIALS AND METHODS

The program was developed in Visual Studio C# 2017, using equations to determine the psychrometric parameters described in section 2.1. The implemented software has two main modes of functionality. The first is the manual, in which the user types the values of two input parameters. In the automatic option, the user configures the serial port to receive the input data. In addition, the user must inform the collection period of the input data. Subsequently, to test the *PsyCalculator* software, a data acquisition system was developed, with the Arduino platform and the one-wire sensor, DHT22, for dry bulb temperature and relative air humidity sensing manufactured by of the Aosong Electronics.

Psychrometric properties of air

The determination of the psychrometric properties of air was performed in the *PysCalculator* software system, using the equations described below.

Saturation vapor pressure and partial vapor pressure

The saturation vapor pressure (P_{sv}) is a key element for psychrometric calculations. Therefore, it must be accurate (SINGH *et al.*, 2002; WILHELM, 1976). The software program uses two equations to determine the saturation vapor pressure for dry bulb temperature values between -40°C and 0°C (eq. 1) and another equation for values between 0°C and 110°C (eq. 2). These two equations were recommended by Wilhelm (1976).

$$\ln(P_{sv}) = 24.2779 - \frac{6238.64}{T_{db}} - 0.344438 \ln(T_{db}) \quad (1)$$

The partial vapor pressure equation (eq. 3) is used when the value of the relative air humidity of the air is known. On the contrary, equation 4 is used. Both equations were discussed by Wilhelm (1976).

$$P_v = \frac{H_r}{100} P_{sv} \quad (3)$$

$$P_{sv} = \frac{P W}{0.62198 + W} \quad (4)$$

wherem

H_r = relative air humidity (%);
 P_{sv} = saturation vapor pressure (kPa);
 P_v = partial vapor pressure (kPa);
 P = atmospheric pressure (kPa); and
 W = mixing ratio ($\text{g}_{\text{vapor}} \cdot \text{kg}_{\text{dry air}}^{-1}$).

Relative air humidity

The relative air humidity was calculated using equation 5.

$$\ln(P_{sv}) = \frac{-7511.52}{T_{db}} + 89.63121 + 0.023998970 T_{db} - 1.1654551 \times 10^{-5} T_{db}^2 - 1.2810336 \times 10^{-8} T_{db}^3 + 2.0998405 \times 10^{-11} T_{db}^4 - 12.150799 \ln(T_{db}) \quad (2)$$

where,

T_{db} = dry bulb temperature (K); and
 P_{sv} = saturation vapor pressure (kPa).

$$H = \frac{P_v}{P_{sv}} 100 \quad (5)$$

where,

P_v = partial vapor pressure (kPa);
 P_{sv} = saturation vapor pressure (kPa), and
 H_r = relative air humidity (%).

Mixing Ratio

The mixing ratio (W), which is the ratio between the amount of water vapor present in the air and the amount of dry air in a volume of mixture, was calculated by equation 6 Wilhelm (1976). When the wet bulb temperature is unknown, equation 7 is used to determine the T_{wb} . The latter is based on the energy balance for adiabatic saturation processes (WILHELM, 1976).

$$W = 0.62198 \frac{P_v}{P - P_v} 100 \quad (6)$$

where,

P = atmospheric pressure (kPa);
 P_v = partial vapor pressure (kPa), and
 W = mixing ratio ($\text{g}_{\text{vapor}} \cdot \text{kg}_{\text{dry air}}^{-1}$).

$$W = \frac{(2501 - 2.411 T_{wb}) W_s - 1.006(T_{db} - T_{wb})}{2501 + 1.775 T_{db} - 4.186 T_{wb}} \quad (7)$$

where,

T_{db} = dry bulb temperature ($^{\circ}\text{C}$);
 T_{wb} = wet bulb temperature ($^{\circ}\text{C}$);
 W = mixing ratio ($\text{g}_{\text{vapor}} \cdot \text{kg}_{\text{dry air}}^{-1}$), and
 W_s = saturation mixing ratio ($\text{g}_{\text{vapor}} \cdot \text{kg}_{\text{dry air}}^{-1}$).

Specific enthalpy

The specific enthalpy (h) was calculated through equation 8 (WILHELM, 1976) and is indicated for dry bulb temperature values between -50°C and 110°C .

$$h = 1.006 T_{bs} + W(2501 + 1.775 T_{bs}) \quad (8)$$

where,

h = specific enthalpy (kJ/kg);

T_{db} = dry bulb temperature ($^{\circ}\text{C}$), and

W = mixing ratio ($\text{g}_{\text{vapor}} \text{kg}_{\text{dry air}}^{-1}$).

Specific volume

The specific volume (v) was calculated through equation 9 (WILHELM, 1976).

$$v = \frac{R T_{db}}{P} (1 + 1.6078 H_r) \quad (9)$$

where,

v = specific volume (m^3/kg);

R = gas constant ($0.28705 \text{ kJ} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$);

T_{db} = dry bulb temperature (K);

P = atmosphere pressure (kPa), and

H_r = relative air humidity (decimal).

Degree of saturation

The degree of saturation was calculated by equation 10.

$$D_s = \frac{W}{W_s} 100 \quad (10)$$

where,

W_s = saturation mixing ratio ($\text{g}_{\text{vapor}} \cdot \text{kg}_{\text{dry air}}^{-1}$)

W = mixing ratio ($\text{g}_{\text{vapor}} \cdot \text{kg}_{\text{dry air}}^{-1}$)

D_s = degree of saturation (%)

Dew point temperature

The dew point temperature (T_d) was calculated using three equations, each one for a dry bulb temperature range: between -50°C and 0°C , equation 11; between 0°C and 20°C , equation 12, both recommended by Wilhelm (1976). For values greater than 20°C , we used equation 13 proposed by Tetens (HJ ANDREWS EXPERIMENTAL FOREST, 2018) because it achieved results to the values tabulated by ASHRAE when compared to the equation recommended by Wilhelm (1976).

$$T_d = 5.994 + 12.41 \alpha + 0.423 \alpha^2 \quad (11)$$

$$T_d = 6.983 + 14.38 \alpha + 1.079 \alpha^2 \quad (12)$$

$$T_d = \frac{273.3 X}{17.269 X} \quad (13)$$

where,

$\alpha = \ln(P_v)$;

$$X = \ln\left(\frac{H_r}{100}\right) + \frac{17.269 T_{db}}{237.3 + T_{db}};$$

T_d = dew point temperature ($^{\circ}\text{C}$);

T_{db} = dry bulb temperature (K), and

H_r = relative humidity (%).

Relationship between altitude and atmospheric pressure

The relationship used to calculate the atmospheric pressure through the altitude is indicated in equation 14 (NOVA *et al.*, 2002).

$$P = 101.3 \left(\frac{288 - 0.0065H}{288} \right)^{5.257} \quad (14)$$

where,

P = atmosphere pressure (kPa), and

H = height (m).

Routines used by the program

The use of the psychrometric calculations requires the knowledge of at least a pair of parameters, which can be: (i) dry bulb temperature and wet bulb temperature, or; (ii) dry bulb temperature and relative air humidity, or; (iii) dry bulb temperature and dew point temperature. For each pair of the chosen parameters, a computer program routine was implemented, named routine 01, routine 02 and routine 03, respectively. Figure 1 shows the program flowchart for automatic and manual modes:

Input parameters: dry bulb temperature and relative humidity, routine 01

Considering as input parameter the dry bulb temperature, T_{db} and humidity, H_r , the program performs routine 01:

1. Calculation of the saturation pressure, P_{sv} and mixing ratio at saturation pressure, W_s ;
2. Calculation of the properties of vapor pressure, P_v , mixing ratio, W , degree of saturation, D_s , volume, v , enthalpy, h and dew point, T_d ; and
3. Calculation of wet bulb temperature, T_{wb} through iterations using (1) or (2) and (7) equations by trial and error.

Input parameters: dry bulb temperature and wet bulb temperature, routine 02

Considering as input parameter the dry bulb temperature, T_{db} and wet bulb temperature, T_{wb} , the

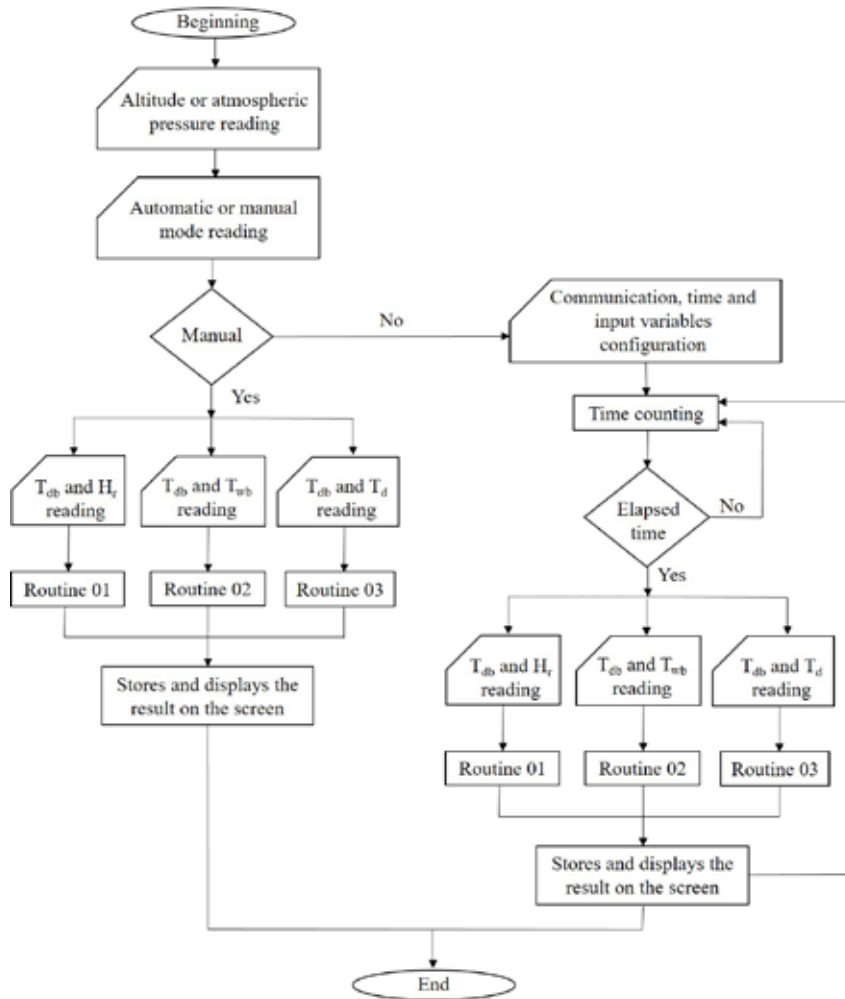


Figure 1. Flowchart for psychrometric calculations.

program performs routine 02:

1. Calculation of the saturation pressure, P_{sv} and mixing ratio at saturation pressure, W_s using wet bulb values;
2. Calculation of the saturation pressure, P_{sv} and mixing ratio at saturation pressure, W_s , using dry bulb values; and
3. Calculation of the mixing ratio properties, W , vapor pressure, P_v , relative humidity, H_r , volume, v , enthalpy, h , dew point temperature, T_d , degree of saturation, D_s .

Input parameters: dry bulb temperature and dew point temperature, routine 03

Considering as input parameter the dry bulb temperature, T_{db} and dew point temperature, T_d , the program performs routine 03:

1. Calculation of saturation pressure, P_{sv} and mixing ratio at saturation pressure, W_s ;

2. Calculation of the properties of vapor pressure, P_v , mixing ratio, W , degree of saturation, D_s , volume, v and enthalpy, h ; and
3. Calculation of the wet bulb temperature through iterations using (1) or (2) and (7) equations by trial and error.

Automatic system for psychrometric calculations

The automatic system for data acquisition, developed to perform the psychrometric calculations, is composed of sensors that measure two input parameters required by the *PsyCalculator* software system, as mentioned in section 2.2, and a microcontroller that performs the communication between the sensors and the developed program. In the automatic system, several types of sensors and even actuators can be used. However, the automatic system developed in this work demands sensors that measure dry bulb temperature and relative air

humidity or dry bulb temperature and wet bulb temperature or dry bulb temperature and air dew point temperature, besides a microcontroller that performs the readings of these sensors and the analogical digital conversion, if necessary, and sends the values to *PsyCalculator* software system, when requested.

The system, developed in this work for testing, used a DHT22 sensor to measure dry bulb temperature and relative air humidity and the Arduino platform, using serial communication for the communication between the *PsyCalculator* software system and the sensor, as shown in Figure 2.

DHT22 sensor

The DHT22 is a digital sensor based on the use of a thermistor for temperature measurement and a capacitive sensor for relative air humidity measurement. It is a sensor capable of measuring temperatures between -40°C and 80°C and values of relative air humidity between 0% and 99.9%, with accuracy of $\pm 0.5^{\circ}\text{C}$ and $\pm 2\%$ and resolution of 0.1°C and 0.1%, respectively. For using this sensor, the transmission distance of the data must not exceed 20 meters. The distance used at this project was no more than one meter. The minimum response time for this sensor is two seconds, an important parameter that might prevent its selection for certain projects that require faster readings (AOSONG, 2018; MARTÍN-GARÍN *et al.*, 2018).

The sensor uses the one-wire communication protocol, in other words, the communication is

conducted using only one communication line. Therefore, the microcontroller communicates with the sensor using only one data pin. This sensor was chosen due to the ease of working with the Arduino and the fact that it measures the dry bulb temperature and the relative humidity of the air simultaneously, thus meeting one of the possibilities of input pairs of parameters for psychrometric calculations.

Arduino Uno

The Arduino Uno is an open source programming platform comprised of an ATmega328 microcontroller with 14 digital outputs/inputs and six analog inputs, which can be powered through USB or external power source. Arduino was selected due to its ease and simplicity of use, besides the compatibility with the temperature and relative air humidity sensor, model DHT22. Another microcontroller, such as PIC (Programmable Interface Controller), may also be used in the psychrometric calculation automatic system. Arduino can be programmed in C/C++ Integrated Development Environment (IDE).

In this study, the developed program verified whether data were available in the serial port. If they were, the program analyzed whether the data matched the pre-defined code for the requisition of the parameters for psychrometric calculations. If they did, the program carried out dry bulb temperature and relative air humidity readings of the air using the multi sensor device. Next, the microcontroller platform, Arduino, sent this information to the *PsyCalculator* software system and awaited the next request, as shown in Figure 3.

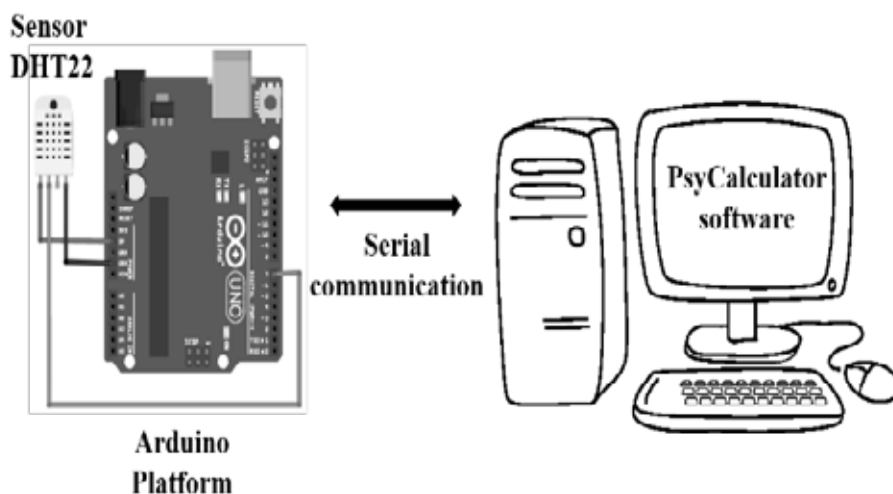


Figure 2. Automatic system developed for psychrometric calculation tests.

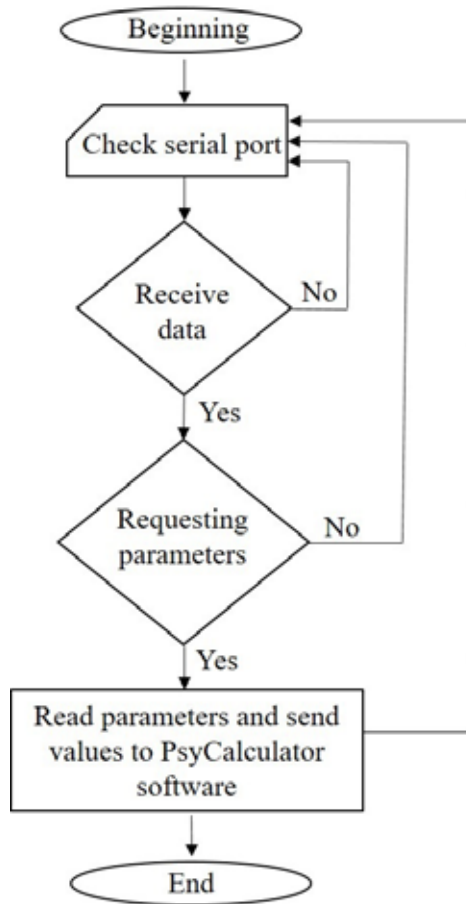


Figure 3. Flowchart of the data acquisition of the micro controller Arduino platform.

Serial communication

The serial communication, a simple and commonly used method, was used between the

Arduino and the *PsyCalculator* software system, that is, the serial port sends and receives bytes of data, in a bit at a time pace.

The settings in both the Arduino and the *PsyCalculator* software system require some parameters to perform this communication, namely, the port, baud rate, parity, stop bits and number of bits. The configuration of the port establishes which port will be connected; baud rate is a measure of speed for communication, i.e., number of bits transmitted per second; parity is a way of verifying serial communication errors; stop bits are used to indicate the end of the communication for a packet; and the number of bits is the number of bits sent per byte, e. g. 8 bits.

After setting this configuration, the user must configure the collection period of input data and the other parameter used as an input besides the dry bulb temperature parameter.

Comparison of results

The values obtained by the *PsyCalculator* software system, the available Grapsi software system 8.1 (MELO *et al.*, 2004; MELO, 2011) and the program developed by Wilhelm (1976) were compared to the values tabulated by ASHRAE and converted to the International System (SI) as shown in table 1. The errors were computed for the three routines developed to calculate psychrometric properties, as well as the dew point temperature, relative air humidity, mixing ratio, specific volume and enthalpy.

Table 1. Tabulated values by ASHRAE

Simulations	T _{db} (°C)	T _{wb} (°C)	T _d (°C)	Relative air humidity (decimal)	Mixing ratio (g _{vapor} ·kg _{dry air} ⁻¹)	Specific volume (m ³ /kg)	Enthalpy (kJ/kg _{dry air})
01 ^[a]	-30	[b]	-40	0.338	0.079	0.698	-30
02 ^[a]	-10	[b]	-17.75	0.492	0.789	0.746	-8.1
03 ^[a]	0	[b]	-1.47	0.885	3.35	0.777	8.38
04 ^[a]	20	[b]	-9.5	0.116	1.68	0.832	24.4
05 ^[a]	20	[b]	18.03	0.884	13	0.848	53.1
06 ^[a]	35	[b]	-0.35	0.106	3.68	0.878	44.6
07 ^[a]	35	[b]	32.97	0.893	32.6	0.918	118.8
08 ^[a]	70	[b]	29.59	0.133	26.6	1.01	140.4
09 ^[a]	70	[b]	68.85	0.951	260	1.38	752.8
10 ^[a]	100	[b]	46	0,100	69,2	1,17	288,2
11 ^[a]	110	[b]	90	0.489	1400	3.6	3871

^a Tabulated values used by Wilhelm (1976).

^b Wet bulb temperature values not determined.

RESULTS AND DISCUSSION

Figure 4 shows the initial screen of the *PsyCalculator* software in manual mode. On the screen, we can see the menus for viewing data in a table; performing data saving; showing program information; and exiting the program. The graph access menu (Figure 5) is only available when the automatic option is selected, since the data is drawn on the graph, according to the information received by the sensors.

The comparison between the results obtained by the *PsyCalculator* software system and ASHRAE tabulated values showed a small error for specific volume (0.44%), followed by enthalpy (0.48%), mixing ratio (0.63%), relative humidity (0.74%), and finally, the dew point temperature (2.14%), as shown in Table 2. In addition, the error of each routine for the parameters under study was analyzed. It was observed that routine 03 presented the smallest error, about 0.33%, as expected, since the largest error, among the variables analyzed, was associated to the determination of the dew point variable, Table 3. Routine 02 and routine 01

presented errors of 1.48% and 0.52%, respectively. The greatest error associated with these two routines may be due to the greater error of determining the dew point temperature parameter. The Grasiop software system presents higher error values not only for both routine 01 and routine 02, but also for the analyzed parameters, except specific volume, when compared to the *PsyCalculator*. It is observed that the developed program, *PsyCalculator*, presents the smallest error for the routine 02, about 63.9% smaller, respectively, when compared to the Grasiop program and about 28% lower, respectively, when compared to the program developed by Wilhelm (1976). For routine 03, the developed program presents a higher error as the Grapsi software 8.1 (0.29%), while the program developed by Wilhelm (1976) presents the lowest error of 0.22%. Since the wet bulb values were not tabulated by ASHRAE, this parameter was not analyzed.

The difference among the results of the software is due to the equations used by each of them. There is no consensus to determine only one equation for the calculation of psychrometric properties, since

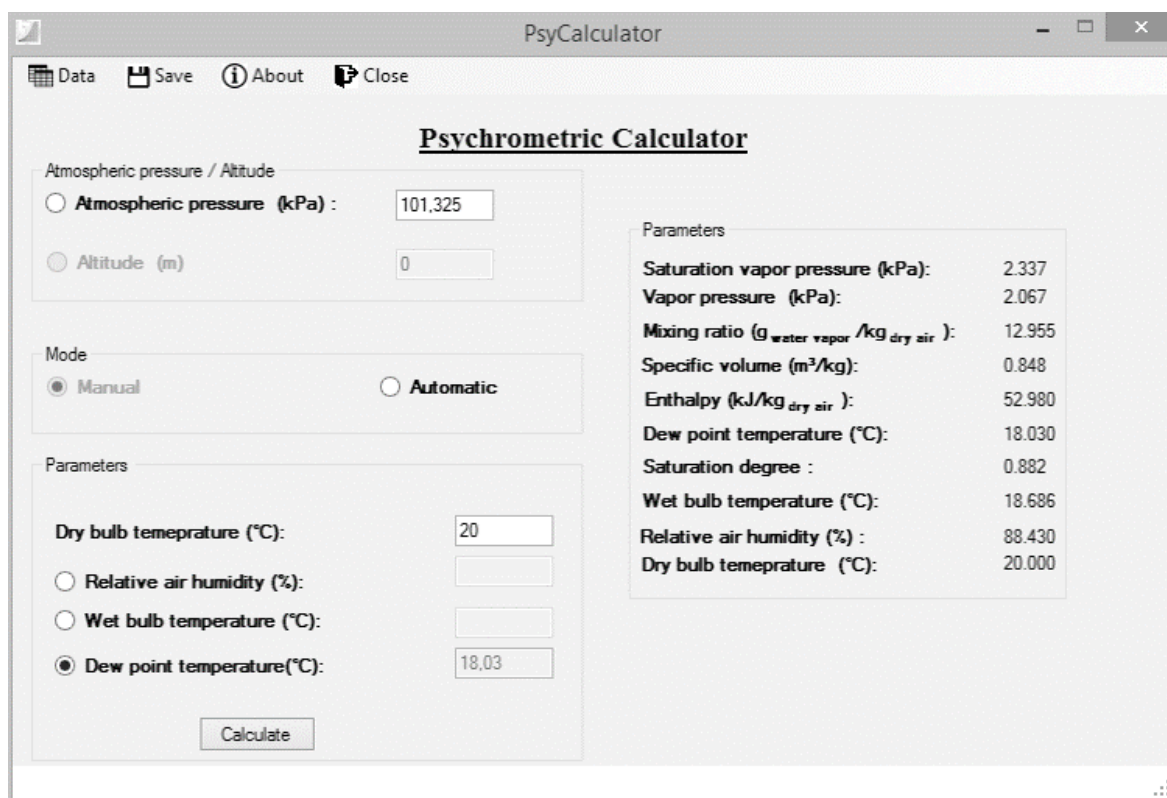


Figure 4. *PsyCalculator* software main screen in manual mode with some results.

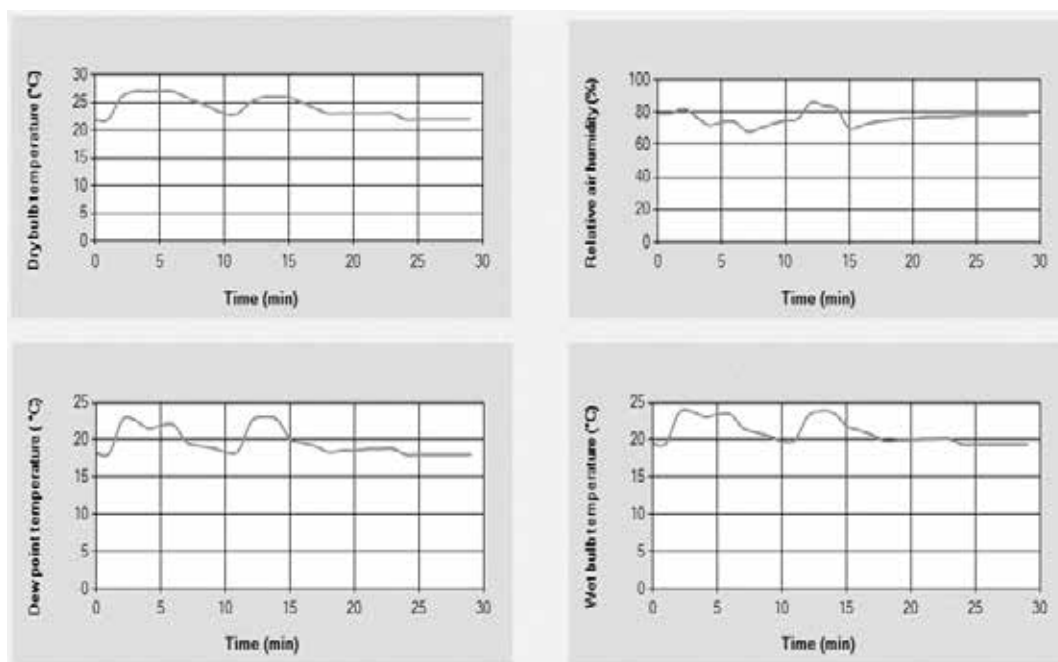


Figure 5. Example of graphical output of the *PsyCalculator* software.

Table 2. Comparison among the parameters analyzed for the data provided by Wilhelm, Grapsi 8.1 and the developed *PsyCalculator* software system in relation to the values tabulated by ASHRAE.

Parameters	Error (%)		
	Wilhelm (WILHELM, 1976)	Grapsi 8.1 (MELO <i>et al.</i> , 2004; MELO, 2011)	<i>PsyCalculator</i>
Dew point temperature	0.13	7.14	2.14
Relative air humidity	0.07	1.33	0.74
Mixing ratio	0.45	1.24	0.63
Specific volume	3.24	0.36	0.44
Enthalpy	0.32	0.50	0.48

Table 3. Comparison among routine error for Wilhelm, Grapsi 8.1 and the developed *PsyCalculator* software system in relation to the values tabulated by ASHRAE.

Routine	Average Error (%)		
	Wilhelm (WILHELM, 1976)	Grapsi 8.1 (MELO <i>et al.</i> , 2004; MELO, 2011)	<i>PsyCalculator</i>
01	0.44	1.25	0.52
02	2.05	4.10	1.48
03	0.22	0.29	0.33

the equations were developed over the years with complexity and accuracy (BELL *et al.*, 2017). In addition, the programs used to develop each software system are different and may affect the results.

CONCLUSION

- We discuss the underlying methodology used by the software *PsyCalculator*. The software was developed by the authors to use measured

data to compute psychrometry values such as vapor pressure, mixing ratio, absolute humidity, relative air humidity, specific humidity and degree of saturation.

- The result of the accuracy tests performed by comparing the developed software with those from two other software systems available in the literature guarantees that the software system developed in this work is qualified to be used in system automation or monitoring in the field of agricultural engineering.
- Besides the accuracy of the developed software, it has a differential of calculating real time psychrometric variables automatically; therefore, users do not have to input data into the program manually.
- Finally, the developed software allows the automation and control of processes that required psychrometric variables, in a friendly and precise fashion.

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