ISSN 2359-6562 (ONLINE) 2359-6562 (CD-ROM)

SOFTWARE FOR SIZING PAD-FAN EVAPORATIVE COOLING SYSTEMS OF GREENHOUSES

GABRIELA LOUISE FERREIRA ALCÂNTARA DE OLIVEIRA[1]; DANIELA DE CARVALHO LOPES[1]; ANTONIO JOSÉ STEIDLE NETO[1] E SÉRGIO ZOLNIER[2]

[1] Departamento de Ciências Agrárias, Universidade Federal de São João del-Rei, Rodovia MG 424, Km 47, 35701-970, Sete Lagoas, Minas Gerais, Brasil. gabiilouise@hotmail.com; danielalopes@ufsj.edu.br; antonio@ufsj.edu.br.
[2] Departamento de Engenharia Agrícola, Universidade Federal de Viçosa, Av. Peter Henry Rolfs, s/n, 36570-000, Viçosa, Minas Gerais, Brasil; zolnier@ufv.br

ABSTRACT: The calculations for sizing pad-fan evaporative cooling systems depend on the psychrometric properties of the air inside and outside of the greenhouse, appearing as a constant need for professionals in the agricultural sector. A software capable of performing these calculations is important to speed up this procedure. In this study a free software was developed to estimate the maximum efficiency of the porous panel, the ventilation rate of the exhaust fan and the climatic conditions of pad-fan evaporative cooling systems in greenhouses. The software, called Theoretical Evaporative (TE), was written in Java programming language, using the NetBeans platform. All equations and algorithms used in this development are presented, and were based on the mechanical ventilation and cooling principles. The software was tested by means of comparisons with real system sizing calculations performed manually and in electronic spreadsheet. The TE was efficient in sizing different evaporative cooling systems for greenhouses and can be used for performing consultations in the academic and commercial areas of agricultural sciences, being also advantageous for didactic purposes. Although this software is applied to greenhouse conditions, the methodology presented can be adapted for other environments, such as poultry, cattle and swine facilities.

Keywords: Agriculture; Psychrometry; Protected environment; Ventilation

PROGRAMA COMPUTACIONAL PARA DIMENSIONAMENTO DE SISTEMAS DE RESFRIAMENTO EVAPORATIVO TIPO PAINEL-EXAUSTOR EM CASAS DE VEGETAÇÃO

RESUMO: Os cálculos para o dimensionamento de sistemas de resfriamento evaporativo do tipo painel-exaustor dependem das propriedades psicrométricas do ar dentro e fora da casa de vegetação, sendo uma necessidade constante entre os profissionais do setor agrícola. Um programa computacional capaz de realizar esses cálculos é importante para agilizar esse procedimento. Neste estudo um programa computacional gratuito foi desenvolvido para estimar a eficiência máxima do painel poroso, a taxa de ventilação do exaustor e as condições climáticas de sistemas de resfriamento evaporativo em casas de vegetação. O programa computacional, denominado Teórico Evaporativo (TE), foi escrito na linguagem de programação Java, utilizando a plataforma NetBeans. Todas as equações e algoritmos utilizados neste desenvolvimento são apresentados, e foram baseados nos princípios de ventilação mecânica e resfriamento. O programa computacional foi testado por meio de comparações com dimensionamentos de sistemas reais, realizados manualmente e em planilha eletrônica. O TE mostrou-se eficiente no dimensionamento de diferentes sistemas de resfriamento evaporativo para casas de vegetação, podendo ser utilizado em consultorias nas áreas acadêmica e comercial das ciências agrárias, sendo também vantajoso para fins didáticos. Embora este software seja aplicado a casas de vegetação, a metodologia apresentada pode ser adaptada para instalações de aves, bovinos e suínos.

Palavras-chave: Agricultura; Psicrometria; Ambiente protegido; Ventilação

Recebido em 17/02/2023 e aprovado para publicação em 22/05/2023
DOI: http://dx.doi.org/10.17224/EnergAgric.2023v38n2p14-25

1 INTRODUCTION

The impacts of global warming and the effort to reduce energy consumption implies the search for viable alternatives for air conditioning environments. Numerous studies have been motivated by the growing demand for ecological awareness, focused on eco-efficiency and based on new technologies (SHRIVASTAVA; DESHMUKH; RAWLAN, 2014). Considering sustainable procedures and processes, there is a consensus on the rational use of energy and water, favoring environmental and economic factors (KHOBRAGADE; KONGRE, 2016).

Evaporation of water causes a cooling, and many times results from the decreasing of air temperature and the increasing of relative humidity due to artificial procedures that allow synchronous heat and mass transfer (STEIDLE NETO; ZOLNIER, 2010). The cooling systems are classified according to the thermal energy transfer media, as well as to how air comes in contact with the evaporated water. They can be classified as direct, indirect, double-stage, passive or semi-passive (MISRA; GHOSH, 2018).

The most common evaporative systems used in agricultural environments, such as greenhouses, aviaries, cattle and swine facilities, are based on evaporative panels that enable its entire surface to be coated with water (RONG *et al*., 2017). The water normally permeates the porous material from the top by gravity, so that the contact area with the air passing through the panel is sufficient to provide air cooling. The thickness of the panel and the amount of water introduced into the system depend on the design of the agricultural facility and on the material used in the panel. In this sense, a number of studies have investigated the performance of evaporative cooling systems using different porous materials as evaporation medium (DUAN *et al*., 2022).

The calculations for sizing evaporative systems depend on the psychrometric properties of the air, in addition to the conditions of the environment in which they are installed. This procedure is a constant need for professionals in the agricultural sector, especially those who work with greenhouses (NELSON, 1991; MISRA; GHOSH, 2018). Currently, this sizing is performed manually or through spreadsheets and tables, spending time as it requires caution when considering the values and equations applied (SHOJAEI *et al*., 2021). Thus, a software capable of performing these calculations and speeding up this procedure is required, helping the professionals of the agrarian sciences in their analyses and acting as a didactic tool.

In this work a free software was developed to estimate the maximum efficiency, the ventilation rate and the psychrometric data required for installing evaporative cooling systems in greenhouses.

2 MATERIAL E MÉTODOS

2.1 Sizing of evaporative cooling systems

The calculations implemented in the proposed software were based on the mechanical ventilation and cooling principles, considering the panel-exhaust evaporative air-cooling systems (NELSON, 1991; NGMA, 2008). In these arrangements an adiabatic humidification process occurs, in which the external air is forced into the greenhouse by exhaust fans, passing through a porous panel moistened with water (STEIDLE NETO; ZOLNIER, 2010). Thus, the sizing of panel-exhaust evaporative air-cooling systems includes estimating the maximum efficiency of the evaporative panel and the required porous material area. Other sized parameters are the exhaust fan diameter, the motor power of the exhaust fans and the ventilation rate required by the system.

One of the most important parameters for starting the design of ventilation or cooling systems is the reference ventilation rate (2.5 m^3 min^{-1} m^{-2}), which was experimentally determined as the appropriate rate for air renewal in a greenhouse built at sea level, considering a solar radiation of 500 W m^{-2} (NELSON, 1991). Under these conditions, as the cooled air passes through the greenhouse, it increases around 3.9 °C by the time it reaches the exhaust fans (NGMA, 2008). For different conditions the reference ventilation rate must be adjusted.

At higher altitudes, a greater volume of air is required to provide the equivalent weight of air necessary for removing heat. Thus, an altitude factor is used to compensate the differences of elevation, correcting the reference ventilation rate (BELKADI NETO; MEZGHANI; MAMI, 2021):

$$Fa = (99.187 / P) \quad (1)$$

Where Fa is the altitude factor (dimensionless) and P is the local atmospheric pressure (kPa).

Another important adjustment factor is related to the temperature increase from porous panel to exhaust fan, which is inversely proportional to the airflow rate (NGMA, 2008):

$$Ft = (3.9 / \Delta T) \quad (2)$$

Where Ft is the temperature factor (dimensionless) and ΔT is the increase in air temperature along the length of the greenhouse (°C).

Furthermore, the light intensity within the greenhouse depends on its location and the shading pattern, affecting the amount of heat input into the system. These differences are adjusted by a light intensity factor, based on a moderately shaded greenhouse (NELSON, 1991):

$$Fr = (R / 500) \quad (3)$$

Where Fr is the light intensity factor (dimensionless) and R is the maximum solar radiation within the greenhouse (W m^{-2}).

For distances between the porous panel and the exhaust fan smaller than 30.5 m, the cross-sectional airflow velocity within the greenhouse tends to be very low, leading to the greenhouse seems clammy or stuffy even though the airflow rate is sufficient for heat balance. In these cases, a velocity factor must be applied to produce a more desirable air velocity level within the greenhouse (NGMA, 2008; BELKADI NETO; MEZGHANI; MAMI, 2021).

$$Fv = 10 / (3.28083 C)-1/2 \quad (4)$$

Where Fv is the velocity factor (dimensionless) and C is length of the greenhouse (m).

Considering the adjustment factors and the reference ventilation rate, a theoretical ventilation rate of the system can be estimated (NELSON, 1991):

$$Tv = (A\ Vr\ Fa\ Ft\ Fr\ Fv) / n \quad (5)$$

Where Tv is the theoretical ventilation rate (m^3 min^{-1} exhaust fan^{-1}), Vr is the reference ventilation rate (m^3 min^{-1} m^{-2}), A is the area of the greenhouse (m^2) and n is the number of exhaust fans (dimensionless).

Once the theoretical ventilation rate is determined, the nearest and higher standard commercial value is normally chosen for the real system deployment. Based on this value, other commercially available specifications are selected, such as the porous

Area, and the exhaust fan diameter and motor power.

The total area of porous material is calculated by multiplying the selected commercial and individual area by the number of exhaust fans installed in the greenhouse. Adequate number of fans must provide a spacing of not more than 7.6 m along the exhaust side of the greenhouse (NGMA, 2008). Another sizing parameter is the air velocity in the porous material, determined as (NELSON, 1991):

$$V = Tc\ n / Ap \quad (6)$$

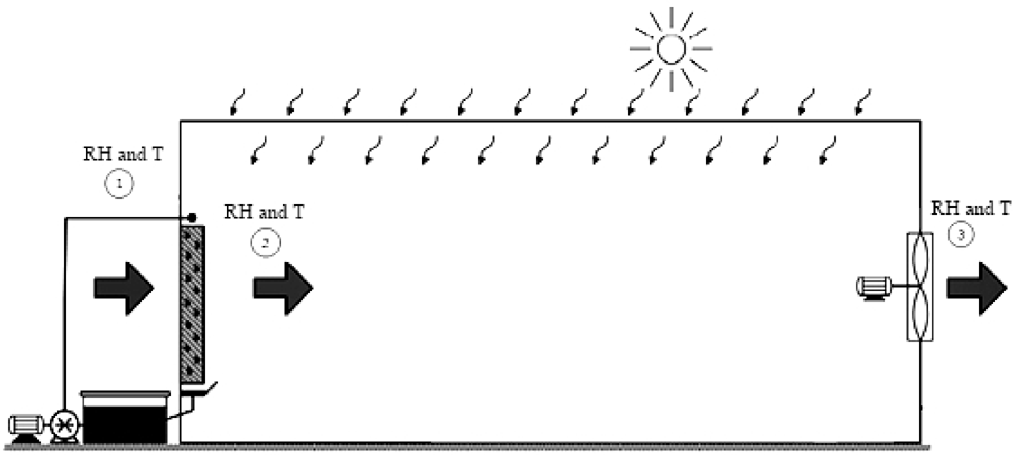
Where V is the air velocity in the porous material (m min-1), Tc is the commercial ventilation rate (m^3 min^{-1} exhaust fan^{-1}) and Ap is the total area of porous material (m^2).

The maximum efficiency of the porous panel mainly depends on its material, the airflow in this material and the thickness of the evaporative panel. In addition to these factors, the efficiency is affected by the variations in temperature and relative humidity of the external air throughout the day. Panels produced by different manufacturers will have different efficiencies, and even with the same porous materials, the efficiency may vary throughout the day (STEIDLE NETO; ZOLNIER, 2010). Thus, the temperature and relative humidity values estimated during the sizing for the indoor air conditions just after passing through the porous panel should be slightly different in real situations, since that these calculations consider the maximum efficiency of the panel.

In this work, the efficiency curves of commercial evaporative cooling panels were digitized (SANTOS; RAMOS, 2001), generating polynomial equations relating the air velocity in the porous material with the panel efficiency for different panel thicknesses. Future works will focus on extending this database, considering other panel models, porous materials and manufacturers.

The changes in air conditions at different locations within the greenhouse due to the evaporative cooling system are directly associated with the psychrometric properties of the air. In this work, the calculations of temperature and relative humidity considered the outside air at the entrance to the greenhouse, the indoor air just after passing through the porous panel and the indoor air at the exit of the greenhouse (Figure 1).

Figure 1. Longitudinal section of a greenhouse showing the evaporative cooling system, exhaust fan and estimated air conditions



Source: The authors

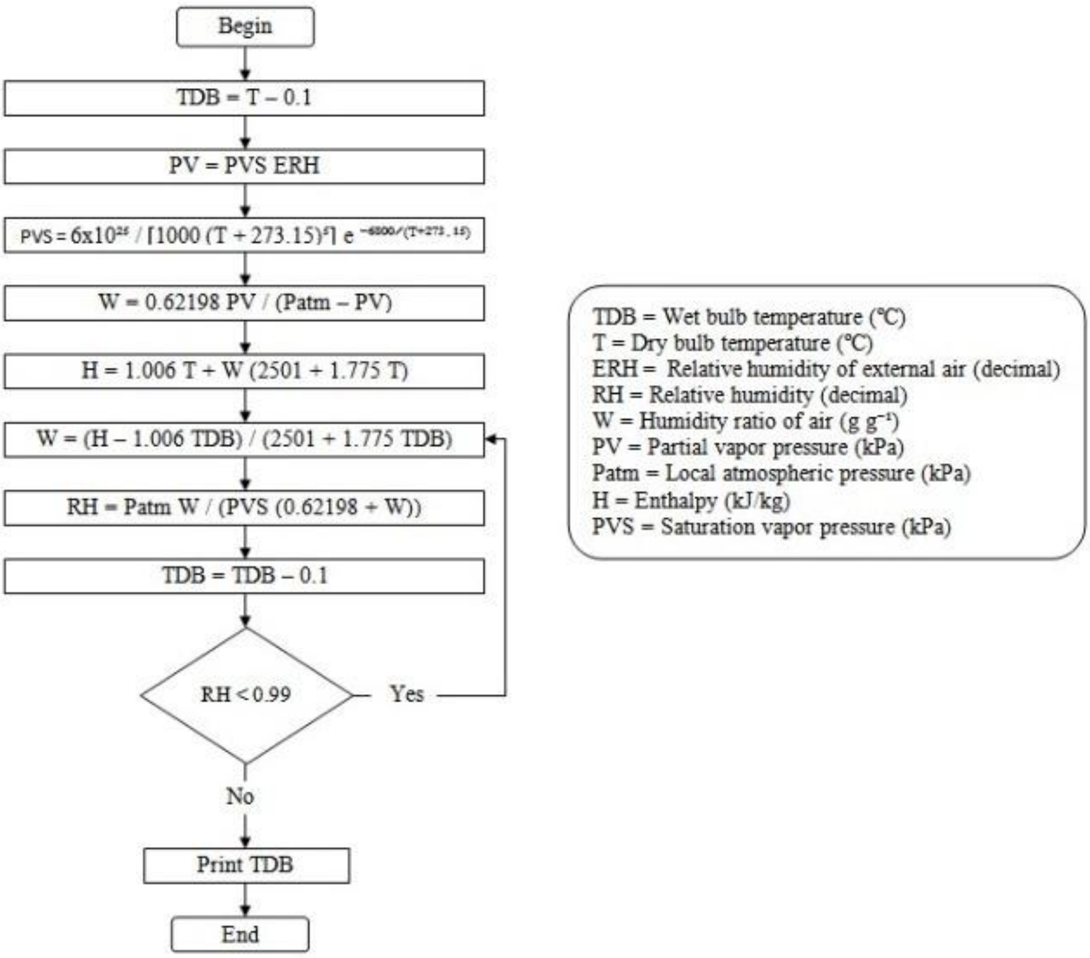
The temperature of the air just after passing through the porous panel depends on the air conditions outside and inside the greenhouse, in addition to the efficiency of the porous panel (STEIDLE NETO; ZOLNIER, 2010):

$$Tp = 100\ Te + \eta\ (TBUe - Te) \quad (7)$$

Where Tp is the dry-bulb temperature of the air just after passing through the porous panel (°C), Te is the dry-bulb temperature of the air outside the greenhouse (°C), η is the maximum efficiency of the porous panel (decimal) and TBUe is the wet-bulb temperature of the air outside the greenhouse

The dry-bulb temperature is the air temperature measured by a standard thermometer, reflecting the cooling impact of dissipating water (SEIN *et al.*, 2021). On the other hand, the wet bulb temperature represents the lowest temperature that can be achieved by adiabatic humidification (SIDEBOTHAM, 2022), and can be measured by a psychrometer or estimated by an iterative method. In this study the second possibility was applied and the wet-bulb temperature was estimated by iteratively decrementing the dry-bulb temperature of the air outside the greenhouse, maintaining constant the enthalpy, until reaching a relative humidity higher than 0.99. At each iteration the relative humidity was recalculated as a function of the external absolute humidity and the decremented temperature by using the psychrometric relations, as show in Figure 2. The adiabatic humidification process takes place by the incorporation of moisture from the air without adding or removing heat, leading to a drop in the air temperature and an increase of the relative humidity, while the air enthalpy does not change (LOPES; STEIDLE NETO; SANTIAGO, 2014). Therefore, the wet bulb temperature of the air just after passing through the panel is considered equal to that of the external air.

Figure 2. Algorithm of the iterative procedure to obtain the wet bulb temperature of the air



Source: The authors

The relative humidity of the air just after passing through the evaporative panel was calculated based on the saturation and partial vapor pressures, both estimated based on the dry-bulb temperature of the air just after passing through the porous panel (SIDEBOTHAM, 2022):

$$RH = 100\ PV / PVS \tag{8}$$

Where RH is the relative humidity of the air (%), PV is the partial vapor pressure (kPa) and PVS is the saturation vapor pressure (kPa).

The saturation and partial vapor pressures were calculated simulating measurements from an aspirate psychrometer (NANDAGOPAL; NUGGENHALLI, 2022):

$$PVS = 6 \times 10^{25}\ e - 6800 / (T+273.15) / [1000\ (T + 273.15)^{5}] \tag{9}$$

$$PV = PSU - 0.00067\ P\ (T - TDB) \quad (10)$$

Where PVS is the saturation pressure of vapor (kPa), T is the dry-bulb temperature (°C), PSU is the saturation vapor pressure at wet-bulb temperature (kPa) and TDB is the wet-bulb temperature (°C).

The indoor air at the exit of the greenhouse corresponds to the temperature of the air just after passing through the evaporative panel added to the temperature increase along the length of the greenhouse. The relative humidity of the air at this location was also calculated by Equation 8, but considering the temperature at the exit of the greenhouse in the calculation of the saturation vapor pressure and changing the equation used to obtain the partial vapor pressure (SIDEBOTHAM, 2022):

$$PV = [P\ (UE + \Delta U)] / [0.622 + (UE + \Delta U)] \quad (11)$$

Where UE is the specific humidity of the air just after passing through the evaporative panel (g g^{-1}) and ΔU is the specific humidity increase along the length of the greenhouse (g g^{-1}).

The specific humidity increase along the length of the greenhouse depends on the air density, the commercial ventilation rate, the number of exhaust fans and the crop evapotranspiration rate, while the mass of water vapor in a unit mass of moist air just after passing through the evaporative panel depends on the partial vapor and atmospheric pressures (STEIDLE NETO; ZOLNIER, 2010; NANDAGOPAL; NUGGENHALLI, 2022):

$$UE = 0.622\ PV / (P - 0.378\ PV) \quad (12)$$

$$\Delta U = 60\ TE / (0.02831685\ \rho\ Tc\ n) \quad (13)$$

$$TE = 0.27778\ (Ev\ A\ To / 100) \quad (14)$$

Where TE is the crop evapotranspiration rate (g s^{-1}), ρ is the air density (kg m^{-3}), Ev is the crop evapotranspiration (mm h^{-1}) and To is the occupied area in the greenhouse (%).

The air density is affected by the variations in temperature and pressure, and was estimated as (LOPES; STEIDLE NETO; SANTIAGO, 2014):

$$\rho = (3483.7\ (Pa - PV) / (Tp + 273.15) + 2166.8\ (PV / (Tp + 274.15))) / 1000 \quad (15)$$

2.2 Software development

The software for sizing evaporative cooling systems of greenhouses was called Theoretical Evaporative (TE), and was developed using the NetBeans programming platform (Sun Microsystems, Vancouver, Canada). This open-source integrated development environment comprises user-friendly interface editor based on Object Oriented Programing, in addition to an editor that highlights source code syntactically and semantically, speeding up the refactoring and the identification of errors. The NetBeans platform also contains APIs that simplify the handling of windows, actions and files, supporting the development of all Java application types, such as Java Standard Edition including JavaFX, Java Mobile Edition, Web, Enterprise JavaBean and mobile applications (BAI, 2020).

Programming was performed in two stages, that were the interface generation and the code writing. During the interface creation, four windows were developed for data input and output, as well as for showing information about the software. These windows were implemented from a dedicated Java library, called Swing toolkit, which is widely used for this purpose (CIRANI *et al*., 2020). This library is native to NetBeans, simplifying the interface programming task and allowing to assemble complex graphical user interfaces (GUI) by placing components, such as buttons, labels, text areas and other, on a panel or a frame (DESCHAMPS; RIES, 2020). The java codes were linked to the buttons of the developed windows, where the equations and algorithms required for sizing the evaporative cooling systems of greenhouses were implemented according to the logical order of the tasks.

During the tests different sizing parameters were used, based on data available in scientific literature for different greenhouse operation conditions (Table 1).

Table 1. Main greenhouse operation conditions used during TE tests

Length (m)	Width (m)	Altitude (m)	Location	Reference
18.3	6.5	648.0	Brazil	STEIDLE NETO e ZOLNIER (2010)
40.0	8.0	599.0	Saudi Arabia	TSAFARAS *et al*. (2021)
6.0	4.5	2256.0	Mexico	OLVERA-GONZALEZ *et al*. (2013)
20.0	8.0	120.0	Greece	FERENTINOS *et al*. (2017)
11.0	5.2	10.0	Japan	KHAMMAYOM, MARUYAMA e CHAICHANA (2022)

Source: The authors

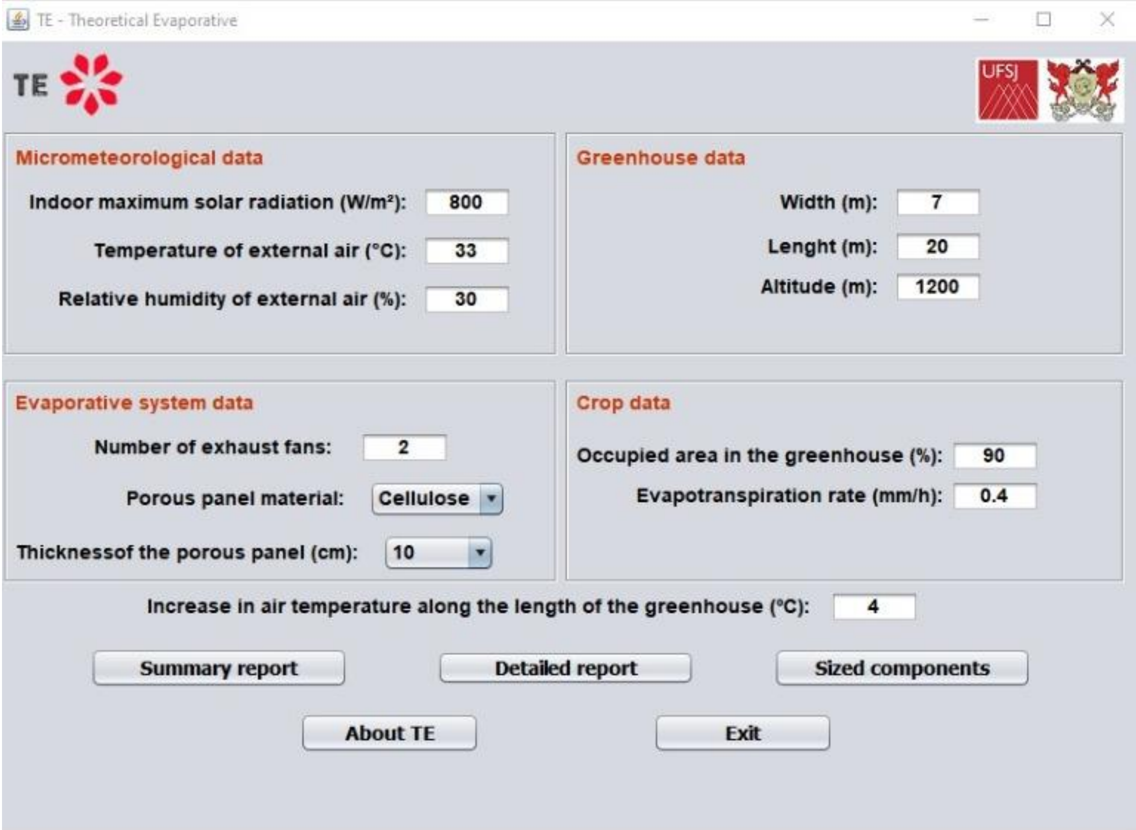
Other parameters were the indoor maximum solar radiation (100 – 1000 W m^2), increase in air temperature along the length of the greenhouse (1.5 – 8.5 °C), number of exhaust fans (1 - 6), external air temperature (25 – 40 °C), external relative humidity (25 – 70%), occupied area in the greenhouse by the crop (50 – 95%) and crop evapotranspiration rate (0.5 – 2.5 mm h^{-1}). All scenarios were sized considering porous panels with 10 and 15 cm of thickness. The reports were generated and compared to the calculations performed manually and in electronic spreadsheet.

3 RESULTS AND DISCUSSION

The software Theoretical Evaporative (TE) is freely available at https://www.ufsj.edu.br/dciag/aplicativos.php. This computational tool is easy-to-use and GUI-based. It can be executed on most Windows and Linux PCs without the need for dedicated cloud-hosted services. The software TE is composed by a main window for data input (Figure 3), where all information required for the sizing procedure are informed. The other windows can be accessed from this through specific buttons. Message dialogs were programmed to display a warning when inconsistent data is informed in this window, preventing the software from proceeding with the calculations. The variables with limited variation ranges in the TE were: greenhouse length (6 – 50 m), greenhouse width (2 – 15 m), altitude (0 – 3000 m), indoor maximum solar radiation (100 – 1200 W m^{-2}), increase in air temperature along the length of the greenhouse (1 – 10 °C), number of exhaust fans (1 - 10), external air temperature (5 – 50 °C), external relative humidity (5 – 99.9%), crop evapotranspiration rate (0 – 5 mm h^{-1}) and the occupied area in the greenhouse by the crop (5 – 95%).

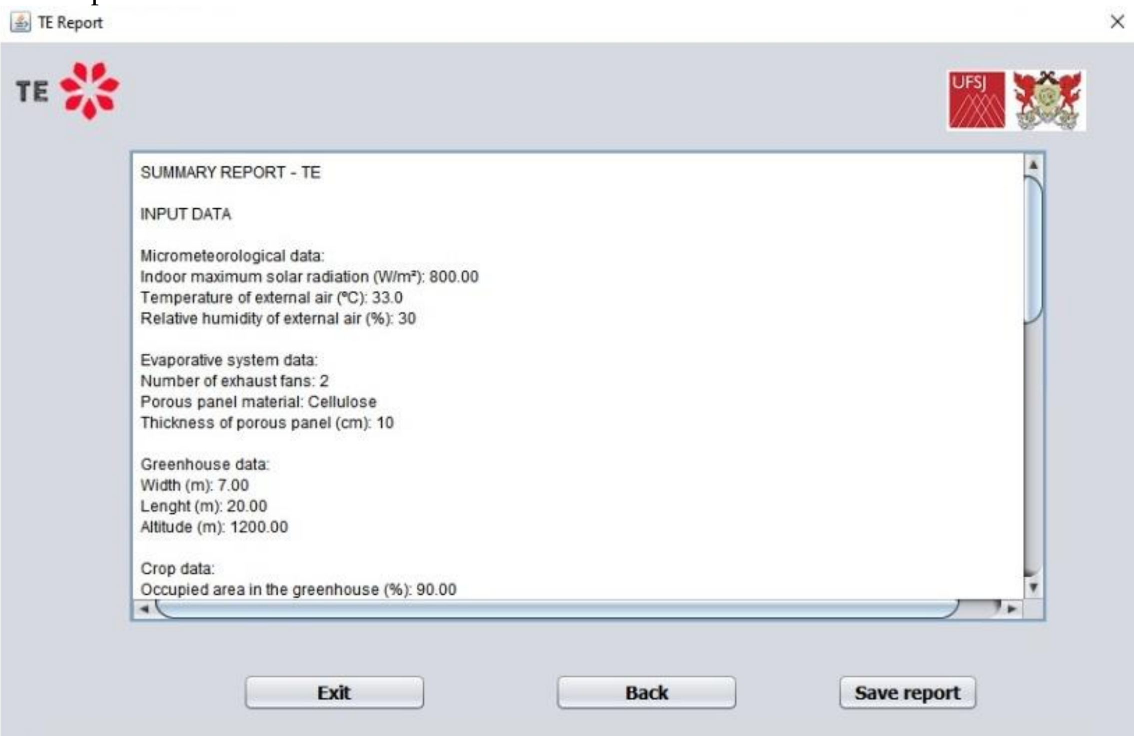
Figure 4 shows the report window, which can exhibit summary or detailed results, depending on user choice. Data can be saved in a text file, with the option of selecting the folder where information will be recorded. The summary report is generally preferred for farmers or greenhouse managers, presenting the results more objectively and focusing on information required for the evaporative system installing. These include the area of the greenhouse, theoretical and commercial ventilation rates, exhaust fan diameter and motor power, total porous material area, panel maximum efficiency, indoor air temperature and relative humidity just after passing through the panel, temperature and relative humidity of the indoor air leaving the de greenhouse. The detailed report is a better option for academic purposes, as it presents all calculations performed during the sizing procedure. That is, in addition to the information presented in the summary report, results of all psychrometric calculations and adjustment factors performed as auxiliary and supplementary calculations are showed.

Figure 3. Main window of the software TE



Source: The authors

Figure 4. Report window of the software TE

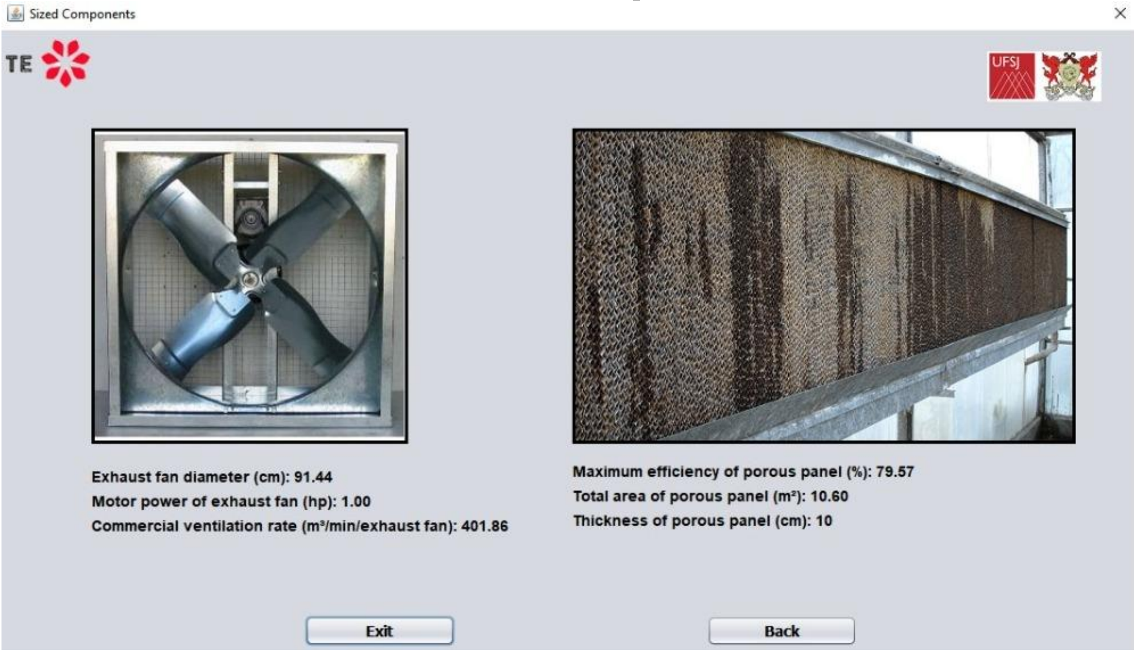


Source: The authors

Figure 5 presents the alternative result window, which shows the main components of the evaporative cooling system and its sized values. This window allows a more direct and objective visualization and understanding of the main data related to the exhaust fan and porous panel sizing.

In all windows the buttons and other graphical elements were inserted aiming at enabling the intuitive use of the software. Thus, the same style (colors, element placement, fonts and font sizes) was applied to all screens, as well as the most common technical terms and parameter units were used in the texts. This standardization allowed to present information and functionalities of the software in a simple and effective manner, helping the easily adaptation to the system and learning about how to use it.

Figure 5. Alternative window with the main sized components



Source: The authors

Regarding the tests with the software TE, the results were identical to those calculated manually and with an electronic spreadsheet. All warning messages were correctly activated when required. When considering the different operation scenarios, TE was capable of correctly sizing the evaporative cooling systems of greenhouses, including the psychrometric properties of the air and the environmental conditions (Table 2).

Table 2. Main sized parameters during the tests performed with the software TE

Parameter	Minimum	Maximum	Average
Temperature drop just after the panel (°C)	2.2	15.0	6.49 (± 4.5)
Relative humidity increase just after the panel (%)	15.0	61.0	35.4 (± 15.4)
Commercial ventilation rate (m^3 min^{-1})	430.2	967.9	680.3 (± 198.9)
Porous area (m^2)	4.0	12.6	7.7 (± 2.6)
Maximum efficiency of porous panel (%)	79.5	89.0	84.2 (± 4.9)
Exhaust fan diameter (m)	60.9	137.2	82.3 (± 31.5)
Exhaust fan motor (hp)	0.3	1.0	0.7 (± 0.3)

Source: The authors

As expected, maximum temperature drops and relative humidity increases were estimated for evaporative cooling systems installed in Saudi Arabia, due to the dry climate of the country. Al-Helal (2007) affirmed that extreme dry climates ensure large effects when using evaporative cooling systems in greenhouses, considerably reducing the air temperature while increasing the humidity, and creating a favorable climate for vegetable production. The estimates obtained with the software TE agreed with Tsafaras *et al*. (2021), who verified temperature drops around 14 °C and relative humidity increases up to 55% when investigating the evaporative cooling effects in two greenhouses located at a desert environment in Saudi Arabia.

The ventilation rate is related with the air changing in the greenhouse, and many times incorrect sizing leads to rates too high, also impacting the values for the exhaust fan diameter and power (KHAMMAYOM; MARUYAMA; CHAICHANA 2022). Average differences between the revised studies and the estimates performed by the software TE for these parameters were approximately 9%.

When considering the porous areas and the maximum efficiency of the cooling pads, porous material with greater thickness were 10.4% more efficient on average, also resulting in 27.7% smaller areas on average. The higher efficiency of the panels with larger thickness can be explained since the contact area between water and air mass increases due to the longer contact duration (TEJERO-GONZÁLEZ; FRANCO-SALAS, 2021). This agrees with Prozuments *et al*. (2022), who showed that increases in the cooling pad thicknesses improve saturation effectiveness, temperature drop and water evaporation rate.

In addition to the thickness of the panel and the airflow through the porous material, the momentary efficiency of the porous material is influenced by the variation in temperature and relative humidity of the outside air throughout the day. Since the estimates of the software TE consider the maximum efficiency of the porous panel, as well as average external climate conditions, the temperature and relative humidity values just after the air passes through the panel and at the exit of the greenhouse may be slightly different in real situations for different times of day and seasons.

4 CONCLUSIONS

The software Theoretical Evaporative (TE) is capable of speeding up the evaluation and planning of evaporative cooling systems in greenhouses, and can also be used for didactic purposes. The GUI and ready-to-run free download for Windows or Linux improves accessibility to the proposed tool. The methodology used in the development of this software can be adapted for different applications, such as aviaries and facilities for swine and cattle. It can further be used in control and automation systems, through adaptations in the algorithm and connection with adequate data acquisition systems. Future works include to expand the panel database, including other porous materials, different manufacturers and thicknesses.

5 REFERENCES

AL-HELAL, I. M. Effects of ventilation rate on the environment of a fan-pad evaporatively cooled, shaded greenhouse in extreme arid climates. **Applied Engineering in Agriculture**, St. Joseph v. 23, p. 221-230, 2007. DOI: doi.org/ 10.13031/2013.22605. Available at: https://elibrary.asabe.org/ abstract.asp?aid=22605. Accessed on: 22 nov. 2023.

BAI, Y. **Oracle Database Programming with Java**. Boca Raton: Auerbach Publications, 2020.

BELKADI NETO, A.; MEZGHANI, D.; MAMI, A. Energy study of a greenhouse and optimization of the choice of shape and covering material: based on an improved static model. **Engenharia Agrícola**, Jaboticabal, v. 41, n. 3, p. 297-310, 2021. DOI: http://dx.doi.org/10.1590/1809-4430-Eng.Agric.v41n3p297-310/2021. Available at: https://www.scielo.br/j/eagri/a/ TPJDFCbNZcQf5zrDWZzVTRf/?lang=en&format=pdf. Accessed on: 22 nov. 23.

CIRANI, S.; PICONE, M.; VELTRI, L.; ZACCOMER, L.; ZANICHELLI, F. ZWT: A new cross-platform graphical interface framework for Java applications. **SoftwareX**, New York, v. 12, article 100599, p. 1-6, 2020. DOI: https://doi.org/10.1016/j.softx.2020.100599. Available at:

https://www.sciencedirect.com/science/article/pii/S2352711020303125. Accessed on: 22 nov. 23.

DESCHAMPS, J.; RIES, J. EMU: reconfigurable graphical user interfaces for Micro-Manager. **BMC bioinformatics**, New York, v. 21, n. 1, p. 1-13, 2020. DOI: https://doi.org/10.1186/s12859-020-03727-8. Available at: https://bmcbioinformatics.biomedcentral.com/articles/10.1186/s12859-020-03727-8. Accessed on: 22 nov. 23.

DUAN, Z.; WANG, M.; DONG, X.; LIU, J.; ZHAO, X. Experimental and numerical investigation of wicking and evaporation performance of fibrous materials for evaporative cooling. **Energy and Buildings**, New York, v. 255, article 111675, p. 1-6, 2022. DOI: https://doi.org/10.1016/j.enbuild.2021.111675. Available at: https://www.sciencedirect.com/science/article /abs/pii/S0378778821009592. Accessed on: 22 nov. 23.

FERENTINOS, K. P.; KATSOULAS, N.; TZOUNIS, A.; BARTZANAS, T.; KITTAS, C. Wireless sensor networks for greenhouse climate and plant condition assessment. **Biosystems Engineering**, New York, v. 153, p. 70-81, 2017. DOI: https://doi.org/10.1016/j.biosystemseng.2016.11.005. Available at: https://www.sciencedirect.com/science/article/abs/pii/S1537511016302847. Accessed on: 22 nov. 23.

KHAMMAYOM, N.; MARUYAMA, N.; CHAICHANA, C. The effect of climatic parameters on strawberry production in a small walk-in greenhouse. **AgriEngineering**, St. Alban-Anlage, v. 4, n. 1, p. 104-121, 2022. DOI: https://doi.org/10.3390/agriengineering4010007. Available at: https://www.mdpi.com/2624-7402/4/1/7. Accessed on: 22 nov. 23.

KHOBRAGADE, N.; KONGRE, S. Experimental Performance of Different Evaporative Cooling Pad Material of Direct Evaporative Cooler in Hot and Dry Region. **International Journal of Innovative Technology and Research**, New Delhi, v. 4, n. 3, p. 2920-2923, 2016.

LOPES, D. C.; STEIDLE NETO, A. J.; SANTIAGO, J. K. Comparison of equilibrium and logarithmic models for grain drying. **Biosystems Engineering**, New York, v. 118, p. 105-114, 2014. DOI: https://doi.org/10.1016/j.biosystemseng.2013.11.011. Available at: https://www.sciencedirect.com/science/article/abs/pii/S1537511013001955. Accessed on: 22 nov. 23.

MISRA, D.; GHOSH, S. Evaporative cooling technologies for greenhouses: a comprehensive review. **Agricultural Engineering International**: CIGR Journal, Beijing, v. 20, n. 1, p. 1-15, 2018.

NANDAGOPAL, P. E.; NUGGENHALLI, S. **Fluid and Thermal Sciences**. Cham: Springer, 2022.

NELSON, P. V. **Greenhouse operation and management**. New Jersey: Prentice Hall, 1991.

NGMA. **Ventilation & cooling**. Littleton: National Greenhouse Manufacturer’s Association, 2008.

OLVERA-GONZALEZ, E.; ALANIZ-LUMBRERAS, D.; IVANOV-TSONCHEV, R.; VILLA-HERNÁNDEZ, J.; OLVERA-OLVERA, C.; GONZÁLEZ-RAMÍREZ, E.; ARAIZA-ESQUIVEL, M.; TORRES-ARGUELLES, V.; CASTANO, V. Intelligent lighting system for plant growth and development. **Computers and Electronics in Agriculture**, New York, v. 92, p. 48-53, 2013. DOI: https://doi.org/10.1016/j.compag.2012.11.012. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0168169912002694. Accessed on: 22 nov. 23.

PROZUMENTS, A.; BRAHMANIS, A.; MUCENIEKS, A.; JACNEVS, V.; ZAJECS,

D. Preliminary study of various cross-sectional metal sheet shapes in adiabatic evaporative cooling pads. **Energies**, St. Alban-Anlage, v. 15, article 3875, p. 1-7, 2022. DOI: https://doi.org/10.3390/en15113875. Available at: https://www.mdpi.com/1996-1073/15/11/3875. Accessed on: 22 nov 23.

RONG, L.; PEDERSEN, P.; JENSEN, T. L.; MORSING, S.; ZHANG, G. Dynamic performance of an evaporative cooling pad investigated in a wind tunnel for application in hot and arid climate. **Biosystems Engineering**, New York, v. 156, p. 173-182, 2017. DOI: https://doi.org/10.1016/j.biosystemseng.2017.02.003. Available at: https://www.sciencedirect.com/science/article/abs/pii/S153751101630842X. Accessed on: 22 nov. 23.

SANTOS, W. L.; RAMOS, M. M. **SACRID -** Software para aquisição de coordenadas reais de imagens digitais. Viçosa, MG: Universidade Federal de Viçosa, 2001.

SEIN, Z. M. M.; ULLAH, I.; IYAKAREMYE, V.; AZAM, K.; MA, X.; SYED, S.; ZHI, X. Observed spatiotemporal changes in air temperature, dew point temperature and relative humidity over Myanmar during 2001–2019. **Meteorology and Atmospheric Physics**, Wein, v. 134, n. 1, p. 1-17, 2021. DOI: https://doi.org/10.1007/s00703-021-00837-7. Available at: https://link.springer.com/article/10.1007/s00703-021-00837-7. Accessed on: 22 nov 23.

SHRIVASTAVA, K.; DESHMUKH, D. S.; RAWLANI, M. V. Experimental analysis of coconut coir pad evaporative cooler. **International Journal of Innovative Research in Science, Engineering and Technology**, Jaipur, v. 3, n. 1, p. 8346-8351, 2014.

SIDEBOTHAM, G. **An Inductive Approach to Engineering Thermodynamics**. Cham: Springer, 2022.

SHOJAEI, M. H.; MORTEZAPOUR, H.; JAFARINAEIMI, K.; MAHARLOOEI, M. M. An estimation method for greenhouse temperature under the influence of evaporative cooling system. **Journal of Thermal Engineering**, Istanbul, v. 7, n. 4, p. 918-933, 2021. DOI: https://doi.org/10.18186/thermal.930907. Available at: https://jten.yildiz.edu.tr/article/35. Accessed on: 22 nov. 23.

STEIDLE NETO, A. J.; ZOLNIER, S. Desempenho de um sistema de resfriamento evaporativo do ar em casa-de-vegetação. **Revista Irriga**, Botucatu, v. 15, n. 2, p. 1450-150, 2010. DOI: https://doi.org/10.15809/irriga.2010v15n2p140. Available at: https://irriga.fca.unesp.br/index.php/irriga/article/view/14/14. Accessed on: 22 nov. 23.

TEJERO-GONZÁLEZ, A.; FRANCO-SALAS, A. Optimal operation of evaporative cooling pads: A review. **Renewable & Sustainable Energy Reviews**, New York, v. 151, article 111632, p. 1-14, 2021. DOI: https://doi.org/10.1016/j.rser.2021.111632. Available at: https://www.sciencedirect.com/science/article/pii/S1364032121009072. Accessed on: 22 nov. 23.

TSAFARAS, I.; CAMPEN, J. B.; STANGHELLINI, C.; ZWART, H. F.; VOOGT, W.; SCHEFFERS, K.; AL HARBI, A.; AL ASSAF, K. Intelligent greenhouse design decreases water use for evaporative cooling in arid regions. **Agricultural Water Management**, Amsterdam, v. 250, article 106807, p. 1-10, 2021. DOI: https://doi.org/10.1016/j.agwat.2021.106807. Available at: https://www.sciencedirect.com/science/article/pii/S037837742100072X. Accessed on: 22 nov. 23.