GREGORY MURAD REIS

ZADEH'S PRINCIPLE EXTENSION APPLIED TO THE EVAPORATIVE PAD COOLING SYSTEMS

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GREGORY MURAD REIS

ZADEH'S PRINCIPLE EXTENSION APPLIED TO THE EVAPORATIVE PAD COOLING SYSTEMS

PRINCÍPIO DE EXTENSÃO DE ZADEH APLICADO AOS SISTEMAS DE RESFRIAMENTO EVAPORATIVO DO TIPO PAD COOLING

Dissertação apresentada à Universidade Federal de Lavras, como parte das exigências do Curso de Pós-Graduação em Engenharia de Sistemas, área de concentração em Modelagem de Sistemas Biológicos, para a obtenção do título de Mestre.

APROVADA em 17 de março de 2014.

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LAVRAS – MG

2014

À minha família, com o meu amor.

DEDICO

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“Tudo tem o seu tempo, e há tempo para
todo o propósito debaixo do céu.”

Eclesiastes 3:1

RESUMO

Sistemas de resfriamento evaporativo envolvem processos de transferência de calor e massa no resfriamento do ar, porém existe uma incerteza na variável de fração de área molhada da placa. Modelos matemáticos foram desenvolvidos com o objetivo de representar o princípio de extensão de Zadeh, que é uma forma de estender uma função do domínio real para o domínio *fuzzy*, com alguma variável sendo especificada como imprecisa. Essa teoria é uma forma apropriada de representação de conhecimento incerto e impreciso. Assim, os modelos *fuzzy* desenvolvidos se tornaram funções *fuzzy*, ao invés de funções de valores reais. O desenvolvimento de um software para esse modelo, bem como um teste com dados coletados de uma casa de vegetação da Universidade Federal de Lavras, mostraram que esses modelos são capazes de representar o sistema de resfriamento evaporativo, fornecendo uma maior generalização, maior precisão e se tornando uma ferramenta importante para a produção agropecuária. Além disso, esses modelos *fuzzy* podem ser usados para aumentar a eficiência de sistemas reais de resfriamento evaporativo.

Palavras-chave: Sistema de resfriamento evaporativo. Princípio de extensão de Zadeh. Modelagem matemática.

ABSTRACT

Evaporative cooling systems involve heat and mass transference processes in air cooling, however, there is an uncertainty in the wet area fraction variable of the board. Mathematical models were developed with the objective of representing the Zadeh extension principal, which is a way of extending a function from the real domain to the *fuzzy* domain, with a variable being specified as imprecise. This theory is an appropriate form of representing uncertain and imprecise knowledge. Thus, the developed *fuzzy* models became *fuzzy* functions instead of real value functions. The development of a software for this model, as well as a test with data collected from a greenhouse of the Universidade Federal de Lavras, show that these models are capable of representing the evaporative cooling system, providing larger generalization, higher precision and becoming an important tool for agriculture and livestock production. In addition, these *fuzzy* models may be used to increase the efficiency of real evaporative cooling systems.

Keywords: Evaporative cooling system. Zadeh extension principle. Mathematical modeling.

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1 INTRODUCTION

Mathematical modeling is the translation of the observation of a specific system, that is, the process of developing a model using experimental or theoretical concepts, mathematical concepts and using a given language. An efficient model is able to describe a system, predict, make decisions, analyze behavior and explain real-world phenomena. Mathematical modeling is used in various fields of natural sciences, engineering, and social sciences, among others.

Among the various types of existing models, there are the models that represent dynamical or statistical systems, differential equations, among others. Some authors divide the mathematical models in deterministic or stochastic, static or dynamic, continuous or discrete, individual or structured and qualitative or quantitative. The development of a mathematical model is also important for testing theories, evaluation of conjectures, optimization and design of systems that exist in nature or developed by man. The efficiency of a model is related to its ability to describe the real-world system that it represents.

When that objective is the representation of subjective concepts, vague and imprecise, especially when it is necessary to treat a qualitative problem in a quantitative way, the most appropriate model is the one based on the fuzzy set theory, developed by Professor Lotfi Askar Zadeh in 1965 (ZADEH, 1965). Due to its high flexibility, adaptability and applications in several areas of knowledge, fuzzy logic has been used to pattern recognition, robotics, systems development, and more recently in the area of animal welfare.

The Brazilian poultry industry stands out nationally and internationally, with Brazil being the largest exporter of poultry meat in the world. Thus, to maximize productivity, it is essential to combine a high genetic potential of the animals with nutritionally adequate feeding in aseptic environment and tailored to the needs of the poultry. In this context, the production environment plays a fundamental role in modern poultry production, since this aims to achieve high productivity in a relatively reduced physical space and time.

The thermal environment inside commercial broiler houses is usually maintained at levels more adequate to production by using ventilation and evaporative cooling systems. These systems have deficiencies in the management and design in various situations, which significantly affect the productivity of the animals and the total production of the farm. Among the cooling systems used, those made of wet porous plates (pad coolers), which equip the broiler houses with negative pressure ventilation systems stand out. These porous plates can be made of different materials; however, the most used are cellulose or expanded clay, though the latter has several advantages such as lower cost, durability and ease of cleaning.

It is noteworthy that there are few models developed for modeling wet porous plates, which most often are inaccurate or too specific. Therefore, the fuzzy modeling may provide greater accuracy and greater possibility of generalization.

2 OBJECTIVES

The main objective of this study is to apply the theory of Zadeh’s extension principle into the evaporative cooling process, which involves heat and mass transfers. This application was performed in order to deal with the uncertainty involved in the fraction of surface area of the pad that is wet. The specific objective is to develop a tool, using the fuzzy models, which is able to calculate the final air temperature and final humidity ratio.

3 THEORETICAL FRAMEWORK AND LITERATURE REVIEW

3.1 The evaporative cooling system

The evaporative cooling system is traditionally applied in regions with hot and dry climate (SMITH; HANBY; HARPHAM, 2011) and has been increasingly used due to low cost of development and maintenance, and their potential for high efficiency (CHEN et al., 2010; HEIDARINEJAD et al., 2009). Naticchia et al. (2010) also indicates the use of this system for temperate regions with long summer seasons. These systems help reduce the electricity use, contribute to reducing emissions of greenhouse gases and have been used in industrial, agricultural and residential sectors (RIANGVILAIKUL; KUMAR, 2010).

Several authors have studied the use of evaporative cooling systems. Almeida et al. (2010) analyzed the cost benefit ratio of these systems on milk production. Almeida et al. (2011) studied the effect of thermal comfort in Girolanda cows. Carvalho et al. (2009) performed the zoning potential of its use and Smith et al. (2011) performed a probabilistic analysis of the use of evaporative systems in temperate climates, reaching the conclusion that these systems will become an efficient technique for low-cost energy for hot climates in the future. Titto et al. (2012) conducted an experiment using this cooling system and found that the production of dairy cows has increased due to the increased thermal comfort generated by the deployed system.

Osorio et al. (2012) implemented a computational model in Computational Fluid Dynamics (CFD) that allows several forms of simulation of different configurations of evaporative cooling system, in which the user can vary the porosity, pad thickness and inlet air velocity; which may improve the efficiency of evaporative cooling systems using cooling pads in many ways.

3.2 Fuzzy logic

Due to the difficulty of analyzing large amounts of information and complexity that relate the parameters of agricultural production systems, there was a need to seek mathematical methods that incorporate subjective knowledge of experts who and that are able to simulate situations for decision support (AMENDOLA; SOUZA, 2004).

A fuzzy system is comprised of input and output variables. For each variable, fuzzy sets that characterize these variables are formulated, and for each fuzzy, a function is constructed. Subsequently, the rules that relate the input and output variables to the respective fuzzy sets are defined. The computational evaluation of a fuzzy system is formed by fuzzification (building variables which define the exit of the study), inference (the fuzzy reasoning applying fuzzy output), and defuzzification (translation of linguistic value for numerical value) (FERREIRA et al., 2007).

In controlled agricultural environments, such as animal production facilities, it is necessary to use control techniques of the environmental variables. Data mining and fuzzy logic, among other tools for decision making and for more precise actions, have contributed to the progress and speed of research in animal production (PERISSINOTTO et al., 2009).

Several authors have used fuzzy logic to evaluate the environment and welfare in poultry (FERREIRA, 2009; OLIVEIRA; AMENDOLA; NÄÄS, 2005) and according to Amendola et al. (2004), studies show the potential of using fuzzy set theory to establish more objective criteria in the decisions of producers.

3.3 Zadeh's Principle Extension

Fuzzy logic was first introduced by Professor Lotfi A. Zadeh in 1965 as a form of representation of uncertain and imprecise knowledge (ZADEH, 1965). In fuzzy theory, a fuzzy function is usually obtained from a function of real value through the Zadeh's extension principle. A function f is a mapping from an arbitrary set X, in an arbitrary set Y, in which each element x, belonging to X, is associated with a single object, f(x), and called the value of f in x Y. According to this principle, a function f can be extended to F(X) → F(Y), where F(X) is the class of all fuzzy sets in X and F(Y) is the class of all sets fuzzy Y as follows (KERRE, 2011):

$$f: \mathcal{F}(X) \rightarrow \mathcal{F}(Y) \tag{1}$$

$$A \mapsto f(A), \forall A \in \mathcal{F}(X) \tag{2}$$

With $f(A)$ given as:

$$f(A): Y \rightarrow [0,1] \tag{3}$$

$$y \mapsto 0, \forall y \in Y \setminus rng(f), \tag{4}$$

$$y \mapsto \sup\{A(x) | x \in X \ e \ f(x) = y, \forall y \in Y\} \tag{5}$$

$$\forall \ y \in rng(f) \tag{6}$$

Where $rng(f)$ denotes the range of f

The same reasoning can have when, from a mapping $X \rightarrow Y$, f induces mapping $\mathcal{F}(Y) \rightarrow \mathcal{F}(X)$, denoted f^{-1}:

$$f^{-1}: \mathcal{F}(Y) \rightarrow \mathcal{F}(X) \tag{7}$$

$$B \mapsto f^{-1}(B), \forall B \in \mathcal{F}(Y) \tag{8}$$

Where $f^{-1}(B)$:

$$f^{-1}(B): X \to [0,1] \tag{9}$$

$$x \mapsto B\big(f(x)\big), \forall x \in X \tag{10}$$

Zadeh's extension principle has been studied and applied by many authors. Bzowski and Urbanski (2013) performs an analysis of the extension principle of Zadeh expressed by the generalized form of the theorem Nguyen-Fuller-Keresztfalvi. Scheerlinck, Vernieuwe and Baets (2012) states that a direct implementation of Zadeh's extension principle is still computationally infeasible for practical use and the author applies various optimization algorithms in order to find the output values of the fuzzy interval. Chalco-Cano, Lodwick and Bede (2011) studies the fuzzy differential equations, where the right part of the equation is a fuzzy function generated by application of Zadeh's extension principle, and concludes that the application of this principle is more suitable for obtaining fuzzy functions than fuzzy functions obtained by using the usual fuzzy interval arithmetic. Roman-Flores et al. (2011) studies the dynamic properties of the fuzzy function obtained by Zadeh's extension principle when the original continuous function is turbulent and erratic. Huang (2010) studies the extension applied to fuzzy value continuous functions by using the sendograph-method. Román-Flores and Chalco-Cano (2008) study some aspects of fuzzy chaotic systems, concluding that these systems are a powerful tool for modeling many problems, especially those whose variables or parameters involved has a non-deterministic nature.

4 METHODS

Zadeh's Extension Principle was applied to a mathematical model based on equations for mass and heat transfer in order to determine the efficiency of the wet porous plates evaporative cooling systems. Thus, the fuzzy model was validated with data collected in the field and simulations were performed.

This section is divided according to the development of the fuzzy model. First, the equations (models) for final air temperature and final humidity ratio of the air were found by using heat and mass transfers. Second, Zadeh's extension principle was applied in order to develop a fuzzy model.

4.1 Balance of heat and mass transfer in wet porous plates

The energy balance shown in Figure 1 can be expressed as the sum of the variation of energy of water and air, according to the equation 11.

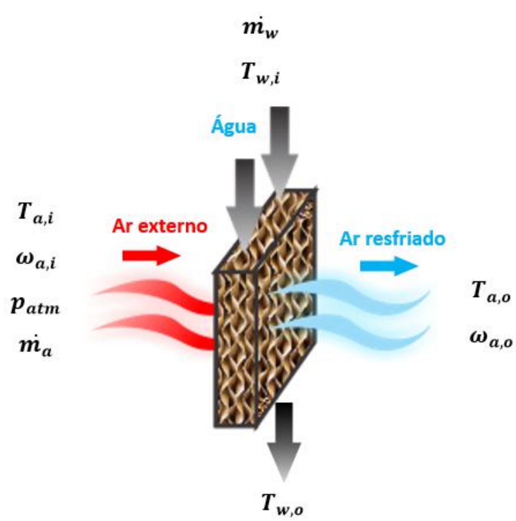

Figure 1 Schematic of a porous plate with its input and output variables

$$dq_w = -dq_a \tag{11}$$

The variation of the energy of the water can be expressed by equation 12.

$$dq_w = d\left(\dot{m}_w \cdot c_{p,w} \cdot T_w\right) \tag{12}$$

Where,
dq_w: variation of energy of water (W);
$\dot{m}_w$: mass flow rate of water through the wet porous plate (kg water s^{-1});
$c_{p,w}$: specific heat of water (J kg^{-1} $^oC^{-1}$);
T_w: water temperature (^oC).

In turn, the variation of energy of the air can be calculated by the sum of the changes in sensible and latent energy (equation 13).

$$dq_a = dq_{a,s} + dq_{a,l} \tag{13}$$

Where,
dq_a: variation of energy of the air (W);
$dq_{a,s}$: variation of sensible energy (W);
$dq_{a,l}$: variation of latent energy (W).

The sensible heat transfer can be calculated as expressed in equation 14.

$$dq_{a,s} = \dot{m}_a \cdot c_{p,a} \cdot dT_a = h \cdot (T_w - T_a) \cdot dA \tag{14}$$

Where,

$\dot{m}_a$: mass flow rate of dry air through the wet porous plate (kg s^{-1});

$c_{p,a}$: specific heat of air (J kg^{-1} ºC $^{-1}$);

dT_a: variation of air temperature (ºC);

h: coefficient of heat transfer by convection (W m^{-2} ºC $^{-1}$).

The latent heat transfer can be expressed by equation 15.

$$dq_{a,l} = \dot{m}_a \cdot h_{f_g} \cdot d\omega_a \tag{15}$$

With,

h_{f_g}: latent heat of vaporization of water (kJ kg^{-1}).

$d\omega_a$: variation of specific humidity in the air mass ($kgágua \cdot kg^{-1}_{ar\ seco}$).

4.1.1 Transfer of sensible heat

After rearranging the equation 14 to calculate the transfer of sensible heat and applying variable substitution (dA), there is the equation 16.

$$\frac{1}{(T_w - T_a)} \cdot dT_a = \frac{h}{\dot{m}_a \cdot c_{p,a}} \cdot \sigma \cdot \beta \cdot W \cdot H \cdot dx \tag{16}$$

with,

σ: surface area of the porous material comprising the pad cooling per unit volume (m^2 m^{-3});

β: fraction of surface area of the porous material that is wet (decimal);

W: pad length (m);

H: pad height (m);

dx: variation of the pad cooling thickness (m).

Once the integration in equation 16 is applied, the equation 17 is given for later calculation of $T_{a,o}$.

$$\int_{T_{a,i}}^{T_{a,o}} \frac{1}{(T_w - T_a)} \cdot dT_a = \frac{h}{\dot{m}_a \cdot c_{p,a}} \cdot \sigma \cdot \beta \cdot W \cdot H \cdot \int_0^L dx \tag{17}$$

With,

$T_{a,i}$: initial air temperature (before passing through the wet porous plate) (ºC);

$T_{a,o}$: final air temperature (after passing through the wet porous plate) (ºC);

L: pad cooling thickness (m).

The integration in equation 17 results the equation 18, which is used for the calculation of $T_{a,o}$.

$$T_{a,o} = T_w + \left(T_{a,i} - T_w\right) \cdot e^{-\frac{h}{\dot{m}_a \cdot c_{p,a}} \cdot \sigma \cdot \beta \cdot W \cdot H \cdot L} \tag{18}$$

4.1.2 Mass transfer

The mass variation of vapor water of a certain mass of air that passes through a wet porous plate can be expressed by equation 19.

$$\dot{m}_a \cdot d\omega_a = k_d \cdot \left[\omega_{a,s}\,(T_w) - \omega_a\right] \cdot dA \tag{19}$$

With,

$d\omega_a$: variation of humidity ratio of the air for the saturation condition, calculated based on the air temperature T_a ($kg_{water} \cdot kg_{dry\ air}^{-1}$);

k_d: coefficient of mass transfer by convection based on the use of specific humidity ($kg_{air} \cdot m^{-2} \cdot s^{-1}$);

$\omega_{a,s}(T_w)$: humidity ratio for the saturation condition, calculated based on the water temperature T_w ($kg_{water} \cdot kg_{dry\ air}^{-1}$);

ω_a: humidity ratio of the air for the saturation condition, calculated based on the air temperature T_a ($kg_{water} \cdot kg_{dry\ air}^{-1}$);

dA: total surface area through which the evaporation may occur for the thickness dx.

The mass transfer coefficient by convection is related to k_d through the equation 20.

$$k_d = h_m \cdot \rho_a \tag{20}$$

With,

h_m: mass transfer coefficient (m s^{-1});

ρ_a: dry air density (kg m^{-3}).

By replacing the equation 20 in the equation 19 and by applying the integration, the equation 21 is given:

$$\int_{\omega_{a,i}}^{\omega_{a,o}} \frac{1}{\omega_{a,s}(T_w)-\omega_a} \cdot d\omega_a = \frac{h_m \cdot \rho_a}{\dot{m}_a} \cdot \sigma \cdot \beta \cdot W \cdot H \cdot \int_0^L dx \tag{21}$$

With,

$\omega_{a,i}$: initial humidity ratio of the air (before passing through the wet porous plate) ($kg_{water} \cdot kg_{dry\ air}^{-1}$);

$\omega_{a,o}$: final humidity ratio of the air (after passing through the wet porous plate) ($kg_{water} \cdot kg_{dry\ air}^{-1}$).

The integration of the equation 21 results in the equation 22 for the calculation of the humidity ratio of the air after passing through the wet porous plate, $\omega_{a,o}$, which is similar to the integration performed for the heat balance.

$$\omega_{a,o} = \omega_{a,s}(T_w) - \left[\omega_{a,s}(T_w) - \omega_{a,i}\right] \cdot e^{-\frac{h_m \cdot \rho_a}{\dot{m}_a} \cdot \sigma \cdot \beta \cdot W \cdot H \cdot L} \tag{22}$$

4.2 Application of Zadeh's principle extension

Zadeh's principle extension was applied to the equations 18 and 22 for the calculation of final air temperature $T_{a,o}$ and final humidity ratio of the air $\omega_{a,o}$. The variable β of the model was considered uncertain (fuzzy), in both equations. This variable was chosen as uncertain because there is an uncertainty in the determination of the fraction of the wet area of the porous plate, mainly due to the uneven (irregular) distribution of water flow throughout the pad material, the potential problems and the heterogeneity of the water flow by the emitters, among other reasons.

The variable β ranges from 0 to 1, with 0 being a plate that is completely dry and 1, a plate that is completely wet. Intermediate values can determine the efficiency of functioning of the evaporative cooling systems and cannot be determined precisely. The larger the wet surface area, the higher the cooling efficiency. Therefore, for a specific value of β, there is a corresponding membership value ($\mu(x)$), with x being the value of β. When, for a certain value of β, $\mu(x) = 1$, it indicates that that value of β is the correct percentage of the surface area that is wet. When the value of $\mu(x)$ moves away from 1, approaching a lower value, it indicates that the percentage of the surface area that is wet is around the value of x, but not exactly that. The latter case represents best what happens in a real-world evaporative cooling system. For values 0 and 1 for the variable β, the membership value was 0. The first one because when the system is functioning, some surface area is supposed to be wet in order to cool the air that is pulled through the pad; and the second one because it is unlikely to have a completely and homogeneously surface area that is wet in a real-world evaporative cooling system.

This developed fuzzy model was implemented in Java language 1.7.5 (available for free on Java Website: http://java.com/en/download/index.jsp), using the software NetBeans® 7.2.1 (available for free on NetBeans Website: https://netbeans.org/downloads/) as the integrated development environment. The software is best used in the operating systems Windows®.

4.3 Experimental data measurements

Data from an evaporative cooling system, with wet porous plate, were collected in a greenhouse of the Department of Plant Pathology, at the Federal University of Lavras (UFLA), in Lavras (21 º 14 'S latitude, 45 ° 00' W longitude, 918 m altitude), state of Minas Gerais. The climate in the city is tropical of altitude.

The greenhouse has dimensions of 22.10 x 12.85 x 2.9 m, east-west oriented, transparent plastic arched covering, four hoods, ventilation system in tunnel mode with negative pressure and a porous plate made of expanded clay with dimensions of 12.85 x 1.56 x 0.12 m, positioned at 1 m distance from the wet porous plate.

The porous material of the pads was physically characterized by determining the density, porosity, average diameter, average volume and surface area. Fifty units of expanded clays for each sample were used (randomly collected in the porous plate).

The density of the porous material was determined by the method of supplementary volume:

$$\rho = \frac{m}{V} \tag{23}$$

Where,

ρ: density of the porous material ($g\ cm^{-3}$);

m: mass of the porous material (g);

V: volume of the porous material (cm^3).

To determine the porosity of the porous material, a fluid was used to fill the pores of the expanded clay sample until it saturates the entire the whole sample. Then, the volumes of the fluid and the sample were measured for determining the total porosity (ARAÚJO, 2004).

$$P = \frac{V}{V_{total}} \cdot 100 \tag{24}$$

With,

P: total porosity of the clays (%);

V: pore volume (cm^3);

V_{total} : total volume of the container (cm³).

The average diameter, average volume and surface area of the samples were obtained from three photographs obtained in a (4.0 mega-pixels) digital camera at different angles. The images were then imported into AutoCAD ® 2006 software (Autodesk), so then, from image manipulations, the desired variables were calculated.

In the greenhouse, to obtain the remaining variables, pre-programmed sensors/portable recorders (± 3%), to collect data of air temperature (T_a) and relative humidity (RH) were installed close to the two faces of the plate at intervals of two seconds. To calculate the average temperature of the water dripped onto the plate, a digital thermometer (± 0.2 ° C), placed inside the water tank and gutter, was used to collect water temperatures at intervals of thirty minutes.

To obtain the air flow through the porous plate, it was determined a sampling region with dimensions 1.56 x 1.45 m, divided into nine equidistant points, where the collection of air velocity were performed, from a digital anemometer (± 3%), when the system was in operation, performing twelve repetitions. The air flow was determined by the product of the measured air velocity and the area of the plate.

5 RESULTS

This is the organization of the results section: first, the software developed is presented, as well as its functions; then, the collected data are shown and the validation of the software is made.

5.1 Software development

Based on the models developed by using heat and mass transfer theory and by applying Zadeh's extension principle in the variable β (percentage of the surface area that is wet), a software was developed. This software contains a main window (Figure 2), which had the fields for the user to enter the values of the variables. There are fields that correspond to variables involved in both heat and mass transfer processes and there are specific fields for these processes too. The user is allowed to choose between final air temperature ($T_{a,o}$) and final humidity ratio of the air ($\omega_{a,o}$).

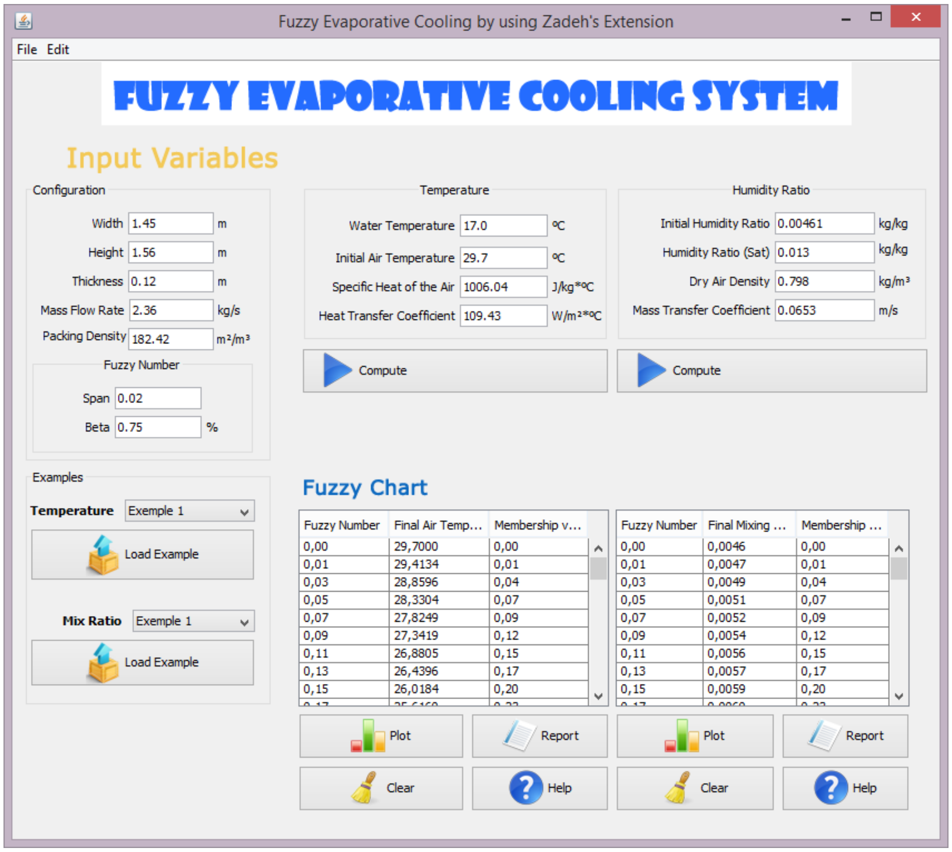

Figure 2 Main window of the software developed

The fields for the input values the are used for both processes are: W (pad length - m), H (pad height - m), L (thickness of the pad - m), $\dot{m}_a$ (mass flow rate of dry air through the wet porous plate - kg s^{-1}), σ (surface area of the porous material comprising the pad cooling per unit volume - m^2 m^{-3}), the span and β (fraction of surface area of the porous material that is wet - decimal).

For the final air temperature, the fields are T_w (water temperature-ºC), $T_{a,i}$ (initial air temperature - ºC), $c_{p,a}$ (specific heat of air - J kg^{-1} K^{-1}) and h (coefficient of heat transfer by convection - W m^{-2} K^{-1}).

When the final humidity ratio of the air is required, the fields are $\omega_{a,i}$ (initial humidity ratio of the air - $kg_{water} \cdot kg_{dry\ air}^{-1}$), $\omega_{a,s}(T_w)$ (humidity ratio for the saturation condition, calculated based on the water temperature T_w - $kg_{water} \cdot kg_{dry\ air}^{-1}$), ρ_a (dry air density - kg m^{-3}) and $c_{p,w}$ (specific heat of water - J kg^{-1} K^{-1}), h_m (mass transfer coefficient - m s^{-1}).

If the heat transfer process is the one required by the user, then they must press the 'Compute' button that is located under the temperature panel. This button is responsible for calculating the final air temperature $T_{a,o}$ (ºC) and for applying Zadeh's principle extension. Once this button is pressed, a table, called 'Fuzzy chart', is completed and it shows the values of the fuzzy number, final air temperature and the membership values. It means that for each value of β, there are the final air temperature and its corresponding membership value.

If the mass transfer process is required, the user is supposed to select the panel for humidity ratio of the air and do the same as the previous case.

A triangular membership function was chosen to represent the fuzzy number β, once it best represents the profile of the variable.

The window also has additional buttons. The button 'Plot' under the table for the temperature case is responsible for generating three new windows (Figures 3, 4 and 5) with three different plots, 'Fuzzy number x Membership value', 'Fuzzy number x Final air temperature' and 'Final air temperature x Membership value' for the heat transfer process. The button 'Plot' under the table for the humidity ratio case is responsible for generating the plots 'Fuzzy number x Membership value', 'Fuzzy number x Final humidity ratio' and 'Final humidity ratio x Membership value' for the final humidity ratio of the air. 'Clear' is responsible for clearing the filled fields, 'Help' shows some guidelines for first users, 'Info' shows some information related to the software and its purpose and 'Report' generates a document with the input values entered by the user.

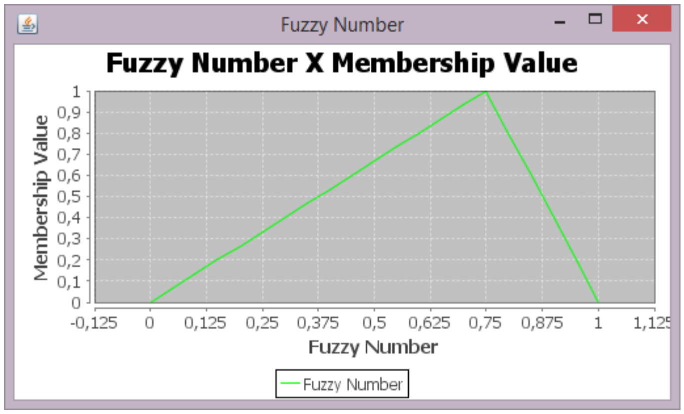

Figure 3 Generated plot by the software of ‘Fuzzy Number x Membership Value’ for the final air temperature

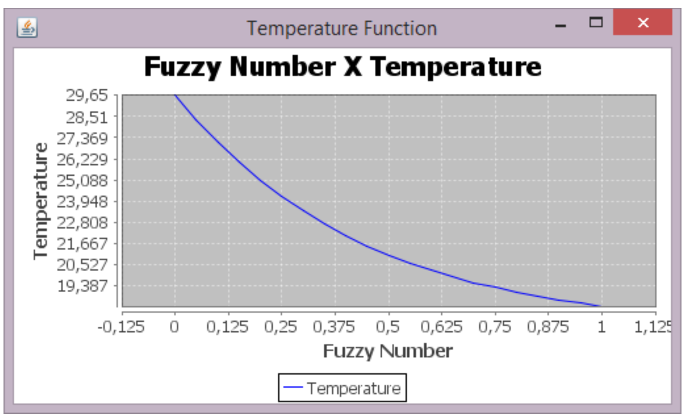

Figure 4 Generated plot of ‘Fuzzy Number x Temperature’ for the final air temperature.

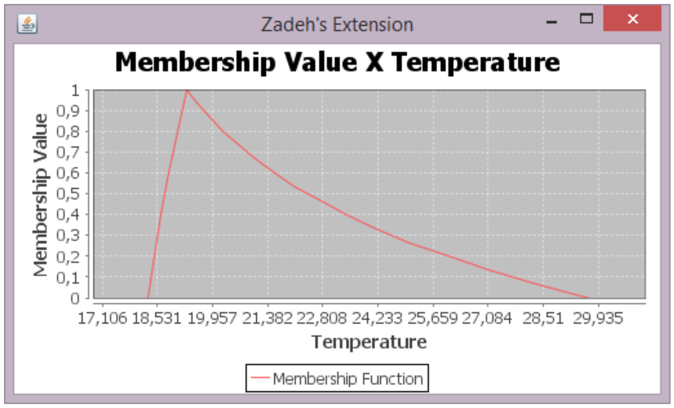

Figure 5 Generated plot of 'Temperature x Membership Value' for the final air temperature

5.2 Software Application

Five thousand, two hundred and ninety-seven data were collected for each variable involved in the model, except for the variable β. These data were analyzed and applied in the model in order to find the corresponding values of β. Then, the mean value of all the values found for β was used in the fuzzy model (after the application of Zadeh's extension principle) in order to validate this developed model. In other words, once there were values for each variable involved in the model, except for β, this was found algebraically. Then its mean value was calculated and used in the validation of the software. Table 1 shows the descriptive statistics for each variable involved in the heat transfer process, including β and Table 2 shows the descriptive statistics for each variable involved in the mass transfer process.

Table 1 Descriptive statistics for the collected values for each variable involved in the heat transfer process

Variables	Mean	Median	Minimum	Maximum	Standard deviation
T_w ($°C$)	17.0	17.0	16.8	17.5	0.2
$T_{a,i}$ ($°C$)	29.7	29.5	25.6	32.8	2.3
$\dot{m}_a$ (kg s^{-1})	2.36	2.36	2.36	2.36	0.00
$c_{p,a}$ (J kg^{-1} ºC^{-1})	1006.04	1006.03	1006.01	1006.14	0.031
h (W m^{-2} ºC^{-1})	109.43	114.21	47.74	136.80	22.819
σ (m^2 m^{-3})	182.42	182.42	182.42	182.42	0.00
β (decimal)	0.75	0.76	0.50	0.94	0.10
W (m)	1.45	1.45	1.45	1.45	0.00
H (m)	1.56	1.56	1.56	1.56	0.00
L (m)	0.12	0.12	0.12	0.12	0.00

Table 2 Descriptive statistics for the collected values for each variable involved in the mass transfer process

Variables	Mean	Median	Minimum	Maximum	Standard deviation
$\omega_{a,s}(T_w)$ $(kg \cdot kg^{-1})$	0.013	0.013	0.0133	0.0139	$1.77 \cdot 10^{-4}$
$\omega_{a,i}$ ($°C$)	0.00461	0.00461	0.00459	0.00465	$1.26 \cdot 10^{-5}$
$\dot{m}_a$ $(kg\ s^{-1})$	2.36	2.36	2.36	2.36	0.00
ρ_a $(kg \cdot m^{-3})$	0.798	0.798	0.793	0.799	$1.4 \cdot 10^{-3}$
h_m $(m \cdot s^{-1})$	0.0653	0.0653	0.0653	0.0653	0.00
σ (m^2 m^{-3})	182.42	182.42	182.42	182.42	0.00
β (decimal)	0.75	0.76	0.50	0.94	0.10
W (m)	1.45	1.45	1.45	1.45	0.00
H (m)	1.45	1.45	1.45	1.45	0.00
L (m)	1.45	1.45	1.45	1.45	0.00

From the observed data, the mean value for β is 0.75, which implies that this is the value that has the corresponding membership value 1. The developed fuzzy model uses this value to find a set with the approximate values for β, once this variable is imprecise. Therefore, the software performs Zadeh's extension principle for β values ranging from 0 to 1, but with 0.75 being the value with the highest membership value, 1. This indicates that 0.75 is the approximate percentage of the surface area that is wet. Any value that departs from this value has a lower membership value, indicating that that percentage is inappropriate, rare or the system is malfunctioning. The representation of Zadeh's extension principle process is shown in the Figures 6 and 7 for the final air temperature function and humidity ratio function, where x is the fuzzy number, $f(x)$ represents the function, (x) is the membership function for the fuzzy number and $\mu(y)$ is the membership function for the values of $f(x)$.

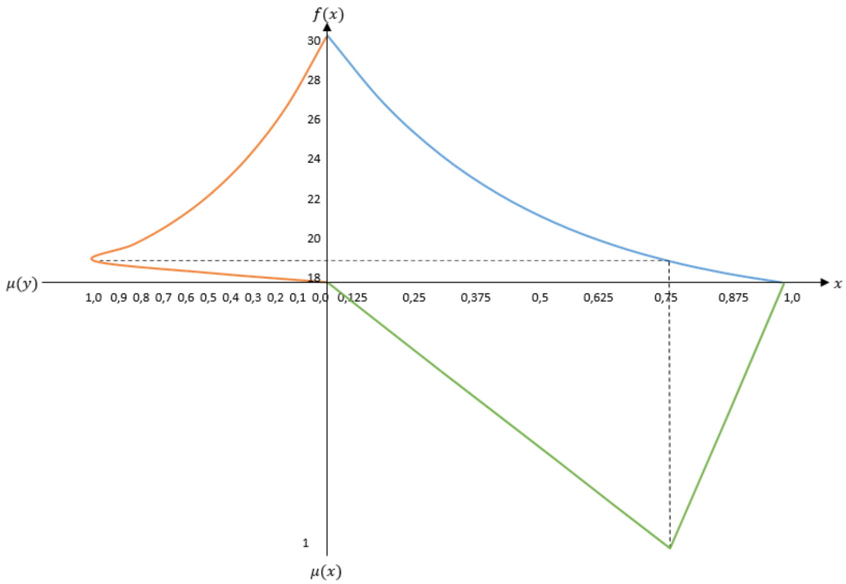

Figure 6 Graphic process of Zadeh's extension principle for the final air temperature function

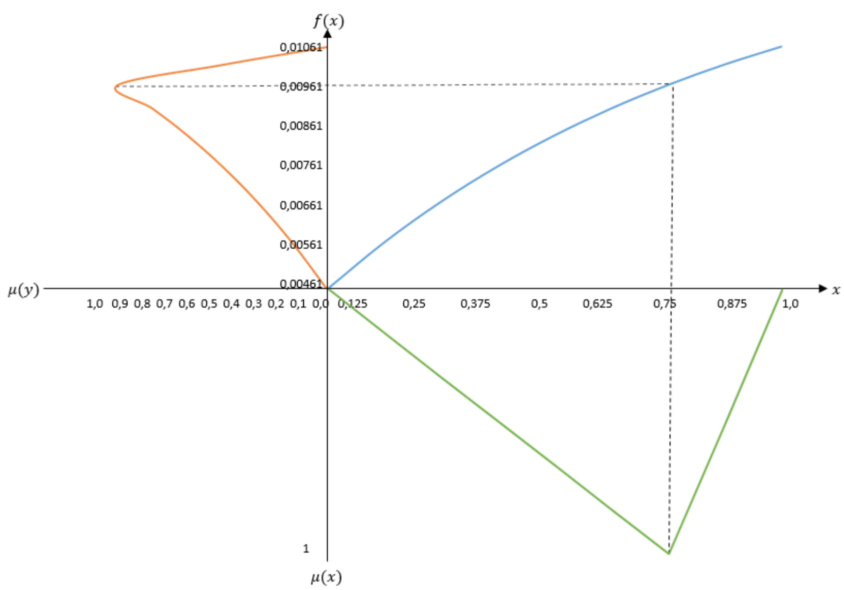

Figure 7 Graphic process of Zadeh's extension principle for the final humidity ration function

6 CONCLUSION

From the results obtained in this study, it was possible to extend the theoretical and practical knowledge of the evaporative cooling system using wet porous plates, and develop a model that simulate its functioning considering the uncertainty involved in the wetting of the plates through Zadeh's principle extension. The software developed for engineers and students of engineering can be used to predict the output variables involved in the evaporative cooling process, which can be useful for optimizing the building of a system that uses this process. Furthermore, it is possible to see in plots the variations of the output variables involved, which is easier for the user to understand the decrease and increase of values depending on the configuration of the system.

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