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PREDICTING THE HYDROPHOBIC NATURE OF KNITTED FABRIC USING FUZZY LOGIC MODELING

KABBARI M.[1, *], GHITH A.[1], FAYALA F. [2], AND LIOUANE N .[1]

[1] ATSI (UNITE DE RECHERCHE AUTOMATIQUE TRAITEMENT DE SIGNAL ET IMAGE)
[2] LESTE (LABORATOIRE D'ETUDE DES SYSTEMES THERMIQUES ET ENERGETIQUES)
NATIONAL ENGINEERING SCHOOL OF MONASTIR - MONASTIR UNIVERSITY

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ABSTRACT

In this research, fuzzy modeling method was used to predict the hydrophobic nature of knitted fabrics samples after a stain repellent treatment. This study undertaken to maximize the values of contact angle with maintain of air permeability of fabrics. Hence, we attempt to formulate a theoretical model of predicting the behavior of the contact angle after applying a chemical treatment with a fluorocarbon resin towards the variation of the input parameters. To choose the most relevant input parameters, we used the fuzzy c-means algorithm to detect the impact of each input parameter in our experimental field of interest. Results obtained showed that the hydrophilic samples were transformed to hydrophobic one in some tests.

KEYWORDS

Contact angle; fuzzy logic; air permeability; hydrophobic nature; fuzzy c-means.

1. INTRODUCTION

Knitting fabrics are widely used thanks to their ability to conform to shapes and their improved drape ability. Because of good flexibility of knitting technology, more knitted structures have been developed for technical applications in recent years [Araújo. M et al, 2004]. However, the stain repellent was usually applied on woven fabrics more than knit ones. The literature suggests that many studies are conducted to predict the behavior of different textile structure towards such treatment.

Fluorochemical coatings dominate the stain repellency textile apparel market. Out of all existing textile chemicals, only fluorochemicals have shown the unique property to provide fabrics a sufficiently low surface energy coating able to resist penetration of both oil and water-based stains (polar and non-polar liquids). Unfortunately, fabrics modified with fluorochemicals by conventional textile finishing methods often show poor performance with laundering or wear [Kathirvelu. S, 2010]. Application of perfluorochemicals can be accomplished in a variety of ways, many of which impart hydrophobicity and/or oleophobicity to fabrics in addition to other desirable properties. Scientists at the German Textile Research Centre North west, for example, obtained a hydrophobic coating of perfluoro-4-methylpent-2-ene by photonic surface treatment with a pulsed UV-laser [Holme. I, 2007]. Similarly, pulsed plasma polymerization of monomers with long perfluoroalkyl chains by Badyal and co-workers yielded a hydrophobic thin film coating [Badyal, J.P, 2001].

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[*] : Corresponding author. Email : moniakabbari@yahoo.fr

Superhydrophobic mats have been prepared with initiated chemical vapor deposition involving polymerization of perfluoroalkylethyl methacrylate [Bubert. H, 2011], While Gleason and co-workers used initiated chemical vapor deposition to coat electrospun non-woven fabrics with superhydrophobic character [Ma, M.L et al, 2007]. In a very different approach, direct fluorination of twaron fiber with elemental fluorine not only changed the nature of the fiber surface, it also increased mechanical and thermal properties of a fiber composite [Maity. J et al, 2008]. Sol-gel methods have been successfully employed to impart oil/water repellency and anti-bacterial capability to cotton using fluorocarbon polymer/SiO2 and silver nanoparticle-doped silica hybrid materials, respectively [Tarimala. S et al, 2006, Yeh. J-T et al, 2007]. Lastly, nanoparticles of fluorochemical coated silica and of gold have been applied to cotton and other fabrics to create a chemically inert fiber surface with superlyophobic properties [Wang. T et al, 2007; Hoefnagels, H.F et al, 2007; Xue, C.H et al, 2008; Wang. H et al, 2008; Leng. B et al, 2009; Zhao. Y et al; 2010]. This broad range of approaches reflects the interest and challenges in this area.

For plush knit fabrics which are used for baby clothes, this character was not yet studied. That is why in this work, we investigate the impact of the input parameters of a chemical treatment on predicting hydrophobic character of plush knitted. In addition, the results from a fuzzy analysis using different membership functions are compared to determine which one is more accurate in predicting the high value of contact angle with maintain of the air permeability.

2. METHODS

2.1. Fuzzy logic technique

The foundation of fuzzy logic, which is an extension of crisp logic, was laid by Lotfi A. Zadeh [Zadeh. L, 1965]. The theoretical aspects of fuzzy logic and fuzzy arithmetic have been explained in many standard textbooks authored by [Zimmerman, H. J, 1996], [Berkan, R. C., and Trubatch, S. L, 2000], [Kartalopoulos, S. V, 2000], [Klir, G. J., and Yuan, B, 2000] and [Bector, C. R., and Chandra, S, 2004]. In crisp logic, such as binary logic, variables are true or false, black or white, 1 or 0. In fuzzy logic, a fuzzy set contains elements with only partial membership ranging from 0 to 1 to define uncertainty of classes that do not have clearly defined boundaries. For each input and output variable of a fuzzy inference system (FIS), the fuzzy sets are created by dividing the universe of discourse into a number of sub-regions, named in linguistic terms (high, medium, low etc.). Several studies [Altinoz, C., and Winchester, S. 2001, Jaouachi, B , 2010; Hyung, T, 2001] are conducted using a fuzzy approach in order to simulate, predict and evaluate textile structure properties. In fact, several advantages make fuzzy logic theory among the tools of forecast which are most used by researchers. Altinoz suggests that fuzzy logic is an enabling technology that can be used to capture expertise and compute using linguistic rules for supplier selection. Usually, the fuzzy logic method is based on four essential steps. First, fuzzification consists to convert the feature values of input and output parameters. Second, design of the fuzzy rules to implement the model for prediction. Third, the fuzzified values are then inferred to provide decisions by the inference engine with the support of the fuzzy rule base. Finally selection by défuzzification converts fuzzy sets into a crisp value [Cox, E. 1995]. In our work, triangular (Trimf), gaussian (Gauss), sigmoid (Sigm), trapezoidal (Trapf) and generalized bell (Gbellf) membership functions were used to evaluate and predict the contact angle and air permeability of plush knitted fabric after a stain repellent treatment.

2.2. Selection procedure of relevant input parameters

In this paper, the fuzzy sensitivity criterion developed by Deng et al [X. Deng, P et al, 2006, X. Deng, P, 2007] is used for selecting the most relevant input parameters of plasma process. The main advantage of this method is that it can deal with a limited number of learning data. Its principle consists of calculating distances or variations between individual data samples in the input space (process parameters) and the output space (quality features), respectively. Then, fuzzy logic is used to evaluate the sensitivity variation of each input variable related to the output variable. The sensitivity for all the input variables is defined according to the two following principles:

1) If a small variation Δx of an input variable corresponds to a large variation of the output variable Δy, THEN this input variable has a great sensitivity value S.
2) If a large variation of an input variable Δx corresponds to a small variation of the output variable Δy, THEN this input variable has a small sensitivity value S.

1. These principles are transformed into a fuzzy model in which the input data variation and the output data variation are taken as two input variables and the sensitivity S as output variable [Zhao, Y et al, 2010; Zimmerman, H. J, 1996].

Given a specific output variable y_l, for any pair of data sample (x_i, y_{jl}) and (x_j, y_{jl}) denoted as (*i*, *j*), the input data variation Δx_{ij} and the output data variation Δy_{ij} are calculated. The corresponding sensitivity in the data pair (*i*, *j*) related to y_l, can be obtained from this fuzzy model, i.e. $S_l(i, j) = FL(\Delta x_{ij}, \Delta y_{ij})$.

When removing x_k from the whole set of input variables, the sensitivity of the remaining input variables in the data pair (*i*, *j*) related to the output y_l can be calculated by $S_{k,l}(i, j) = FL(\Delta x_{ij}, \Delta y)$. The sensitivity variation of the pair (*i*, *j*) can be calculated as follows:

$$\Delta S_{k,l}(i, j) = |FL(\Delta x_{ij}, \Delta y) - FL(\Delta x_{ij}, \Delta y)| \qquad (1)$$

The general sensitivity variation $\Delta S_{k,l}$ for all pairs of data samples when removing the variable x_k is defined by:

$$\Delta Sk, l = \frac{1}{\gamma} \sum_{i=1}^{n} \sum_{j=i+1}^{n} \Delta Sk, l\,(i, j) \qquad (2)$$

Where: $\gamma = n(n-1)/2$ the total number of data pairs.

Bigger is the value of $\Delta S_{k,l}$, more the corresponding variable x_k is relevant to the quality feature y_l.

Based on this fuzzy logic sensitivity criterion, we proposed the following algorithm for selecting the most relevant variables and removing irrelevant ones.

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Inputs: process input variables $X=\{x_1,\dots, x_m\}$ and one related specific output $y_l$
Output: relevant process parameters Xr, and related sensitivity variation value $\Delta S$
$\varepsilon$: threshold of sensitivity variation
Initialise $X'=X$, $Xr=\{\}$, $\Delta S' = \{\}$
While $X' \neq \emptyset$.
Calculate the sensitivity variation of inputs in X' related to $y_l$ denoted
$\Delta S' = \{\Delta S_{1,t}, \dots, \Delta S_{k,l}, \dots, \Delta S_{k,l}\}$
$Xr=Xr\ \{xi\}$, $X'=X' \setminus \{xi\}$ where $\Delta S_{k,l} > 1-\varepsilon$
$X'=X' \setminus \{xj\}$ where $\Delta S_{1,t} < \varepsilon$
End
$\Delta S_{=} \Delta S'$
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This algorithm combines both the forward and the backward search by removing the subset of the most sensitive variables and the subset of the most insensitive variables at each step. A small positive value is defined for eliminating non significant ranking order of variables. All the variables whose sensitivity variations are included between 0 and 1 are considered as the most sensitive variables. The most insensitive variables correspond to the case in which their sensitivity variations are smaller than. When this recurrent procedure is completed, we can obtain a significant and independent list of the most relevant process parameters.

3. EXPERIMENTAL

3.1. Materials

Three different samples made of PES/cotton plush fabric are used for this study. They are all composed with polyester and cotton and used as baby clothes made on a single bed circular machine (Gauge E 20, diameter 30 inch). The difference between them is the metric count of ground yarn and plush yarn. These samples have undergone a stain repellent treatment using a cationic fluorocarbon resin according to the conditions presented in table 1. The objective is to find the best conditions which give the hydrophobic surface without affecting the main hygienic properties.

Table 1: levels of input parameters

Factors	Level 1	Level 2
Temperature of treatment (T (°))	40 °C	60 °C
Time of treatment (t (min))	15 min	25 min
Concentration of product (C (%))	1.5%	3 %
Temperature of drying (Ts (°))	120°C	125°C
Time of drying (ts (min))	7 min	10 min
Weight (Ms (g/ m^2))	210.2	367.3
Thickness (E (mm))	1.44	2.57
Metric count of plush yarn (Nmb)	20	50
Metric count of ground yarn (Nmf)	10	70

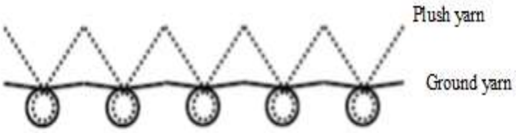
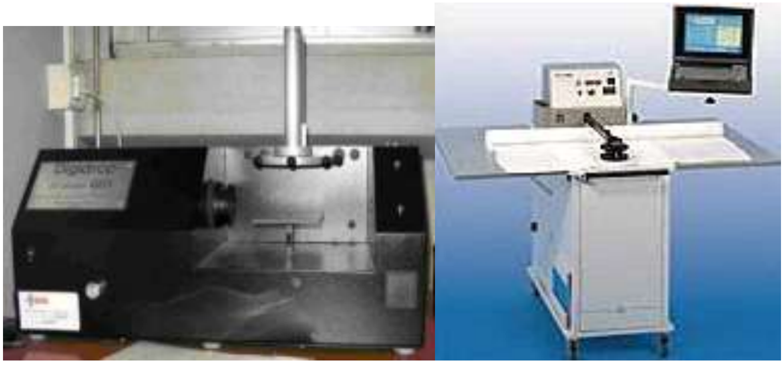


Figure 1. Tying of plush knit

3.2. Experimental equipment

Fabrics were dyed under laboratory conditions in a laboratory-type sample dyeing machine (AHIBA) with the mixture disperse /direct dyes. We used the dyeing procedure according to the 1bath/1time with carrier a temperature equal to 100°C. The samples were then taken from the dyeing tubes, washed and dried.

After dyeing, these samples have undergone a chemical treatment using a cationic fluorocarbon resin according to the conditions presented in table 2. The objective is to found the best conditions which give the quality sought.



2-a: DGIDROP 2-b: Air permeability Tester

Figure 2: Experimental equipment

While observing this table, we found a variation of five factors of treatment which drives us to make a factorial experience plan of type 2^{k-2} .So we are going to study our samples according to eight tests.

All tests were carried out after the samples were conditioned under standard atmospheric conditions (temperature 20 ± 2°C, relative humidity 65 ± 4%).

4. RESULTS AND DISCUSSIONS

4.1. Results

In this study, 4 fabric features and 5 treatment parameters are taken as input parameters to characterize the hydrophobic nature of our samples. These parameters are pre-selected as shown in Table 2.

Table 2: Input and output parameters of the process

Factor	Variables names
Input parameters	Temperature of treatment (x_1), concentration of product (x_2), time of treatment (x_3), time of drying (x_4), temperature of drying (x_5), thickness (x_6), weight (x_7), metric count of plush yarn(x_8), metric count of ground yarn (x_9)
Output parameters	Angle de contact (y_1), perméabilité à l'air (y_2)

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In order to reduce the complexity of modeling and the related field data collection efforts, we use the fuzzy based method presented forward in this paper to select the most relevant input variables and remove irrelevant ones based on the table 3 .

Table 3. Levels of output parameters

Output	**Level 1**	**Level 2**
Contact angle (°)	52	139
Percentage of increasing of air permeability	1,78	18,92

Tables 4 and 5 show the detailed steps for recursively selecting the inputs relevant to water contact angle and air permeability using the fuzzy sensitivity variation criterion.

Table 4: Selection of input variables relevant to water contact angle

	Remaining inputs	Significance ranked by ascending order ΔS	Most relevant inputs	Irrelevant inputs
Step 1	$x_1 .... x_9$	$x_1, x_6, x_4, x_2, x_5, x_3, x_8$	$x_1, x_6, x_4, x_2, x_5, x_3, x_8$	x_7, x_9
Step 2	$x_1, x_6, x_7, x_6, x_3, x_5, x_2, x_3$	$x_4, x_6, x_1, x_2, x_5, x_8, x_3$	x_4, x_6, x_1, x_2, x_5	x_8, x_3

Table 5: Selection of input variables relevant to the percentage of increasing of air permeability

	Remaining inputs	Significance ranked by ascending order ΔS	Most relevant inputs	Irrelevant inputs
Step 1	$x_1 .... x_9$	$x_1, x_4, x_3, x_5, x_7, x_6, x_2, x_9, x_8$	$x_6, x_8, x_1, x_4, x_5, x_3, x_2$	x_9, x_7
Step 2	$x_6, x_8, x_1, x_4, x_5, x_3, x_2$	$x_6, x_8, x_1, x_4, x_5, x_2, x_3$	x_6, x_8, x_1, x_4, x_5	x_2, x_3

According to these tables, it can be noticed that the use of fuzzy sensitivity criterion has reduced the number of inputs by 45%. The results obtained show that the properties of the studied measuring the hydrophobicity knitwear depend not only on the treatment parameters but also the structure parameters. In fact, it is noted that the weight and the metric count of ground yarn were removed by correlation and we can deduct that the treatment time (t) is the less relevant parameter for the two outputs. Thus, the parameters selected as relevant will help to better understand the impact of these on the surface changes made by the resin used in order to optimize treatment. Our input variables of fuzzy logic, now selected, we can pass to the fuzzy reasoning process.

The choice of the best function that gives the optimal result is obtained after the calculation of various errors presented in the table 6.

Table 6: Errors of fuzzy modeling of contact angle

Fonctions d'appartenance	Trimf	Trapf	Gbellf	Gauss	Sigm
RMSE	7,14	6,64	6,29	8,25	15,94
MAE	5,35	5,06	4,85	6,44	12,5
MRAE (%)	5,51	5,2	5,27	6,89	14,17

Where:

RMSE: the square root of the mean square error; $RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(di - yi)\,2}$ (3)

MAE: the mean absolute error; $MAE = \frac{1}{N}\sum_{i=1}^{N}|di - yi|$ (4)

$MRAE$: The average absolute relative; $MRAE = \frac{1}{N}\sum_{i=1}^{N}\frac{|di-yi|}{di}$ (5)

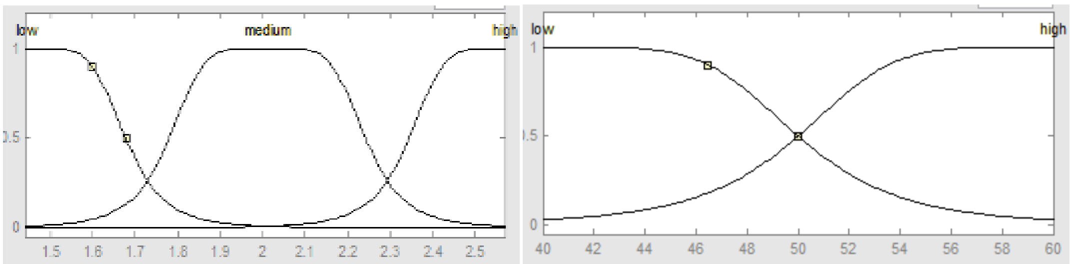
N is the number of examples used, di measured values and yi the values estimated by the model.

From this table, we can deduce that the function generalized bell membership function gives the best result presents minimum errors. The overall rules elaborated, in order to evaluate and predict the contact angle after treatment, are shown below:

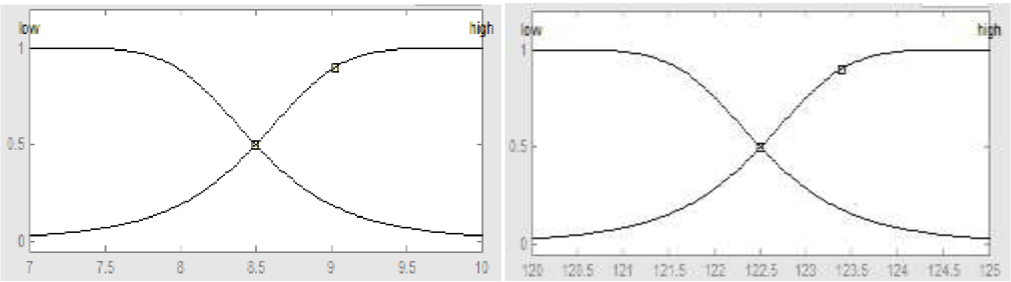
1. If (E is low) and (T is low) and (ts is high) and (Ts is low or high) and (C is low) then (the contact angle is high) (1)
2. If (E is low or medium) and (T is low) and (ts is low) and (Ts is high) and (C is high) then (the contact angle is high) (1)
3. If (E is low or medium)) and (T is high) and (ts is low) and (Ts is low) and (C is low) then (the contact angle is high) (1)
4. SI (E is low or medium)) and (T is high) and (ts is low) and (Ts is high) and (C is high) then (the contact angle is very high) (1)
5. If (E is low or medium)) and (T is low) and (ts is low) and (Ts is low) and (C is high) then (the contact angle is medium)) (1)
6. If (E is low or medium) or high) and (T is high) and (ts is high) and (Ts is high) and (C is high) then (the contact angle is medium)) (1)
7. If (E is low) and (T is high) et (ts is high) and (Ts is low) and (C is high) then (the contact angle is very high) (1)
8. If (E is medium or high) and (T is low) and (ts is high) and (Ts is low) and (C is low) then (the contact angle is medium) (1)
9. If (E is medium) or high) and (T is low) and (ts is high or low) and (Ts is high) and (C is low or high) then (the contact angle is medium)) (1)

10. If (E is medium)) and (T is high) and (ts is high) and (Ts is low) and (C is high) then (the contact angle is low) (1)
11. If (E is high) and (T is low) and (ts is high) and (Ts is high) and (C is low) then (the contact angle is very low) (1)
12. If (E is high) and (T is high) and (ts is low) and (Ts is low) and (C is low) then (the contact angle is very high) (1)
13. If (E is high) and (T is high) and (ts is high) and (Ts is low) and (C is high) then (the contact angle is medium)) (1)

Where (1) represents the weight applied to each rule. In general, the specific weights range from 0 to 1 under the weight setting. The rules have been defined in imprecise sense and hence they are not crisp but fuzzy values. These rules have been shown as membership functions in figure 3.



Thickness T



ts Ts

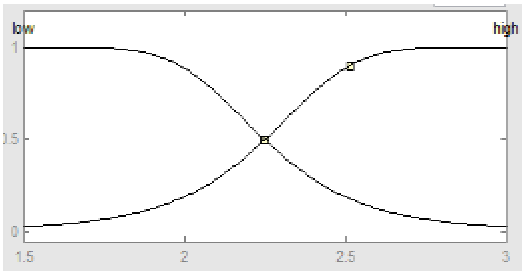


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Figure 3: Membership functions of inputs relative to the contact angle

The input parameters after being read from the sensors are fuzzified as per the membership function of the respective variables. These in additions with the membership function curve are utilized to come to a solution (using some criteria). At last the crisp value of the contact angle is obtained as an answer.

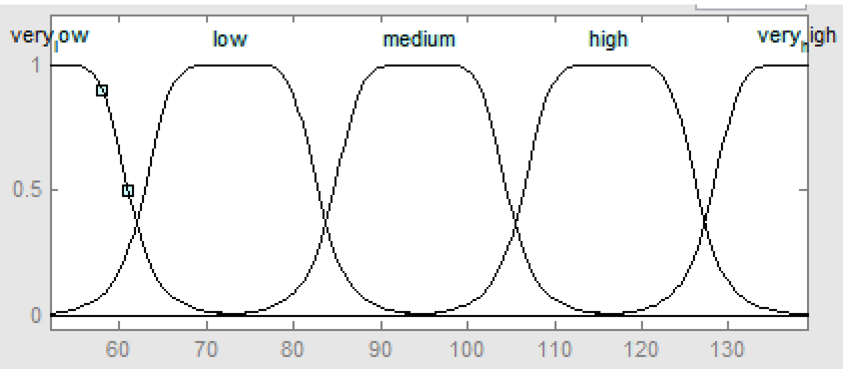


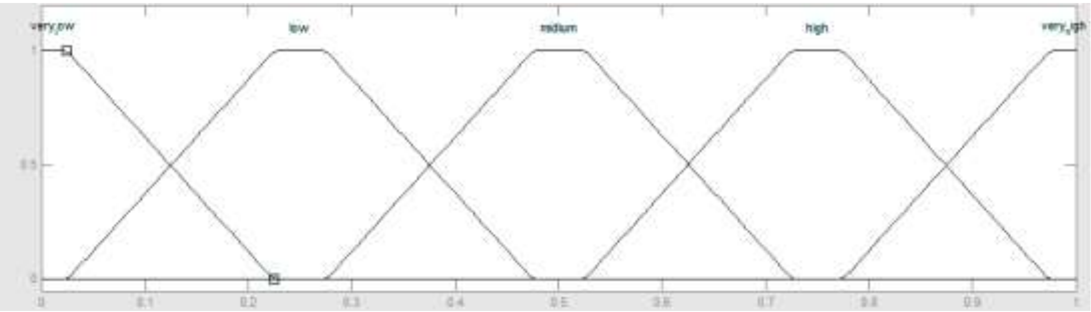
Figure 4: Membership function of contact angle

Concerning the percentage of increasing of air permeability, the trapezoidal membership function was the function that gives the optimal result. We can notice that some experimental conditions induce low values of P_d.

Table 7: Errors of fuzzy modeling of air permeability

Fonctions d'appartenance	Trimf	Trapf	Gbellf	Gauss	Sigm
RMSE	1,25	1,25	1,37	2,02	4,20
MAE	1,01	1	1,1	1,57	2,43
MRAE (%)	15,13	14,86	20,6	31,72	40,60

In the following, after fuzzification of different inputs, we obtain the membership function of P_d.



P_d

Figure 5: Membership function of P_d

The rules that define the relation between P_d and different inputs are cited as follows:

1. If (E is low or high) and (Nmb is high) and (T is low) and (ts is high) and (Ts is low) then (the P_d is high) (1)
2. If (E is low) and (Nmb is high) and (T is low) and (ts is low) and (Ts is high) then (the P_d is very low) (1)
3. If (E is low or medium) and (Nmb is high or low) and (T is low) and (ts is high) and (Ts is high) then (the P_d is low) (1)
4. If (E is low) and (Nmb is high) and (T is high) and (ts is low) and (Ts is low) then (the P_d is high) (1)
5. If (E is low or medium) and (Nmb is high or low) and (T is high) and (ts is low) and (Ts is high) then (the P_d is very low) (1)
6. If (E is low) and (Nmb is high) and (T is high) and (ts is low) and (Ts is low) then (the P_d is low) (1)
7. If (E is low) and (Nmb is high) and (T is high) and (ts is high) and (Ts is low or high) then (the P_d is very high) (1)
8. If (E is medium or high) and (Nmb is low or high) and (T is low) and (ts is low) and (Ts is high) then (the P_d is medium) (1)

9. If (E is medium or high) and (Nmb is low or high) and (T est high) and (ts is low) and (Ts is low) then (the P_d is low) (1)
10. If (E is medium) and (Nmb is low) and (T is high) and (ts is low) and (Ts is high) then (the P_d is very low) (1)
11. If (E is medium) and (Nmb is low) and (T is low) and (ts is low) and (Ts is low) then (the P_d is very low) (1)
12. If (E is medium or high) and (Nmb is low or high) and (T is high) and (ts is high) and (Ts is low or high) then (the P_d is medium) (1)
13. If (E is high) and (Nmb is high) and (T is low) and (ts is high) and (Ts is low) then (the P_d is high) (1)
14. If (E is high) and (Nmb is high) and (T is low or high) and (ts is low or high) and (Ts is high) then (the P_d is medium) (1)
15. If (E is high) and (Nmb is high) and (T is low) et (ts is low) and (Ts is low) then (the P_d is very high) (1)

Different rules provide a low percentage of decreasing of air permeability especially rules number 2, 5 and 10. So, in some experimental conditions, we can obtain a very hydrophobic surface without affecting air permeability.

4.2. Validation of the models

To evaluate the performance of our modeling, we refer to the determination coefficient (R^2) which was found to be 0,90 for the contact angle (figure 6) and 0,95 for the air permeability (figure 7)**.**

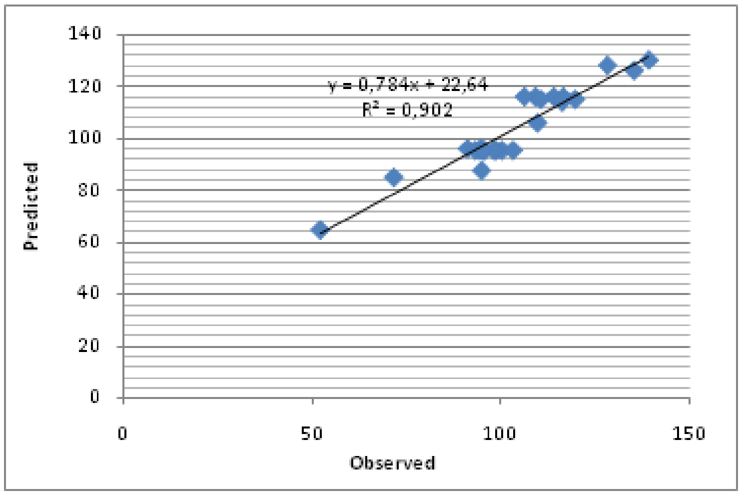


Figure 6: Observed-predicted plot of contact angle

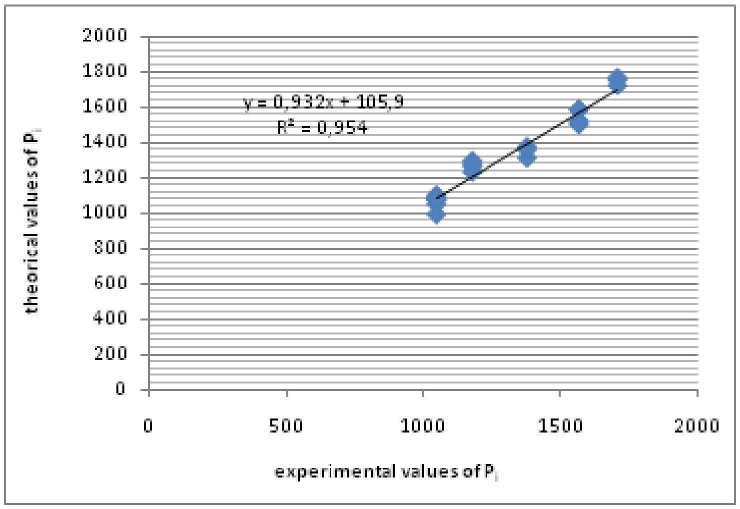


Figure 7: Observed-predicted plot of air permeability

The high correlation between experimental values and predicted ones shows that results of the estimation model exhibited favorable performance of the data set for predicting the treatment system performance.

5. CONCLUSION

At the end of the study, a fuzzy expert system has been developed to model the hydrophobic nature of plush knitted fabrics. The expert system was developed by translating the experimental measures of the contact angle and air permeability into fuzzy inference system. The developed fuzzy rules give a very good understanding about the interaction between treatment and structure parameters and their influence on the fabrics hydrophobicity. The prediction accuracy of the proposed fuzzy system is reasonably good as the mean error % of prediction was below 5% for membership functions selected. The system is quite easy to develop and it could be modified easily if the variation of different parameters is greater. Further attempts are being made to incorporate more input variables in the expert system so that the modeling accuracy could be enhanced.

The values of contact angle obtained after treatment showed that the chemical treatment applied transform the hydrophilic surface to hydrophobic one with maintain of air permeability while choosing the appropriate experimental conditions .

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