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Fuzzy logic modeling of the effect of a Stain Repellency treatment on knitted fabrics

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***Abstract*- This present study is aimed to investigate the effect of a stain repellent treatment on the water-oil repellency characteristics of plush knitted fabrics. An artificial intelligence-based system approach is presented by fuzzy logic modeling in which the effects of the operating parameters and intrinsic features of fabrics are studied. These parameters were pre-selected according to their possible influence on the outputs which were the contact angle and the air permeability. An original fuzzy logic based method was proposed to select the most relevant parameters. The results show that air permeability was influenced essentially by knitted structure's parameters but the variation of treatment parameters has a great effect on the contact angle.**

***Keywords*- Air permeability, fuzzy c-means, fuzzy logic, plush knit, water-oil repellence.**

I. INTRODUCTION

The last few years have witnessed a growing interest in knitted fabrics due to their simple production techniques, low cost, high levels of clothing comfort and wide product range. These attributes make knitted fabrics the commonly preferred choice for wearing. Or, such structure needs some surface transformation to respond to consumers' desire. Nowadays, the use of fluorochemicals to provide stain repellency and/or stain release properties to apparel goods has rapidly grown. Out of all existing textile chemicals, only fluorochemicals have shown the unique property to provide to fabrics a low surface energy film with both high oil and water repellency properties to resist penetration of oil and water-based stains (polar and non polar liquids). A low surface energy is explained by a higher contact angle between water droplets and fabric surface. Roach et al [1] noted, if the contact angle is increased by roughness to greater than 120° the term ultrahydrophobicity should be used and if the contact angle is increased to greater than 150° the term superhydrophobicity should be used. Hence, ultra-hydrophobic surfaces have been generally prepared by modifying the surfaces with various fluorinated polymers, such as PTFE coatings ([2], [3]), fluoroalkylsilanes ([4], [5]) and per-fluorinated polymer monolayers [6].

In order to study the effect of operating parameters of a stain repellent treatment on plush knitted fabrics designed to baby clothes, a fuzzy logic based sensitivity variation criterion was used to select the most relevant input variables. A fuzzy logic model was established to elicit the influence of input parameters on the contact angle and the air permeability.

Fuzzy c-means algorithm:

In this work, we use the fuzzy logic based sensitivity variation criterion developed by Deng et al ([7], [8]) and employed also by Abdjelil et al. [9] to select the most relevant input parameters. The advantage of this approach is the possibility of using small number of learning data. The principle of the method consists of evaluating the fuzzy sensitivity variation of each input variable related to the output variable.

The sensitivity for an input variable is defined according to the two following principles ([8], [9]):

1) IF a large variation Δx of an input variable generate a small variation Δy of the output variable, THEN this input variable has a small sensitivity value S.

2) IF a small variation Δx of an input variable generate a large variation Δy of the output variable, THEN this input variable has a great sensitivity value S.

These principles are used for building a fuzzy model in which the input and output data variation respectively Δx and Δy are taken as input variables and the sensitivity S as output variable. To simplify the selection procedure, we developed an original method using FCM (Fuzzy C-Means), based on this fuzzy sensitivity variation criterion, to classify sensitivity variation values into classes depending on the application. Inputs constitute the smallest class are eliminated; the rest (list CE) is used for the selection algorithm in the next section.

Inputs: process input variables X= $\{x_1,\ldots,x_k,\ldots, x_m\}$ and one related specific output y_l.

Output: relevant process parameters X_r and related sensitivity variation value ΔS.

Corr (x_p, x_k) denotes correlation between x_p and x_k.

1) Calculate the sensitivity variation of inputs in X related to y_l denoted $\Delta S_l = \{\Delta S_{1,l},\ldots, \Delta S_{k,l},\ldots, \Delta S_{size(X),l}\}$.

2) Classify ΔS_l into FCM classes; eliminate inputs constitute the smallest class.

3) For each pair of relevant inputs (x_p, x_k), calculate the linear correlation coefficient.

4) If $\Delta S_{k,l} \in CE$, and $\max_{k\neq p} |\mathrm{corr}(x_p, x_k)| < \alpha$ (correlation threshold), Then xk is considered relevant to y_l.

5) If $\Delta S_{k,l}$ and $\Delta S_{p,l} \in CE$, $|\mathrm{corr}(x_p,x_k)| \geq \alpha$ and $\Delta S_{k,l} > \Delta S_{p,l}$, then x_k is considered relevant to y_l, x_p is correlate to x_k, and should be eliminated.

6) $X_r = CE \backslash x_p = \{ \}$

The 'α' value is defined by the experts. Over α is small, less variables in the final list are correlated. When this procedure is completed, we could obtain a significant and independent list of the most relevant parameters related to specific output y_l.

II. FABRIC TESTING

Three different samples made of PES/cotton plush knit fabric were used. 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 at a temperature equal to 100°C. The samples were then taken from the dyeing tubes, washed and dried. To modify the surface properties of this sample, a chemical treatment was applied after dyeing using a cationic fluorocarbon resin named "FLUOROTEX FO/57W" «Prochimica society» according to the organization chart presented in fig. 1.

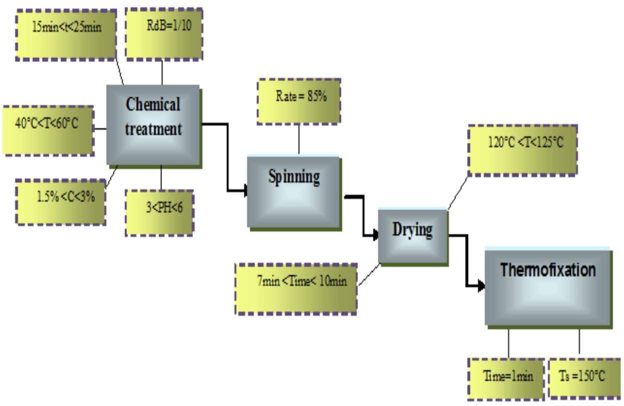

Fig. 1: Processing steps

To choose the appropriate experimental conditions that give the best result, we are carried out to modify five parameters of treatment as presented in table 1. This choice is due to several reasons:

The repellence behaviour is influenced by the surface tension. Or this parameter is function of temperature that is why we choose to vary the temperature of treatment and drying. Many studies have proved also the effect of the variation of the concentration of product used for such treatment and we varied the time of treatment and drying to study the effect of time which is not yet studied.

The processing steps and the equipment used indicate the possibility of varying 5 parameters. Or, the use of a full experimental design of 5 factors involves a number of experiences equal to 32 for one knitting. So to reduce the cost and the experimental time, we choose a reduced plan of type 2^{k-2}. Thus, we will change the characteristics of the samples according 8 tests (table 1).

TABLE 1

EXPERIMENTAL CONDITIONS

Test	T (°C)	C (%)	t (min)	ts (min)	Ts (°C)
1	40	1,5	25	10	120
2	40	3	15	7	125
3	40	1,5	15	10	125
4	60	1,5	15	7	120
5	60	1,5	25	7	125
6	40	3	25	7	120
7	60	3	25	10	125
8	60	3	15	10	120

Experimental measures were made before and after treatment to evaluate the degree of obtained improvement. The objective is to increase the water-oil repellent behavior of surface samples and to find the appropriate experimental conditions which give the best values of contact angle with maintain of air permeability. The characteristics measured are (fig. 2):

- Air permeability using Air Permeability Tester TEXTEST FX 3300 according to the standard ISO 9237.
- Contact angle using the "Digidrop" [10]

(a) (b)

Fig. 2: Experimental equipment given by: (a) Air permeability Tester; (b) DIGIDROP

III. RESULTS AND DISCUSSIONS

In this study, nine parameters were taken as input parameters (table 2). These parameters were pre-selected according to their possible influence on the outputs which were the contact angle and the percentage of decrease of air permeability, as shown in table 3.

Table 2 shows the maximum, minimum, average and standard deviation of knit fabric features and treatment parameters used under study.

TABLE 2
THE MAXIMUM, MINIMUM, AVERAGE AND STANDARD DEVIATION OF INPUT PARAMETERS

Inputs parameters	**Designation**	**Mean value**	**Standard deviation**	**Maximum value**	**Minimum value**
Temperature of treatment T (°)	x_1	50	10,69	60	40
Concentration of product C (%)	x_2	2,25	0,8	3	1,5
Time of treatment t (min)	x_3	20	5,34	25	15
Time of drying ts (min)	x_4	8,50	1,6	10	7
Temperature of drying Ts (°)	x_5	122,50	2,67	125	120
Thickness (E (mm)	x_6	2,005	2,58	1,44	2,57
Weight (g/ m²)	x_7	238,75	79,17	210,2	267,3
Metric count of plush yarn	x_8	40	17,32	50	20
Metric count of ground yarn	x_9	50	34,64	70	10

TABLE 3
THE MAXIMUM, MINIMUM, AVERAGE AND STANDARD DEVIATION OF OUTPUT PARAMETERS

Output parameter	**Designation**	**Mean value**	**Standard deviation**	**Maximum value**	**Minimum value**
Contact angle (water) (°)	y_1 ($\boldsymbol{\theta}_w$)	103,47	18,7	139	52
Contact angle (oil) (°)	y_2 ($\boldsymbol{\theta}_o$)	95,87	21,38	130	31
Percentage of decreasing of air permeability (%)	y_3 (% d)	9,64	4,61	18,92	1,78

A. Selection of relevant parameters:

The fuzzy based method presented forward in this paper was used for selecting the relevant input variables and removing irrelevant ones.

According to our application, $\Delta S_{k,l}$ values are classified into three classes {small, medium, large}. Tables 4 and 5 represents the steps to classify the sensitivity variation of structural parameters, removing small class's inputs and independent list of most relevant inputs related to contact angle and the percentage of decreasing of air permeability respectively.

According to these tables, the relevant parameters selected from this criterion could be ranked in a significant order of relevancy: $x_4 > x_6 > x_1 > x_2 > x_5$ for the contact angles.
For the percentage of decreasing of air permeability, the significant order of relevancy is: $x_6 > x_8 > x_1 > x_4 > x_5$.
Therefore, by using the fuzzy sensitivity variation criterion, the number of input parameters was reduced from 9 to 5. Hence, it can be concluded that the fuzzy sensitivity variation criterion could successfully filter data complexity related to water-oil repellency parameters.

TABLE 4
SELECTION OF INPUT VARIABLES RELEVANT TO CONTACT ANGLES

Step	Inputs	Significance ranked by ascending order ΔS	Most relevant inputs (liste CE)	Irrelevant inputs
Step 1	$x_1 \dots x_9$	$x_1, x_6, x_4, x_2, x_5, x_3, x_8, x_7, x_9$	$x_1, x_6, x_4, x_2, x_5, x_3, x_8$	x_7, x_9
Step 2	$x_1, x_6, x_4, x_2, x_5, x_3, x_8$	$x_4, x_6, x_1, x_2, x_5, x_8, x_3$	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 DECREASING OF AIR PERMEABILITY

Step	Inputs	Significance ranked by ascending order ΔS	Most relevant inputs (liste CE)	Irrelevant inputs
Step 1	$x_1 \dots\dots\dots x_9$	$x_1, x_4, x_3, x_5, x_7, x_6, x_2, x_9, x_8$	$x_6, x_8, x_1, x_4, x_5, x_3, x_2$	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

B. Modeling of the contact angles:

The results from a fuzzy analysis using different membership functions (triangular (Trimf), gaussian (Gauss), sigmoid (Sigm), trapezoidal (Trapf) and generalized bell (Gbellf)) were used and compared to determine which one is more accurate in predicting the high values of contact angle with maintain of the air permeability. Table 4 indicates that the most relevant parameters of contact angles relative to water (θ_w) and oil (θ_o) are the same. 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

Membership functions	Trimf		Trapf		Gbellf		Gauss		Sigm	
	θ_w	θ_o	θ_w	θ_o	θ_w	θ_o	θ_w	θ_o	θ_w	θ_o
RMSE	7,14	9,22	6,64	9,16	6,29	8,58	8,25	11,27	15,94	16,08
MAE	5,35	7,05	5,06	7,029	4,85	6,52	6,44	8,52	12,5	11,4
MRAE (%)	5,51	8,96	5,2	8,85	5,27	8,56	6,89	11,5	14,17	17,53

Where: RMSE: the square root of the mean square error $\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(d_i - y_i)^2}$ (Equation 2)

MAE: the mean absolute error; $\mathrm{MAE} = \frac{1}{N}\sum_{i=1}^{N}|d_i - y_i|$ (Equation 3)

MRAE: The average absolute relative; $\mathrm{MRAE} = \frac{1}{N}\sum_{i=1}^{N}\frac{|d_i - y_i|}{d_i}$ (Equation 4)

N is the number of examples used, d_i measured values and y_i the values estimated by the model.

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

TABLE 9

MATRIX OF FUZZY RULES OF "θ_W"

	Membership level					
Rule n°	E	T	ts	Ts	C	θ_w
1	L	L	H	L or H	L	Level 4
2	L or M	L	L	H	H	Level 4
3	L or M	H	L	L	L	Level 4
4	L or M	H	L	H	H	Level 5
5	L or M	L	L	L	H	Level 3
6	L or M	H	H	H	H	Level 3
7	L	H	H	H	H	Level 5
8	M or H	L	H	L	L	Level 3
9	M	L	L or H	H	L or H	Level 3
10	M	H	H	L	H	Level 2
11	H	L	H	H	L	Level 1
12	H	H	L	L	L	Level 5
13	H	H	H	L	H	Level 3

Where: H: high; M: medium; L: low. Level 1: very low; Level 2: low; Level 3: medium; Level 4: high; Level 5: very high

Figure 3 shows an example of surface plots that depict the impacts of inputs on the contact angles. It can be deduced that the contact angle increases with the increase of the temperature of treatment and the decrease other paramètres. So this model allows us to know the direction in which we must vary the different inputs to optimize the contact angle.

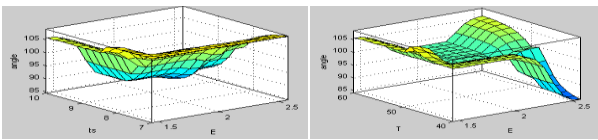

Fig. 3: Examples of surface plot relative to contact angle

C. *Modeling of the air permeability:*

Following the same methodology as modeling of the contact angle, we can denote that the trapezoidal membership function presents the optimal result of modeling of the percentage of decreasing of air permeability (% d) (table 7).

TABLE 7
ERRORS OF FUZZY MODELING OF "% d"

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

the surface plots indicate that the percentage of decreasing of the air permeability decreases with increasing thickness, the temperature of treatment and drying time and the decrease of the metric count of plush yarn and the drying temperature.

D. *Validation of the models:*

To evaluate the performance of our modeling, we refer to the determination coefficient (R^2).

The correlation coefficient was found to be 0,90 for the θ_w (figure 4); 0,82 for θ_o (figure 8) and 0,93 for % d (fig. 4).

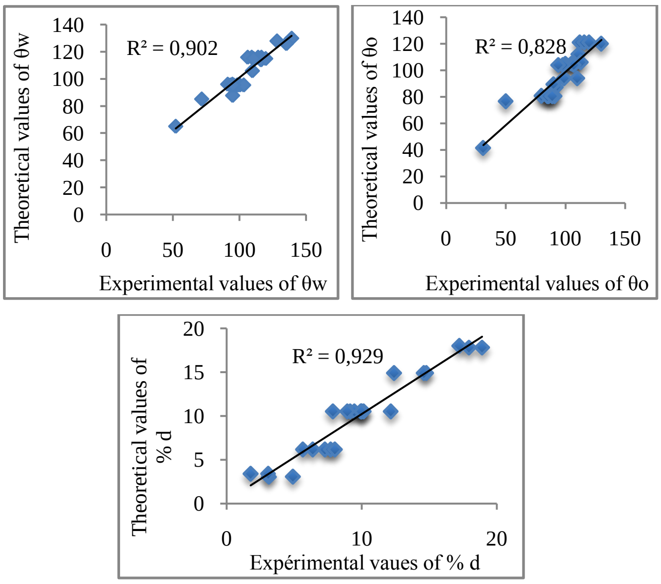

Fig. 4: Observed-predicted plot of outputs

This 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.

IV. CONCLUSION

We have predicted the water-oil repellency characteristics of plush knitted fabrics using fuzzy logic method. Our findings show that the prediction performance is acceptable. Indeed, the results also show that the change of fuzzy membership function affects the prediction accuracy of contact angle and air permeability.

Compared to experimental results, it may be concluded that, overall, theoretical models using fuzzy technique are marked by relatively acceptable correlation coefficients especially using generalized bell membership function for the contact angle and trapezoidal one for the percentage of decreasing of air permeability.

To optimize the treatment applied on PES/cotton plush knit, we should head as follow: The contact angle increases with the increase of the temperature of treatment and the decrease other paramètres and the percentage of decreasing of the air permeability decreases with increasing thickness, the temperature of treatment and drying time and the decrease of the metric count of plush yarn and the drying temperature. Thus, it is believed that artificial intelligence systems could efficiently be applied to the knit industry to explain the relationship between water-oil repellency characteristics and stain repellent treatment parameters and intrinsic features of plush knitted fabrics.

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