(REFEREED RESEARCH)

MODELING AND KINETIC STUDIES ON THE SPREADING PHENOMENON OF INK JET PRINTING OVER POLYESTER FABRIC

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ABSTRACT

The present research deals with an experimental study of the liquid drop through polyester fabric in the spreading regime with no splashing. First, the wetting phenomenon parameters are characterized by the digidrop 3S permitting us to measure correctly the contact angle, the diameter, the height, the volume and the drop profile in contact with porous fabric during experiment time. Results exhibited that the liquid drop impact shows the presence of three different phases. Then, a mathematical model is developed in order to interpret the experimental data in terms of kinetic spreading, evaporation and diffusion phenomena on the porous materials. The theoretical predictions agree well with the experimental data with high correlation coefficients. It is also proved that the kinetic wetting parameters depend on the structure of the woven fabric (weft count), the drop size and the surface tension. This study represents an important contribution for the understanding of the behavior of a liquid drop after its projection on the textile support and it could constitute a prototype of the industry of ink jet printing.

Keywords: Wetting, spreading, Liquid drop, Mathematical model, Woven fabric, Statistical analysis.

1. Introduction

The wetting of solid substrates is a fundamental phenomenon related to lubrication, coating, printing, waterproofing and detergency [1-3]. Many works have concentrated on the study of wetting phenomenon and the spreading of liquid on porous material [4-10]. The wetting phenomenon may be a static one as sessile drop [11] or dynamic phenomenon [12,13]. Indeed, wetting phenomenon is governed by the surface tension, gravitational forces and viscous forces. The wetting of materials was characterized by contact angle and, in most studies, the spreading over smooth homogeneous surfaces has considered [14,15]. However, the roughness property of the majority of solid surface affects the spreading conditions. As a consequence, the contact angle value was shown to be depended on the surface properties and it is found to be very sensitive to surface pre- surface roughness [16]. Harju, *et al.,* detailed the surface properties and roughness on the spreading phenomenon [17].

It also demonstrated that the surface texture and its chemical composition control the spreading phenomenon [18-20]. In addition, it was shown that the fiber composition and the construction parameters of the textile material induce difficulties to predict, correctly, the wetting of a particular textile material [21]. The interface liquid-solid interactions involve many physical phenomena which depend on the intermolecular interaction between the liquid and fiber surface [22]. In other recent research, Raja *et al.,* adopted a new technique based on the principle of embedded image processing in order to measure the horizontal water spread in textile fabric as a function of time [23]. It is found that the doubled yarn count and doubling combinations influence the liquid spread behavior in the fabric.

In the framework related to wetting phenomenon, our previous work [24], dealt with the demonstration of that the coating film structure is deeply affected by drying morphologies.

From this research, it was deduced that the drying conditions influence different parameters of kinetic drop spreading on virgin glass and cotton material in a static mode. In another recent work [25], we developed an experimental study of the impact of water drop on a surface in a spreading regime. Three surfaces were studied: virgin

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glass, coating film and woven cotton fabric. All experiments were carried out using water drop with the same free fall high.

Results show an important effect of the height of the free fall on the drop profile and an important drop deformation at the surface impact was observed. Herein, the aim of the present research was to study the different parameters characterizing the dynamic wetting phenomenon (Ink Jet Printing) through the woven polyester fabric. Adimensional diameter, the height and the volume were analyzed as a function of time. The studied factors were the drying temperature of the coating paste, the drop size of the ink solution, the weft count of woven textile fabric and the time of the spreading experiment. Finally, based on these input factors, a mathematical model was developed in order to determine the main effects and the interactions between factors and response plots.

2. Materials and Methods

2.1. Fabrics and finishing treatments

Before experiment setting, the gill of glass was cleaned with the ultrasonic sounds during 30 seconds in ethanol. Then, rinsed with the same solvent and dried to nitrogen. Further, the surface is treated and activated in an oxidizing solution at 50°C during 30 min. After, the gill of glass is rinsed, with twice distilled water and dried under flux of nitrogen. The dispersive coating solution was supplied from an industrial society specialized in ink-jet printing (Impression Textile du Sahel, Monastir-Tunisia). The characteristics of the dispersive coating solution were given in our previous work [24]. The film of the printing solution was conducted by spin coating on gill of absorbent glass (2.5×2.5 cm2). Experiments were performed on virgin glass and coated textile woven fabrics. The use of the glass material was used in order to better understand the wetting phenomenon, on homogeneous and smooth material. Then, firstly, to essential to analyze the behavior of the paste in contact with the ink drop and, to study the behaviors of this paste depending on the temperature and the drop size.

The weaving structure is plain weave. The warp count was 22 per cm, 40 Nm and the weft count was varied as 11, 17 and 22 per cm, 40 Nm. For the woven fabric (warp count 22 and weft count 22 has the weight of 150 gr/m^2). The used polyester filament has a diameter section between 110 and 350 µm and the yarn has on average 60 filaments per section. As to treat woven fabric, the reverse-rollers coating technique was used to apply the coating paste on fabric. The kinetic spreading parameters were studied using water droplets (5 µl) and the evolution of drop profile was captured with video-camera of GBX Digidrop with 25 captures per second. Every measure was repeated 3 times.

2.2. Experimental design method

The obtained results were analyzed using the software Minitab 15 and the regression model. The main effects, interactions between factors and response plot were determined. Globally, the general behavior of such phenomenon can be represented by the regression model. Different types of equations can model the behavior of the phenomenon and the correlation between parameters. The choice of adequate equation depends on the R²-value of each model and the p-value allows us to determine whether a variable is statistically significant.

Statistical approaches are the ideal means for optimization studies in industrial processes. The level and code of variables considered, in the present study, are given in table 1. The drying temperature, the drop size, the weft count and the time are selected as independent variables.

3. Results and Discussion

3.1. Effect of drying temperature

The thin film of dispersive coating paste is dried at room temperature (25°C) and oven conditions (110°C) during 120 seconds. Then, the ink drop was projected on 100% polyester woven fabric. We observe, from figures 1-3, the presence of three phases of the drop impact on the polyester woven fabric. The drop rebound, at first instants, is followed by a significant spreading and finished by another phase where the diameter is constant [Figure (1.b)] and the height [Figure (2.b)] and volume [Figure (3.b)] continue to decrease. The reservoir corresponding to the volume of the coating film is rightly below the area contact of the drop.

This space depends on the film thickness as well as its drying method. As proved in our previous work [24], the coating film is a function of its diffusion coefficient and its water deficit. Moreover, the spreading rate at 25°C coatings, through much lower as compared to oven-dried mode. This difference in the spreading rate of the two drying method can be explained by the fact that the oven-dried is susceptible to absorb more water quantities. As a consequence, its dehydration level as its reabsorbing water propensity to reabsorb water is very important. That is why it has the highest important amplitude (Dt/D0) for the coating film dried in oven-dried conditions. The variation of the adimensional height and volume agrees well with these results and indicate the presence of the evaporation and the diffusion phenomena at long time.

Table 1. Level and code of variables for experimental design

Variables	Symbols	Coded levels		
		-1	0	1
Drying Temperature	DT (°C)	25	-	110
Drop Size	DS (µl)	1	-	5
Weft Count	WC	11	17	22
Time (s)	T	0, 0.2, 0.4, 0.6, 0,8, 1		

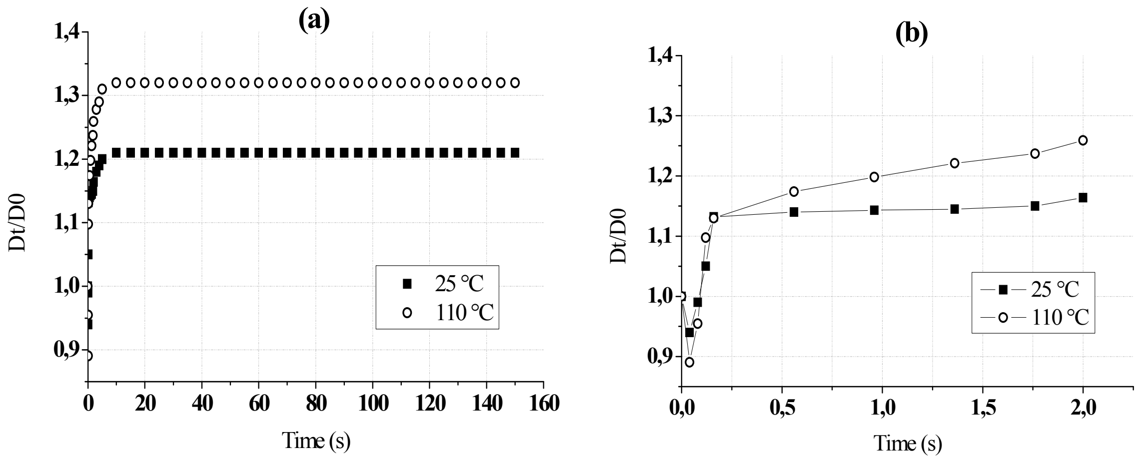

Figure 1. Kinetic of wetting of ink drop solution on the dispersive coating paste dried at 25°C and 110°C: (a) change of diameter for a long time and (b) at first instants

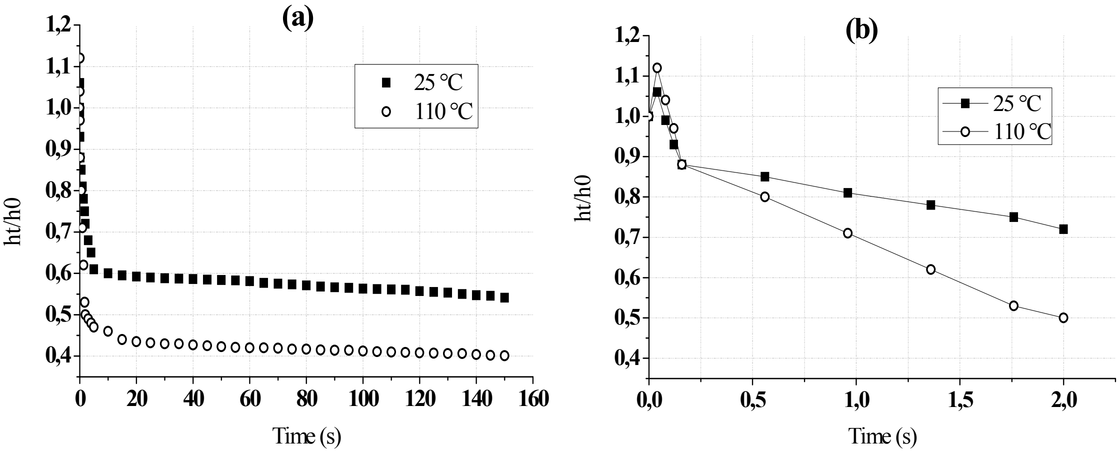

Figure 2. Kinetic of wetting of ink drop solution on the dispersive coating paste dried at 25°C and 110°C: (a) change of height for a long time and (b) at first instants

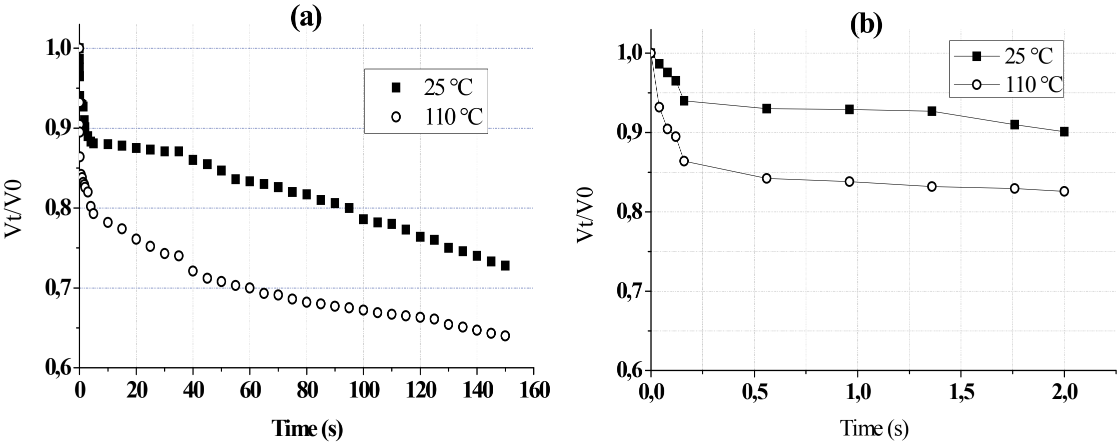

Figure 3. Kinetic of wetting of ink drop solution on the dispersive coating paste dried at 25°C and 110°C: (a) change of volume for a long time and (b) at first instants

3.2. Effect of drop size

Two drop volume were checked 1 and 5 µl, in attempts to study the general behavior of wetting phenomenon and to analyze the effect of the droplet size on amplitude and the kinetic spreading. Results related to the wetting phenomenon parameters such as the adimensional diameter, height and volume of ink drop on the glass substrate in overall duration and in first instants are given, respectively, in Figures 4, 5 and 6. The spreading process follows three stages. During the first stage (at about 150 s), an important rebound was observed. This rebound deformation achieves high amplitude for the big drop size (5 µl). This observation indicates the effect of the gravity and the kinetic energy on the first impact drop-substrate. Then, the drop base (diameter) increased to reach its maximum value 2. At these instants, the curve reveals a maximal spreading speed and important amplitude, indicating the predominance of the spreading on the evaporation. This second phase was followed by a third one, when the drop diameter and height are constant and the adimensional volume decreased slightly confirming the presence of the evaporation phenomenon. The experimental data exhibit that at the same spreading time for the two drop size, the greatest volume reaches rapidly its maximum drop base.

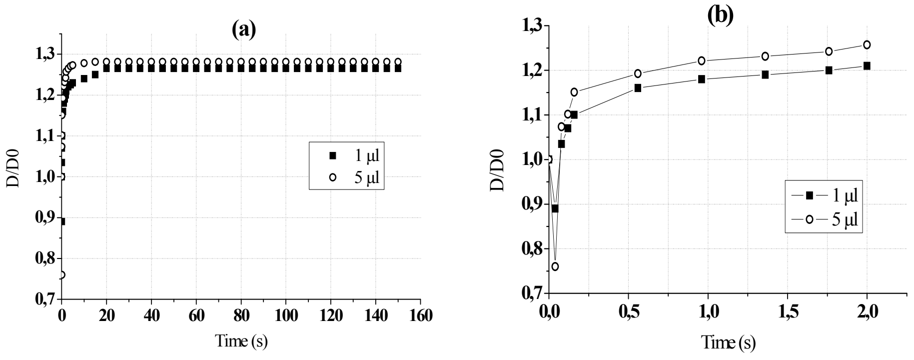

Figure 4. Kinetic of wetting of ink drop solution on the dispersive coating paste using a drop size 1 and 5 µl: (a) change of diameter for a long time and (b) at first instants

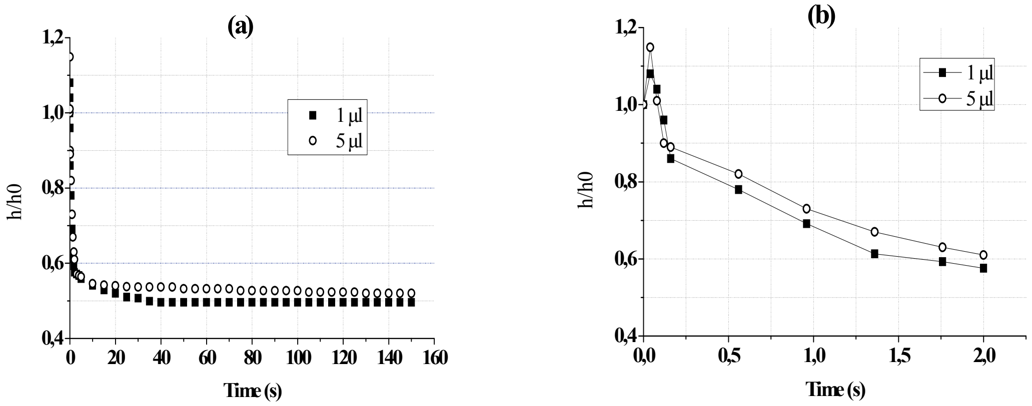

Figure 5. Kinetic of wetting of ink drop solution on the dispersive coating paste using a drop size 1 and 5 µl: (a) change of height for a long time and (b) at first instants

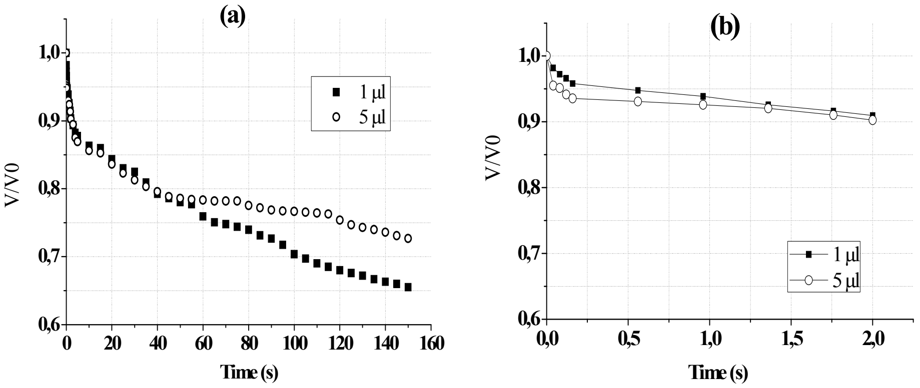

Figure 6. Kinetic of wetting of ink drop solution on the dispersive coating paste using a drop size 1 and 5 µl: (a) change of volume for a long time and (b) at first instants

3.3. Effect of weft count

As globally observed, the variation in weft count affects the capillaries sizes. This has an impact on the transportation of fluid in cloths. For this reason, we check fabrics having the same chemical features but they differ solely by the weft count. To analyze the effect of the weft count during the dynamic wetting of the ink drop on the textile support, we vary the weft count as 11, 17 and 22. The height of fall and the volume of the ink drop size (5 µL) are maintained constant. The graphs characterizing the behavior of the drop during this phenomenon are given in figure 7.

As observed, the drop deformation amplitude is smaller for the weakest weft count. This can be explained by the important spaces inter yarns generating larger capillaries. Indeed, the deformation or the retraction of the drop is more significant for the highest weft count. This can be explained by the importance of the surface opposing to the drop. Thus, it involves a high energy provoking an important drop deformation after impact. For the phenomenon of dynamic wetting of the ink drop on 100% polyester, three phases are mentioned. The first phase which is characterized by an important drop deformation in the vertical sense, is observed rightly after impact. Then, a second phase reveals the increment in the diameter and reaches its maximum. Finally, a third important phase is characterized by the constancy of the diameter. It is obvious that the structure of the textile support controls the rate of spreading and diffusion of the liquid. The profile of the drop presents important deformation, after impact, for the raised weft count. This is explained by the fact that the energy of surface opposing the energy of impact of the drop is very big. Therefore, while increasing this factor, the total surface of liquid contact- fiber is very important.

3.4. Modeling of the spreading behavior

The statistical technique is used to model the relationship between the response variable and the independent input factors. Only the model of the diameter adimensionel or spreading rate (D/D_0) is detailed in this paragraph. Models of the height (h/h_0) and volume (V/V_0) adimensionels are directly clarified. The input factors are the Drying Temperature (DT), the Drop Size (DS), the Weft Count (WC) and the Time (T). These factors were evaluated using factorial design where the main effects, interaction plot and the contour of surface of response were investigated. Main effects of each parameter on diameter adimentional are displayed in figure 8.

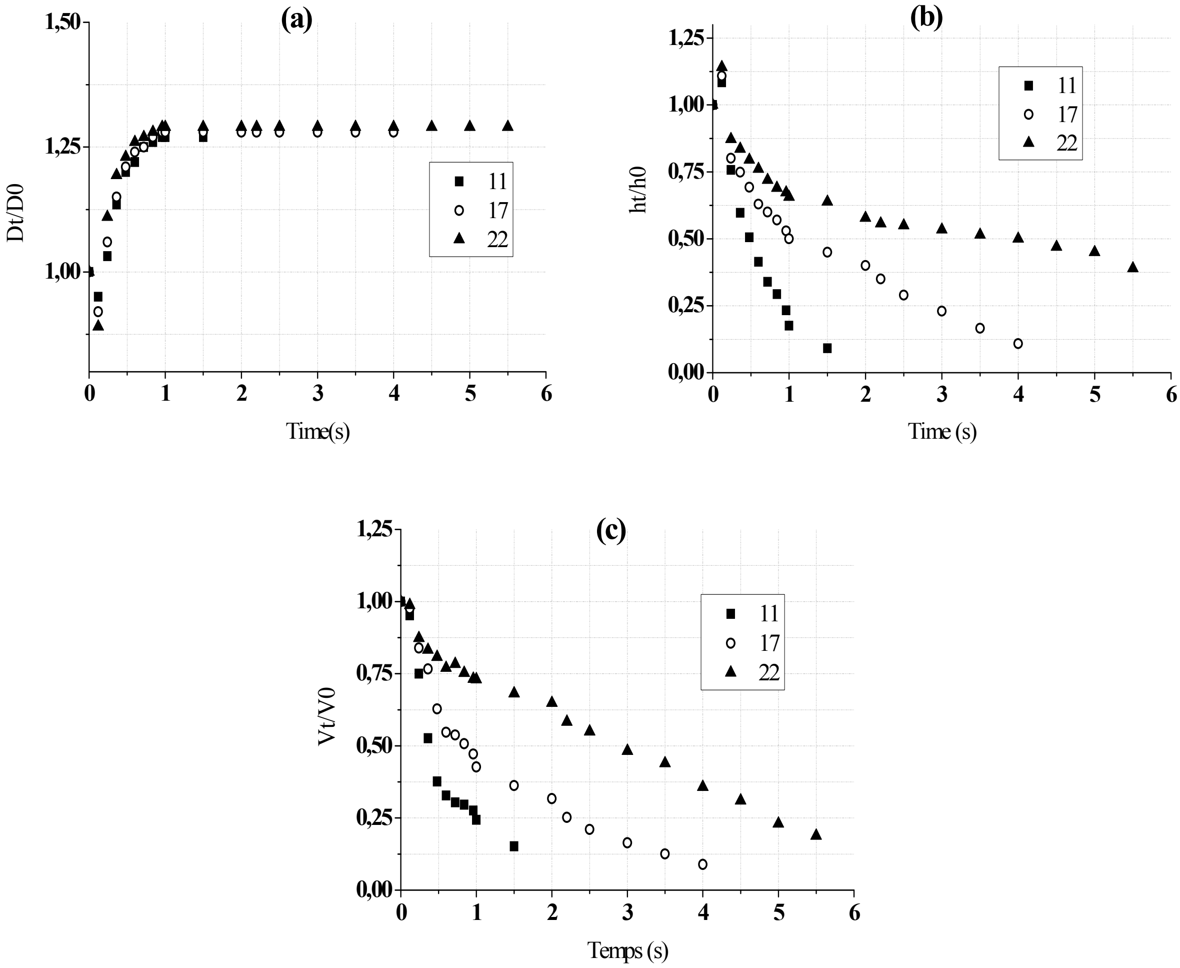

Figure 7. Kinetic of wetting of ink drop solution (5 µl) on the coated woven polyester fabric treated with dispersive coating paste and dried at 25°C: (a) Evolution of the diameter (b) the height and (c) the volume

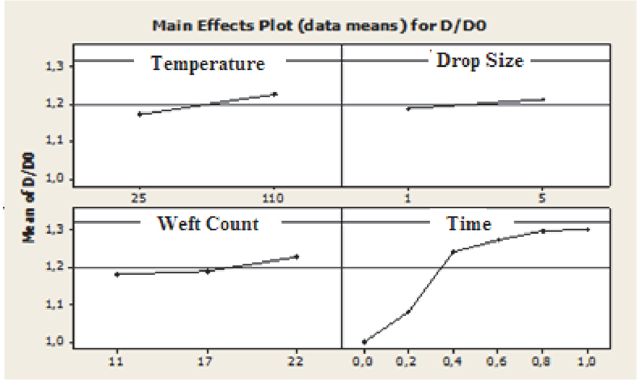

Figure 8. Main effects diagram for a dimensional diameter at different factors

As depicted, the drying temperature is less influential than the time. The influence of the weft count appears very small. The effect of the drop size is negligible. The plots of interaction are represented in Figure 9. The interaction plot is a plot of means of dimensional diameter for each level of one factor with the level of the second factor held constant. In fact, the interactions plots are useful for judging the presence of relations, which means that the difference in the response at two levels of one factor depends upon the level of another factor.

Parallel lines in the interactions plots indicate no interactions. From results, we observe that the interaction diagram reveals negligible interaction between different factors because the lines have the same tendency.

Using Minitab software, the general behavior of the adimensional diameter can be simulated by a mathematical equation. Two sorts of equations Eq.1-3 or Eq. 4-6 can be used in order to model the different responses (D/D_0, h/h_0 and V/V_0). Based on the studied factors, different responses can be written as linear equation or linear equation with interaction:

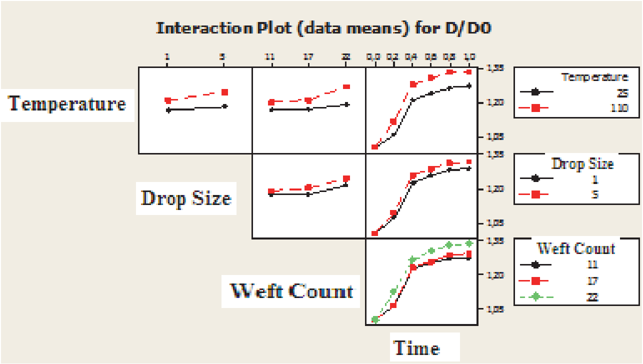

Figure 9. Interaction diagram for a dimensional diameter at different factors

The first three equations shows a simple regression of various components of this phenomenon (diameter, height and volume dimensionless) and the last three shows a linear regression with interactions of the same components. After studying the analysis of variance table, the results show that only the regression linear terms in the model were significant and the interactions in the regression model were no significant (Figure 9 and table 2).

As a consequence, the first sort of equation (Eq.1-3) model was chosen as convenient. The diameter equation, given by the Minitab software model of different response, was written as:

Table 3 shows that the Drop Size factor is not statistically significant (p-value of the constant

was equal to 0,063 ≥ 0,05).

$$D/D_0 = K + a_1\,DT + a_2DS + a_3WC + a_4T \qquad Eq.(1)$$

$$h/h_0 = K + b_1\,DT + b_2DS + b_3WC + b_4T \qquad Eq.(2)$$

$$V/V_0 = K + c_1\,DT + c_2DS + c_3WC + c_4T \qquad Eq.(3)$$

Or

$$D/D_0 = K + a_1\,DT + a_2DS + a_3WC + a_4T + a_{12}DT*DS + a_{13}DT*WC + a_{14}DT*T + a_{23}DS*WC + a_{24}DS*T + a_{34}WC*T$$

$$h/h_0 = K + b_1\,DT + b_2DS + b_3WC + b_4T + b_{12}DT*DS + b_{13}DT*WC + b_{14}DT*T + b_{23}DS*WC + b_{24}DS*T + b_{34}WC*T$$

$$V/V_0 = K + c_1\,DT + c_2DS + c_3WC + c_4T + c_{12}DT*DS + c_{13}DT*WC + c_{14}DT*T + c_{23}DS*WC + c_{24}DS*T + c_{34}WC*T$$

These equations were used to show the behavior of this wetting phenomenon. In fact, it comes from a simple linear regression or linear regression with interactions.

Table 2. Analysis of Variance for D/D_0 (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	4	0,89537	0,889077	0,222269	72,27	0,000
2-Way Interactions	6	0,01622	0,015940	0,002657	0,86	0,527
3-Way Interactions	4	0,00341	0,003385	0,000846	0,28	0,893
4-Way Interactions	1	0,00028	0,000276	0,000276	0,09	0,765
Residual Error	56	0,17223	0,172226	0,003075		
Residual Error	71	1,08751				

$$D/D0 = 0,915 + 0,000627\ DT + 0,00597\ DS + 0,00408\ WC + 0,310\ T \qquad Eq.\ (7)$$

Table 3. p-values of each factor

Predictor	Coef	SE Coef	T	P
Constant	0,91546	0,02937	31,17	0,000
DT	0,0006275	0,0001485	4,23	0,000
DS	0,005972	0,003156	1,89	0,063
WC	0,004075	0,001403	2,90	0,005
T	0,31048	0,01848	16,80	0,000

The other used factors have p-value very negligible in relation to significant value (0,05). Therefore, to get a very meaningful model, it is necessary to avoid the factors that don't have an effect on the response from where the final equation of the diameter response could be rewritten as:

As depicted in the Table 4, all factors are statistically significant. P-value of the constant was equal to 0.000. P-value of the DT factor was equal to 0.000. P-value of the WC was equal to 0.006 << 0.05 and p-value of the T was equal to 0.000. The regression linear model obtained by Minitab software for the diameter is very significant (p = 0.000).

Then, with the same manner as described above, we are interested to the other wetting parameters h/h0 and V/V0. The obtained results are given in equations (9) and (10), respectively, for h/h0 and V/V0. Their corresponding data are summarized in table 5 and 6.

The predictor values for the adimonsional volume were summarized in Table 6.

$$D/D0 = 0,933 + 0,000627\ DT + 0,00408\ WC + 0,310\ T \qquad Eq\ (8)$$

Table 4. p-value of for the adimonsional diameter

Predictor	Coef	SE Coef	T	P	
Constant	0,93338	0,02832	32,96	0,000	
DT	0,0006275	0,0001513	4,15	0,000	
WC	0,004075	0,001430	2,85	0,006	
T	0,31048	0,01882	16,49	0,000	
ANOVA for the adimensional diameter – The regression linear model R2 = 98.4					
Source	DF	SS	MS	F	P
Regression	3	0,88510	0,29503	99,12	0,000
Residual Error	68	0,20241	0,00298		
Total	71	1,08751			

$$h/h0 = 0,606 + 0,000984\ DT + 0,0246\ WC + 0,647\ T$$

$$V/V0 = 0,470 + 0,000621\ DT + 0,0278\ WC + 0,635\ T$$

Table 5. p-value for the adimonsional height

Predictor	Coef	SE Coef	T	P	
Constant	0,60631	0,05068	11,96	0,000	
DT	-0,0009837	0,0002707	-3,63	0,001	
WC	0,024572	0,002558	9,60	0,000	
T	-0,64750	0,03368	-19,22	0,000	
ANOVA for the adimensional diameter – The regression linear model.R^2 = 97.5					
Source	DF	SS	MS	F	P
Regression	3	4,5267	1,5089	158,32	0,000
Residual Error	68	0,6481	0,0095		
Total	71	5,1748			

Table 6. p-value the adimonsional volume

Predictor	Coef	SE Coef	T	P	
Constant	0,46964	0,05751	8,17	0,000	
DT	-0,0006209	0,0002908	-2,14	0,036	
WC	0,027814	0,002748	10,12	0,000	
T	-0,63452	0,03618	-17,54	0,000	
ANOVA for the adimensional diameter – The regression linear model R2 = 98.2.					
Source	DF	SS	MS	F	P
Regression	4	4,6045	1,1511	104,67	0,000
Residual Error	67	0,7368	0,0110		
Total	71	5,3413			

Further, our interested is focused on the application of the response surface method design for finding regions where there is an improvement in response and hence the optimum response desired by the industrial.

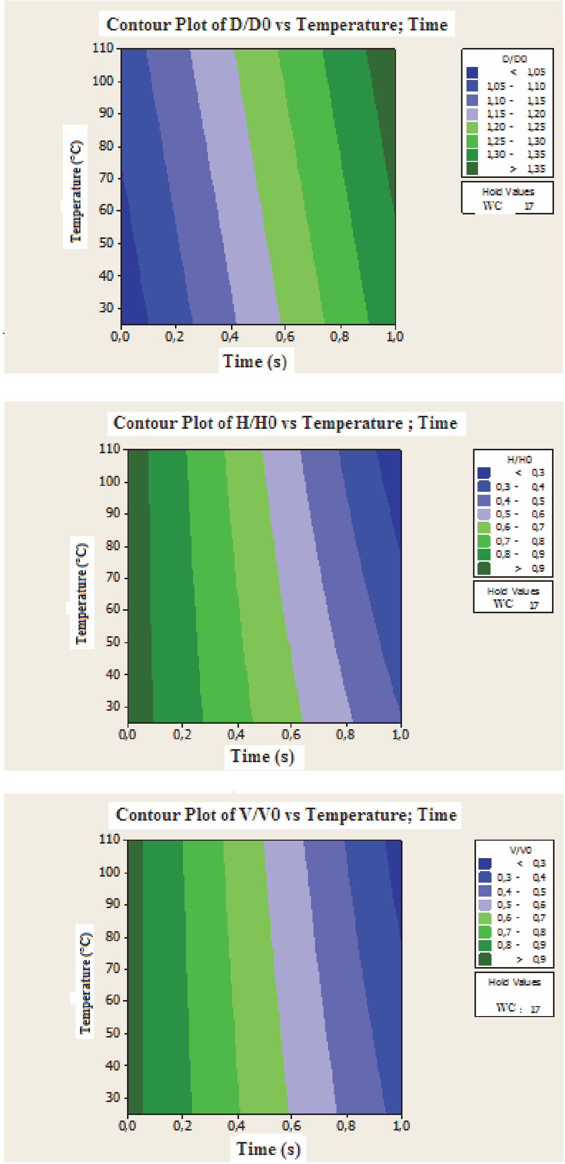

Figure 10. Contour plot versus Temperature and Time at Weft count value 17 of: (a) D/D0, (b) h/h0 and (c) V/V0

Figure 10 gives the contour plots of Drying Temperature (DT) and Time (T) factors for D/D0, h/h0 and V/V0. The contour plots allow us to see the response surface and to find the optimum response of different studied output. Results of the contour of the response surface for the variation of V/V0, h/h0 and V/V0 demonstrate that, at the beginning, the maximum spreading was obtained for the treated fabric and dried at temperature higher than 80°C after 0.8 second. The kinetic spreading and the amplitude were less important for the fabric treated and dried at 25°C. This proves the effect of the temperature on the treated fabric. So the reservoir corresponding which is the volume of the coating film is rightly below the area contact of the drop, depending on its drying method. It is a function of its diffusion coefficient and its water deficit. For this reason, the amplitude and the kinetic of wetting were very significant for the fabric treated and dried under oven drying process. The contour of the response surface of h/h0 and V/V0 confirm the results obtained from the studying the different parameters.

4. Conclusion

To sum up, this study constitutes a very important contribution for the understanding of the behavior of a liquid drop after its projection on polyester fabric. It presents a prototype of the industry of ink jet printing. The liquid drop impact shows the presence of three phases. The drop perturbation was observed at few times. This deformation is relied to the surface energy and it is much intensified for the virgin glass for the important drop size, the oven dried coating film and for the raised weft count of polyester woven fabric. The surface properties affect deeply the drop shape and the spreading rate as well as the weft count and the drying process of coating film. The coating paste encourages the water drop spreading by increasing the hydrophilic character of the woven polyester fabric. A second phase shows a rapid spreading of the drop ink and reaches its maximum. Finally, the stabilization phase was observed after the drop equilibrium. The results obtained from the modeling system comply well with the quantitative results from the variation of different wetting parameters. The industrial concern of this research is the contour of the response surface. This response surface presents directly the outputs of the spreading, diffusion and evaporation phenomena as a function of inputs factors.

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