

## **Single-criterion optimization of the air permeability of woven fabrics using Taguchi method**

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**Abstract :** Woven fabric's breathability is one of the most important characteristics concerning fabrics used as tents, raincoats and uniform shirtings. It is mainly evaluated and compared significantly via fabric air permeability. This study aimed to optimization of the fabric parameters influencing the woven cotton fabrics' air permeability. Twenty seven different fabric combinations using a  $3^3$  full factorial design were diminished to only nine fabric samples according to  $L_9$  Taguchi's orthogonal design. These fabric samples were produced, tested and evaluated. Using S/N ratios, the best combinations of factor levels which yield the highest value of fabric air permeability were detected efficiently.

**Keywords :** Taguchi methodology, Woven fabric, Air permeability, Orthogonal array, Optimization.

### **Introduction**

Woven fabrics have found various and many applications in our daily life and also in the industry because of their strength, flexibility, air permeability and other functional properties. In general, the air volume (in  $\text{cm}^3$ ) passes through one square centimeter of the woven fabrics in a time of one second at a pressure difference of one centimeter of water is termed as fabric air permeability[1]. This functional property, is often used in determining and comparing the coated and uncoated fabric's breathability for several end uses. The performance of raincoats, tents, uniform shirtings, parachutes, air bags, ----etc was evaluated and assessed using their air permeability [2-4].

Clothing comfort which includes three main aspects, namely psychological, thermal and tactile comfort related mainly to ability of fabric to control the temperature of the skin through heat and moisture transfer [5]. Since moisture vapors transfer from the skin to surrounding atmosphere based mainly on the air permeability, it is considered the most important parameter in evaluating woven fabrics' comfort [6]. It was reported that fabrics' air permeability is considered one of six major factors in the consideration of comfortable apparel [7].

Woven fabrics' air permeability is significantly influenced by different factors such as, fiber, yarn and fabric parameters. Generally, basic fabric structure, fiber type, yarn and fabric constructions are considered the major effects on the outerwear garment air permeability; and finishing techniques were found to be the

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secondary influence [8]. Construction factors of spun yarns such as yarn diameter, crimp and twist level significantly affect warmth, and appearance of the woven fabrics [9].

Woven fabric porosity is affected by its weave structure, warp and weft yarn crimp. The higher the more spacing is covered by the yarns, the lower is the air permeability. Increasing twist level of ring spun yarns diminishes the yarn diameter and lead it to be more compact and dense, which in turn increases the fabrics' air permeability [10]. Type of the yarn or spinning method has a great influence on fabric air permeability. It was found that open-end yarn fabrics is more permeable to air than those made from ring spun yarns [10].

Many research works have been conducted on the prediction and evaluation of physical and mechanical properties of woven fabrics [10-20], while minor ones operated on the optimization of these properties. The purpose of this study is to optimize woven fabrics' air permeability using Taguchi's approach.

### Experimental work

According to the Taguchi orthogonal array which has been selected for this study, nine different woven fabrics were produced. These fabrics were woven from warp yarns of count 40 Ne and weft yarns with different three counts. The warp yarn density for these woven fabrics was kept at 60 ends/inch for all samples, while weft yarns have three different twist multipliers and densities. All fabric samples were woven on Tsudakoma Air-Jet weaving machine with running speed 580 rpm.

Throughout this study, woven cotton fabrics' air permeability is selected from among many quality characteristics as a research quality characteristic. Air permeability was measured according to ASTM standard D737-04 using Textest FX 3300 air permeability tester. Then, the larger the better of the Taguchi method is used to analyze the air permeability. Weft yarn linear density, twist factor and No. of picks per inch were used as control factors in this analysis. Each factor has been set at three levels.

1. Weft yarn count can be set at 30Ne, 40 Ne and 50 Ne. In general, the higher the yarn count, the lower is the yarn diameter, which in turns increasing the fabric air permeability.
2. The three levels of twist factor of the weft yarns are, 3.9, 4.1 and 4.3 respectively. Increasing yarn twist factor diminishes yarn diameter which increases the pore size in fabric structure, then increases air permeability.
3. The weft yarn density may be 50, 60 and 70 ppi respectively. The higher the weft yarn density, the lower the fabric air permeability.

Depending to the control factors, the total number of freedom is equal to six ( $5 \times (3-1) = 6$ ); and the orthogonal array of  $L_9(3^4)$  was chosen for this experiment. The different levels of the control factors were listed in table 1.

**Table 1: Levels of the experimental (control) factors**

Control factors	Levels		
	1	2	3
Weft yarn count ( $N_e$ )	20	30	40
Weft yarn twist factor ( $\alpha_e$ )	3.9	4.1	4.3
Weft yarn density (ppi)	55	65	75

Using the software MINITAB version 16, the S/N ratios were calculated for the selected orthogonal array of the control factors

In the present work, an  $L_9(3^3)$  Orthogonal Array table was used. There are three control factor each of which has three levels, so to investigate all possible factor – level combinations, a total of twenty seven ( $3^3$ ) full factorial experiments would be demand. The experiments will consume much effort and cost in the case of full factorial design. Therefore, the Orthogonal Array of  $L_9(3^3)$  is required urgently because of nine experiments will be conducted and it is displayed in table 2.

**Table 2.**  $L_9$  ( $3^3$ ) Orthogonal array used in this study

Experiment NO.	Control factors levels		
	Count of weft yarn ( $N_c$ )	Twist factor of weft yarn ( $\alpha_c$ )	Weft density (ppi)
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

There are three main characteristics categories upon which the S/N ratio will be calculated. These are as following :

Higher- the- better::

$$S / N = -10 \log \left[ \frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} \right] \text{----- (1)}$$

Lower-the-better:

$$S / N = -10 \log \left[ \frac{1}{n} \sum_{i=1}^n y_i^2 \right] \text{----- (2)}$$

Nominal-the-best :

$$S / N = 10 \log \left[ \frac{-2}{\frac{y}{S}} \right] \text{----- (3)}$$

Where,

$n$  = observations numbers,

$y_i = i^{\text{th}}$  experimental measured value,

–

$\bar{y}$  = Arithmetic mean of the observed data, and

$S^2$  = variance of the observed data

## Results and discussion

Shortly, the following steps summarize the concept of optimization using Taguchi's methodology:

(1) S/N ratio measures the measurement accuracy scale for predicting abnormal conditions. It is expressed in decibels (dB). The lower error of the prediction is characterized by the higher value of S/N ratio. Generally, S/N ratios are very important to enhance the measurement accuracy and diminish the cost of the analysis.

Equation No. 1 was used to calculate S/N ratios. The values of S/N ratios were analyzed using ANOVA to disclose the factors that have a significance influence. After that the S/N ratio with highest value corresponding to the level of significant factor is chosen as the optimum level.

S/N ratios are calculated by Equation No. 1 correspond to of woven fabric air permeability for each experimental run are listed in table 3.

(2) Determining the average value of the influence of each variable on fabric quality characteristic, namely air permeability, is the second step in Taguchi's methodology.

**Table 3: L<sub>9</sub> (3<sup>3</sup>) orthogonal array, average air permeability values and corresponding S/N ratios.**

Experiment No.	Factors and their levels			values of air permeability (cm <sup>3</sup> /cm <sup>2</sup> .sec)	Value of S/N ratio
	A	B	C		
1	1	1	1	26.0	28.31282
2	1	2	2	16.16667	24.17241
3	1	3	3	9.193	19.26915
4	2	1	2	15.7	23.89584
5	2	2	3	11.97333	21.56430
6	2	3	1	30.6	29.71443
7	3	1	3	13.3	22.47703
8	3	2	1	34.55	30.76896
9	3	3	2	20.08	26.05527

Table 4 displays the average of each factor influence at their different levels in relation to S/N ratio. In this table, the optimum level of each factor was marked using an asterisk.

The optimum level is that one which corresponds to the maximum average influence of the factor. Table 4 displays the average influence of each factor; and figure 1 depicts the plot of the main effect for S/N ratios.

**Table 4: S/N ratios at different factor levels**

Control factors	Average S/N ratios			Delta (gain)
	Level1	Level 2	Level 3	
Weft yarn count	23.92	25.06	26.43*	2.51
Twist factor	24.90	25.50*	25.01	0.6
Weft density	29.60*	24.71	21.1	8.5

### Optimum factor level

The difference between larger and lower values of S/N ratios is termed as delta or the gain in this ratio. Generally, the positive gain refers to the useful variable. This means that the factor change affects the fabric air permeability significantly.

From figure 1 it is shown that the weft density of the woven cotton fabrics has a higher main effect compared to the other control factors, i.e. count and twist factor of the weft yarn. In this graph, the highest value of S/N value which is preferred for each factor is marked by a red circle. We can deduce from this figure that A<sub>3</sub>B<sub>2</sub>C<sub>1</sub> is the combination which satisfies the maximum air permeability. The corresponding factor levels which yield the maximum air permeability of woven fabrics are listed in table 5.

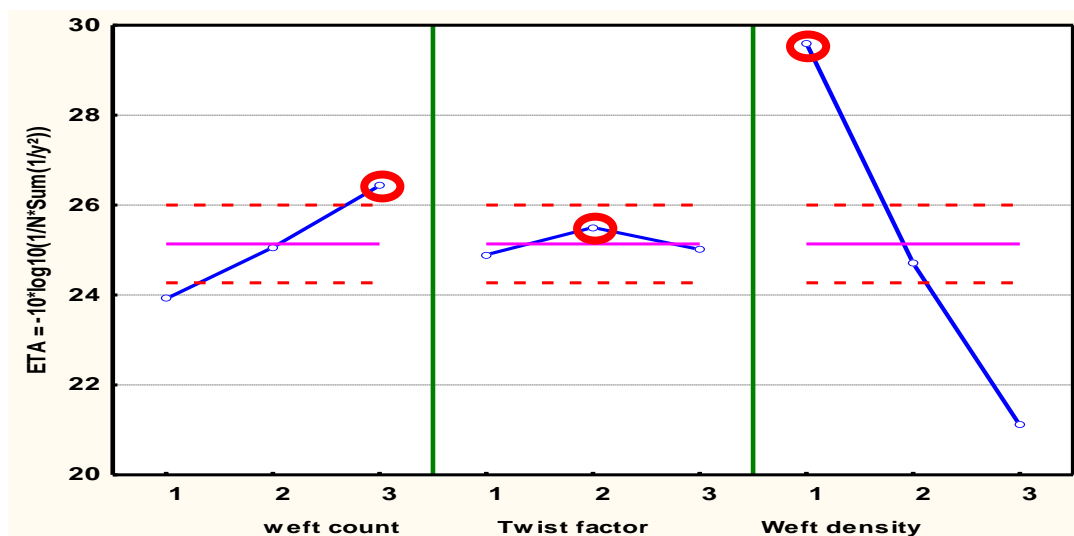


Figure 1. Plot of main effects for S/N ratio of control factors.

Table 5: Optimum value of factor and their levels

Level of optimal control	Value
A (3)	50 N <sub>e</sub>
B(2)	4.1 α <sub>e</sub>
C(1)	55 picks / inch

#### Results of the Analysis of variance (ANOVA) .

ANOVA is considered a quantitative and efficient statistical analysis to measure and detect each control factor influence on the fabric quality characteristics, i.e. air permeability. From the results of such analysis, we can conclude the significant variables affecting air permeability. Also the importance and the contribution percentage of each factor effect on air permeability can be detected. This well known analysis was performed using SPSS version 17 software program. The significant factors were determined at significant level 0.05. The ANOVA results were presented in table 6.

Table 6: ANOVA results

Factor	SS	Degree. of Freedom	MS	F	p-value	% contribution
weft count	137.99	2	69.00	41.878	0.000000	26.9
Twist factor	30.27	2	15.14	9.187	0.001479	7.9
Weft density	1688.31	2	844.15	512.373	0.000000	92.2
Error	32.95	20	1.65			
Total		26				

From this table and the statistical analysis it was depicted that weft density has the highest significant effect on fabric air permeability followed by weft yarn count and twist factor. The contribution of each control factor in influencing fabric air permeability in ascending order is as follows: twist factor (7.9%) < weft yarn count (7.9%) < weft density (92.2%).

#### Confirmation of the experiment

The optimum level of each control factor was determined depending on the results of the ANOVA and the average values of S/N ratios,. As described before, the optimum combinations of factor levels that yield the

highest air permeability were  $A_3B_2C_1$ . The final step in Taguchi's methodology is the confirmation of the experiment. The main object of experiment confirmation is to confirm that the optimum conditions derived from Taguchi method have indeed the projected improvement. S/N ratios at optimum factor levels ( $\eta_0$ ) can be predicted according the following equation:

$$\eta_0 = \eta_m + \sum_{i=1}^j (\eta_i - \eta_m) \text{----- (4)}$$

where,

$\eta_0$  = optimum S/N ratio,

$\eta_m$  = S/N ratio average value of the experimental runs,

j = control factors numbers, and

$\eta_i$  = S/N ratio corresponding the optimum factor level.

Substituting different values in the above equation will yield the optimum S/N ratio. It was found that the value of optimum S/N ratio equal to 31.2 dB. This value is very close to the value obtained from design of experiment that is equal to 30.8. By substituting with  $\eta_0=31.2$  in the Equation NO.1, the obtained value of fabric air permeability is  $36.5 \text{ (cm}^3/\text{cm}^2.\text{sec})$ . That is the optimum air permeability predicted for such fabrics used in this study. The other combinations' air permeability values can be predicted from the same equation. Optimum fabric design was  $A_3B_2C_1$

**Table 7: Air permeability results for optimum ( $A_3B_2C_1$ ) and initial ( $A_1B_1C_1$ ) fabric designs**

Fabric design	Air permeability values ( $\text{cm}^3/\text{cm}^2.\text{sec}$ )						Average air permeability	S/N ratio
Optimum ( $A_3B_2C_1$ )	34.6	33.1	36.8	34.6	33.6	34.8	34.7	30.8
Initial ( $A_1B_1C_1$ )	26.04	26	26	26.3	26.2	25.5	26	28.3

The optimum fabric design was  $A_3B_2C_1$ , namely woven from weft yarn of count 40 Ne, with twist factor 4.1 and weft yarn density is 55 ppi. The average air permeability for this type of fabric was  $34.7 \text{ cm}^3/\text{cm}^2.\text{sec}$  (table 7) which approaches the value predicted using Taguchi design (predicted by Equation No.1) ( $36.5 \text{ cm}^3/\text{cm}^2.\text{sec}$ ).

Also, the S/N ratio for both initial and optimum fabric designs was calculated in order to detect the enhancement in the S/N ratio (table 8). From this table, it is shown that the enhancement of S/N ratio due to the optimum design was 2.4. It is also shown that the improvement for predicted and verification results are close to each others which confirms the results. It is also calculated that the arithmetic mean value of initial fabric design 's air permeability was  $26 \text{ cm}^3/\text{cm}^2.\text{sec}$  that is increased to  $34.7 \text{ cm}^3/\text{cm}^2.\text{sec}$ . This means that the increase in fabric air permeability using Taguchi's methodology is clearly observed.

**Table 8: Verification experiment results**

	S/N ratios	
	Predicted	Verified
Initial design	28.3	28.3
Optimum design	30.87	30.7
improvement	2.48	2.4

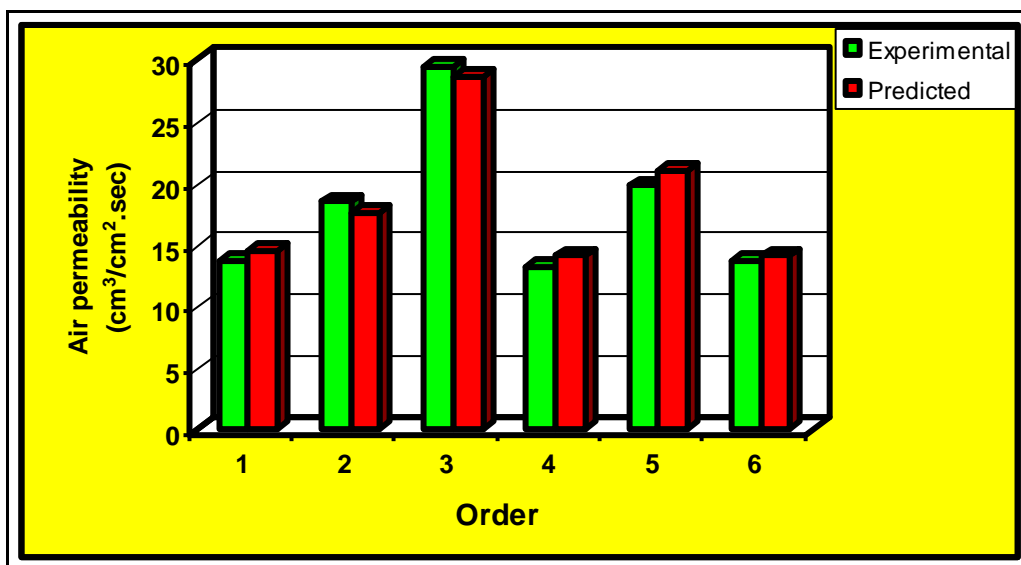
#### Other woven fabric designs' air permeability

The prediction of other fabric samples' air permeability which are not tested before can be forecasted efficiently using the Taguchi method. Using equations No.1 and No.4, the air permeability of fabrics that are not included in  $L_9$  orthogonal array can be predicted. The air permeability predicted values of such fabrics

compared to their corresponding experimental results were listed in table 9. The relative error between experimental and predicted results was also shown in table 9. Figure 2 illustrates the relevant results. It can be noticed from this figure that the predicted values are very close to the experimental air permeability and the error among them is very small.

**Table 9: Experimental and predicated air permeability values**

Sample No.	A	B	C	Air permeability ( $\text{cm}^3/\text{cm}^2.\text{sec}$ )		Relative error, %
				Experimental	Predicted	
1	1	1	2	13.7	14.50	5.84
2	1	3	2	18.5	17.60	4.86
3	2	2	1	29.5	28.70	2.71
4	2	3	3	13.2	14.10	6.82
5	3	2	2	19.8	21.00	6.06
6	3	3	3	13.7	14.10	2.92



**Figure 2: Experimental versus predicted air permeability values**

## Conclusion

The results of this study can be sum up as follows:

- The optimum factors for maximizing cotton woven fabrics' air permeability can be evaluated and determined efficiently by simple and low-cost experiment using Taguchi' approach.
- As conducting the cause and effect diagram, weft yarn count, weft yarn twist factor and weft yarn density are determined as control factors influencing woven fabrics' air permeability.
- In planning step of Taguchi's method, an  $L_9$  ( $3^3$ ) orthogonal array was used. The larger – the – better equation was also used to maximize air permeability .
- Depending on S/N ratios and ANOVA results, the weft yarn density was determined as the most important control factor influencing fabric air permeability followed by weft yarn count.
- The optimum level of control factors which yield the highest woven fabrics' air permeability were  $A_3B_2C_1$ . In other words, the optimum fabric sample which gives the highest value of air permeability composed of weft yarns of count 50 Ne, weft yarn twist factor 4.1  $\alpha_e$  and weft yarn density 55 ppi respectively.
- Using Taguch's method, the product quality characteristic (Air permeability in this study) was improved significantly.

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