The Effect of Low Pressure Oxygen Plasma Treatment on Comfort Properties of Polyester/Cotton Blend Fabric

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Abstract
In this research, low pressure oxygen plasma was used to improve the comfort properties of a polyester/cotton blended fabric (65%/35%) under hot environmental conditions. The Taguchi method was used to design the experiment and analyze the optimal parameter level and the greatest influence of the factor during treatment. Special attention was paid to the investigation of wicking properties, water vapour permeability, heat resistance, air permeability and surface morphology. All the tested comfort properties of the mixed fabric were improved. In particular, the wicking of the fabric increased by 49.8% and 45.3% respectively in warp and weft direction within 5 minutes of the absorption time, while the thermal resistance decreased by 34.3% on average. The Taguchi analysis also confirmed that pressure had the greatest influence on permeability and air permeability during treatment, flow rate on relative water vapour permeability and water vapour resistance, and power on thermal resistance. In addition, the quantitative evaluation of the AFM surface topography revealed that both the polyester and cotton fibres increase in roughness after plasma treatment.
Keywords: Low pressure plasma, blend fabric, comfort, Taguchi method, Permetest, AFM

I. INTRODUCTION

For apparel fabrics, comfort is the main concern of all consumers, regardless of age, gender, religion, economic status and culture. The definition of garment comfort in a single sentence is very difficult and complex because it is multi-disciplinary [1]. However, many researchers have tried to define it differently according to their understanding [2]. The most frequently explained definition of comfort was given by Slater. He explained that comfort is the pleasant state of physical, psychological and physiological integration between the environment and the human body. All these aspects make an equal contribution to comforting people [3]. Clothing fabrics are usually made of either natural fibres and/or a blend of natural fibres and synthetic fibres [4]. Today, synthetic fibres are very important for the production of fabrics due to their low cost, chemical and physical properties compared to natural fibres. However, in terms of their comfort properties, they do not replace natural fibres [5]. In addition, the synthetic fibres (polymers) present in the blended fabric exhibit a zero or low moisture absorption tendency. To eliminate this disadvantage, plasma technology could be a promising technique [6].

Tonks and Langmuir had used the word "plasma" for the first time in 1929 by using "theory of electronic and ionic oscillation in an ionized gas" [7]. Over time, the definition of plasma became broader and resulted in the agreement that plasma contains radicals, atoms, photons, molecules, positive and negative ions [8]. After a long time, plasma physics was founded in the 1970s as a basic technique for producing various types of circuits for microelectronic devices. Plasma technology is an environmentally friendly process and is used in various industries such as food packaging, automotive, textile, biomedical, semiconductor, etc. The special feature of plasma technology is to change the outermost surfaces of a material in the nanometre range without affecting bulk properties. However, plasma treatment changes the physical and chemical properties of the surface layers of a substrate. This changes the surface properties of a substrate from hydrophilic to hydrophobic, or vice versa [8-11]. Through the use of "low-temperature plasma" (low and/or atmospheric pressure), which was started in the 1960s, intensive research was carried out in the field of polymers and textiles [12]. The application of plasma technology in textiles includes desizing, scouring, bleaching, mercerizing, dyeing, printing and finishing, but is not limited to this [13-18].

Previously, some researchers had investigated the thermal properties, water vapour permeability, wettability, air permeability and mechanical properties as well as the surface properties of cotton fabrics before and after plasma treatment [9, 19-22]. The comfort properties of polyester fabrics were not investigated. Rather, wettability, adhesion, dyeability, printability and flame retardancy properties of polyester were discovered [23-27]. So far, the comfort properties of polyester/cotton blended fabrics have not been investigated.

In this research, 65% polyester/ 35% cotton (P/C) blend fabric comfort and surface properties have been investigated by using low pressure oxygen plasma treatment. The plasma parameters are gas flow rate, discharge power, duration of treatment and operating pressure. Thermal resistance, wickability, air permeability, water vapour permeability and water vapour resistance properties of the P/C blend fabric were discussed. The surface morphology of the blend fabric has been studied by Atomic Force Microscopy (AFM). The experimental process of plasma treatment has been designed by Taguchi Method.

II. MATERIAL AND METHODS

2.1 Material

Polyester/cotton blend fabric for shirt cloth was used for measuring wickability (warp and weft direction), water vapour permeability, water vapour resistance, air permeability and thermal resistance properties (Table 1). The size of 30cm x 25cm sample was cut out from woven blend fabric.

TABLE 1: BLEND FABRIC PROPERTIES

Blend ratio, %		Yarn count Ne		Reed & Pick count		Fabric weight (g/m^2)	Thickness (mm)	Type of weave
Polyester	Cotton	Warp	Weft	EPI	PPI			Plain
65	35	44	44	144	72	115	0.22	

EPI: ends per inch; PPI: picks per inch; Ne: Number English

2.2 Methods

2.2.1 Low Pressure Plasma Treatment of Blend Fabric

In this research, low-pressure plasma laboratory system (Tetra 30 PC, Diener electronic GmbH + Co. KG, Germany) was used [28]. All plasma treatment is fully automated. Oxygen was used as plasma gas during treatment. The blend fabric samples were put on the tray inside the vacuum chamber; then all the process parameters have been fed in the software as seen in Table 2.

The experimental run and the parameter combination (Table 2) have been designed by Taguchi method (Minitab 18). In this design, variables are sorted according to their influence on the response variable. The quantitative relationship between the variables and responses are analyzed based on the signal to noise (S/N) ratio approach. This approach has three alternatives to make analysis: “nominal is the best”, “smaller is better” and “larger is better”. Finally, Taguchi method has shown the optimum parameter levels for the plasma treatment [29]. But in this research, “smaller is better” and “larger is better” were used.

TABLE 2: OXYGEN PLASMA TREATMENT PARAMETERS (4 FACTORS & 3 LEVELS)

Experimental Run	Flow Rate (sccm)	Pressure (mbar)	Power (%)	Time (min)
1	40	0.2	60	5
2	40	0.4	70	10
3	40	0.5	80	20
4	50	0.2	70	20
5	50	0.4	80	5
6	50	0.5	60	10
7	60	0.2	80	10
8	60	0.4	60	20
9	60	0.5	70	5

Note: maximum power of the device is 1000W (i.e. 100%)

2.2.2 Vertical Wicking Test

According to DIN 53924 (1978), water absorption of blend fabric has been measured by the height of rise method. The peak of the liquid rise boundary is recorded every 1min interval till 5min wicking time [30].

2.2.3 Air Permeability

The air permeability of treated and untreated sample was measured using SDLATLAS Mozia Air Permeability Tester (USA) according to ASTM D737 and DIN 53887 test standards. An average of ten readings was taken from every sample before and after oxygen plasma treatment in mm/s [31].

2.2.4 Water Vapour Permeability and Thermal Resistance

Relative water vapour permeability (Pwv), water vapour resistance Ret [mPa/W] and thermal resistance Rt [$mK.m^2/W$] of the fabric sample were carried out using Permetest (Skin Model) instrument, which is similar to the ISO standard 11092 [32].

Sample Conditioning: The P/C blend fabric has been conditioned for 24 hours before plasma treatment as well as before and after plasma treatment for comfort property tests at atmospheric conditions of 65 % ± 2 % relative humidity and 20 ºC ± 2 ºC temperature (Textile Laboratory, Albstadt-Sigmaringen University, Germany) [33].

2.2.5 Surface Morphology

Oxygen plasma treated and untreated fabric surfaces were studied using Atomic Force Microscopy (AFM, NANOSURF AG, Switzerland) [34]. During investigation, images of cotton and polyester fibres have been taken from the same blend fabric. Then the fibres have been analysed regarding their surface features.

III. RESULTS AND DISCUSSION

3.1 Results of P/C blend fabric comfort properties

The results of comfort properties of plasma treated and untreated P/C blend fabric and their S/N ratio values have been tabulated in Table 3. In this paper, as mentioned earlier in section **2.2.1**, "smaller is better" and "larger is better" were used. The "smaller is better" was applied to water vapour resistance (R_{et}) and thermal resistance (R_t), whereas "larger is better" was used for vertical wicking in warp and weft direction (W_{wp}, W_{wf}), relative water vapour permeability (P_{wv}) and air permeability (A_p) as shown in Table 3.

TABLE 3: COMFORT PROPERTIES OF PLASMA-TREATED & UNTREATED P/C BLEND FABRIC

Run	Experimental results (Mean values)						S/N Ratios (dB)					
	W_{wp} (mm)	W_{wf} (mm)	A_p (mm/s)	P_{wv} (%)	R_{et} (m^2. Pa/W)	R_t (mK. m^2/W)	W_{wp}	W_{wf}	A_p	P_{wv}	R_{et}	R_t
1	58.3	57.3	105.2	72.9	1.88	4.87	35.3	35.1	40.4	37.3	-5.52	-13.75
2	64.3	52.3	116.2	72.7	1.85	3.48	36.1	34.4	41.3	37.2	-5.36	-10.85
3	61.7	52.7	117.0	71.8	1.90	3.53	35.8	34.4	41.4	37.1	-5.59	-10.97
4	57.3	60.0	117.1	73.4	1.88	3.45	35.1	35.5	41.4	37.3	-5.51	-10.76
5	61.0	56.0	116.7	73.8	1.78	2.82	35.7	34.9	41.3	37.4	-5.04	-9.00
6	58.0	52.7	114.1	74.8	1.73	4.82	35.3	34.4	41.1	37.5	-4.80	-13.66
7	57.3	57.3	108.3	73.0	1.82	4.08	35.2	35.2	40.7	37.3	-5.21	-12.23
8	63.3	54.3	115.5	73.0	1.87	4.8	36.0	34.7	41.3	37.3	-5.44	-13.63
9	58.0	54.3	119.1	71.9	1.98	4.22	35.3	34.6	41.5	37.1	-5.95	-12.50
Untreated	40.0	38.0	111.1	71.4	2.02	6.1						

Note: W_{wp} - vertical wicking in warp direction; W_{wf} - vertical wicking in weft direction; A_p - air permeability; P_{wv} - relative water vapour permeability; R_{et} - water-vapour resistance; R_t - thermal resistance.

3.2 Wicking Properties

As mentioned above in **2.2.2**, the wicking properties of plasma treated and untreated P/C blend fabric (250mm × 30mm) was evaluated by height rise method. The results of the wicking height (mm) both in warp and weft direction were improved after low-pressure oxygen plasma treatment as recorded in Table 3. The wicking height of treated samples was increased by 49.8% and 45.3% on average (9 runs) when compared with untreated samples within 5min. wicking time in warp and weft direction respectively. Both in the treated and untreated fabric, the wicking height of the warp was greater than the weft due to its high yarn density (i.e. EPI ×PPI: 144×72).

Thus, a remarkable enhancement in the wicking height of plasma-treated blend fabric was observed. This is the result of etching, activation and cleaning effect of oxygen plasma gas on the fabric surface during treatment. Oxygen plasma has the potential to introduce polar groups on the fabric surface and remove hydrophobic contaminants from the fabric surface; thus, it produces more hydrophilic fibre surfaces [35]. The hydrophilic nature of the fibres has great contribution to comfort by maintaining the moisture; either it comes from the body or the surrounding environment. This experiment confirmed that it is possible to enhance the wicking property of polyester/cotton blend fabric by applying low-pressure oxygen plasma treatment.

The wickability of the blend fabric mainly depended on flow rate, operating pressure, and treatment time and discharge power. As per the delta value, the discharging pressure had the largest effect on the wickability of the blended fabrics in the warp and weft direction. The optimum parameter levels and the largest parameter effects of wicking in warp and weft direction have been explained in Table 4 & 5 and Figure 1 & 2 respectively.

TABLE 4: RESPONSE TABLE FOR S/N RATIO OF TREATED FABRIC WICKING IN THE WARP DIRECTION

Level		Flow Rate (sccm)	Pressure (mbar)	Power (%)	Time (min)
Average S/N, dB	1	35.72*	35.16	35.51	35.41
	2	35.34	35.95*	35.49	35.52
	3	35.48	35.43	35.53*	35.61*
Delta		0.38	0.79	0.05	0.20
Rank		2	1	4	3

Note: *: Optimum parameter level.

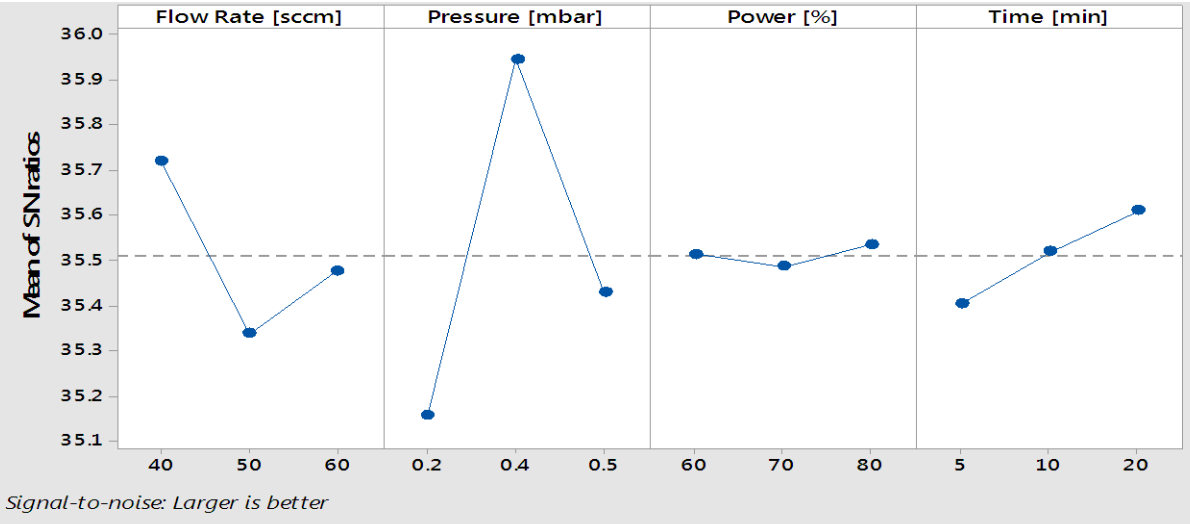

Figure 1: Main effects plot for S/N ratio of treated fabric wicking in the warp direction

TABLE 5: RESPONSE TABLE FOR S/N RATIO OF TREATED FABRIC WICKING IN THE WEFT DIRECTION

Level		Flow Rate (sccm)	Pressure (mbar)	Power (%)	Time (min)
Average S/N, dB	1	34.63	35.25*	34.75	34.88*
	2	34.95*	34.67	34.81	34.65
	3	34.81	34.47	34.84*	34.86
Delta		0.31	0.78	0.09	0.23
Rank		2	1	4	3

Note: *: Optimum parameter level.

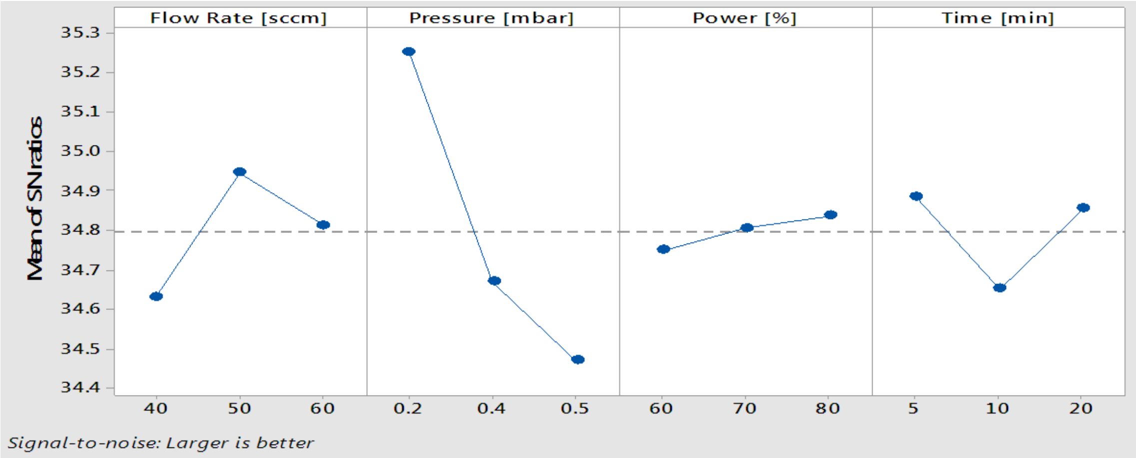

Figure 2: Main effects plot for S/N ratio of treated fabric wicking in the weft direction

3.3 Air permeability

The air permeability results of plasma-treated and untreated blend fabric have been shown in Table 3 (Column 4). The increase of air permeability after plasma treatment was 3% on average of 9 runs when compared with untreated fabric. Only the air permeabilities of run 1 and 7 had less than the untreated fabric. In this case, different reasons may be taken into account to explain the reduced air permeability. First, hairiness could be formed on the cotton fibres. This hairiness could reduce the passage of air in the fabric. Additionally, the polyester fibre surfaces could become rougher at higher discharge power treatment and thus are supposed to contribute to poor air permeability of the blend fabric. Despite the same pressure conditions in run 4, even an increase in air permeability can be observed. This supports the assumption that the influence of the parameter duration of action in the case of air permeability due to increased material removal and surface activation rather confirms the actual trend towards increasing the air permeability. Interestingly, previous research works have shown different results regarding air permeability, even with the same fabric (cotton) [9, 19].

Thus, air permeability of the blend fabric was governed by plasma condition and types of fibre. As per the delta value, pressure has the largest influence, whereas the flow rate has the smallest effect on air permeability of 65% polyester/ 35% cotton blended fabrics. The optimum parameter levels and the largest parameter influence on air permeability of a blend fabric have been tabulated in Table 6 and Figure 3: Medium flow rate and power conditions, but higher pressure and longer treatment time appear to be favourable.

TABLE 6: RESPONSE TABLE FOR S/N RATIO OF TREATED FABRIC AIR PERMEABILITY

Level		Flow Rate (sccm)	Pressure (mbar)	Power (%)	Time (min)
Average S/N, dB	1	41.02	40.82	40.93	41.08
	2	41.28*	41.29	41.39*	41.03
	3	41.14	41.33*	41.11	41.32*
Delta		0.26	0.51	0.45	0.29
Rank		4	1	2	3

Note: *: Optimum parameter level.

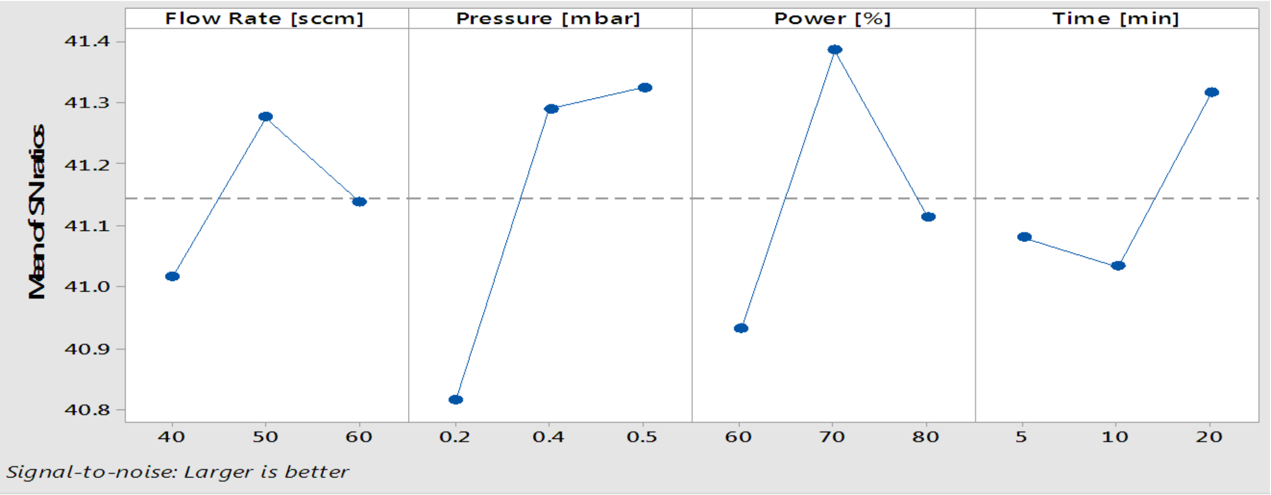

Figure 3: Main effects plot for S/N ratio of treated fabric air permeability

3.4 Relative Water Vapour Permeability

The results of the relative water vapour permeability of the blend fabric were recorded by Permetest (skin model), as shown in Table 3 (column 5). The relative water vapour permeability of plasma-treated samples increased by 2.3% compared to untreated mixed fibres. This improvement is probably due to the formation of cracks and grooves and the eroded surface of polyester and cotton fibres in the blended fabric by oxygen plasma treatment.

As a result of this effect, the plasma-treated fabric had better comfort property by regulating water vapour than the untreated blended fabric. In other words, better comfort property could be provided by increased water vapour permeability through plasma treatment.

With respect to the delta value, the oxygen gas flow rate had the greatest effect, while the pressure had the least effect on the relative water vapour permeability of the polyester/cotton blend. The optimum parameters and the greatest influence of the parameters on the relative water vapour permeability of a blended fabric are shown in Table 7 and Figure 4.

TABLE 7: RESPONSE TABLE FOR S/N RATIO OF TREATED FABRIC RELATIVE WATER VAPOUR PERMEABILITY

Level		Flow Rate (sccm)	Pressure (mbar)	Power (%)	Time (min)
Average S/N, dB	1	37.20	37.27	37.33*	37.25
	2	37.38*	37.28*	37.22	37.32*
	3	37.22	37.24	37.24	37.23
Delta		0.18	0.04	0.11	0.09
Rank		1	4	2	3

Note: *: Optimum parameter level.

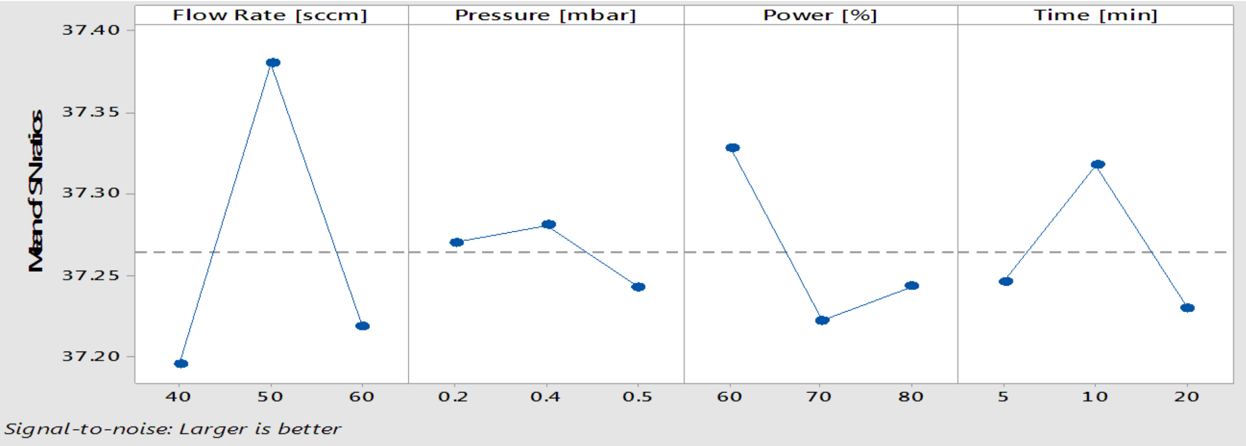

Figure 4: Main effects plot for S/N ratio of treated fabric relative water vapour permeability

3.5 Water Vapour Resistance

The results of the water vapour resistance of the P/C blended fabric are shown in Table 3 (column 6). The water vapour resistance of the plasma-treated blended fabric was on average 10% lower than that of the untreated fabric due to the cleaning effect of the oxygen plasma treatment. It is the reciprocal of water vapour permeability. Water vapour transmission through clothing provides better comfort both indoors and outdoors. If the clothing layers are impermeable, moisture is trapped between the skin and clothing and heat accumulates on the body. As a result, heat and moisture form, leading to discomfort and wet skin [36].

The optimum parameters and the greatest influence of the parameters on the water vapour resistance of a blended fabric are described in Table 8 and Figure 5. With respect to the delta value, the flow velocity had the largest and the pressure the smallest influence on the water vapour resistance of P/C blended fabrics, which is in good agreement with the results for relative water vapour permeability. Only the values for power and time are reversed, which is not surprising because of the measurement uncertainty due to the almost identical order of magnitude of the delta values.

TABLE 8: RESPONSE TABLE FOR S/N RATIO OF TREATED FABRIC WATER VAPOUR RESISTANCE

Level		Flow Rate (sccm)	Pressure (mbar)	Power (%)	Time (min)
Average S/N, dB	1	-5.490	-5.416	-5.252	-5.504
	2	-5.113	-5.276	-5.606*	-5.121
	3	-5.534*	-5.446*	-5.280	-5.512*
Delta		0.421	0.171	0.353	0.391
Rank		1	4	3	2

Note: *: Optimum parameter level.

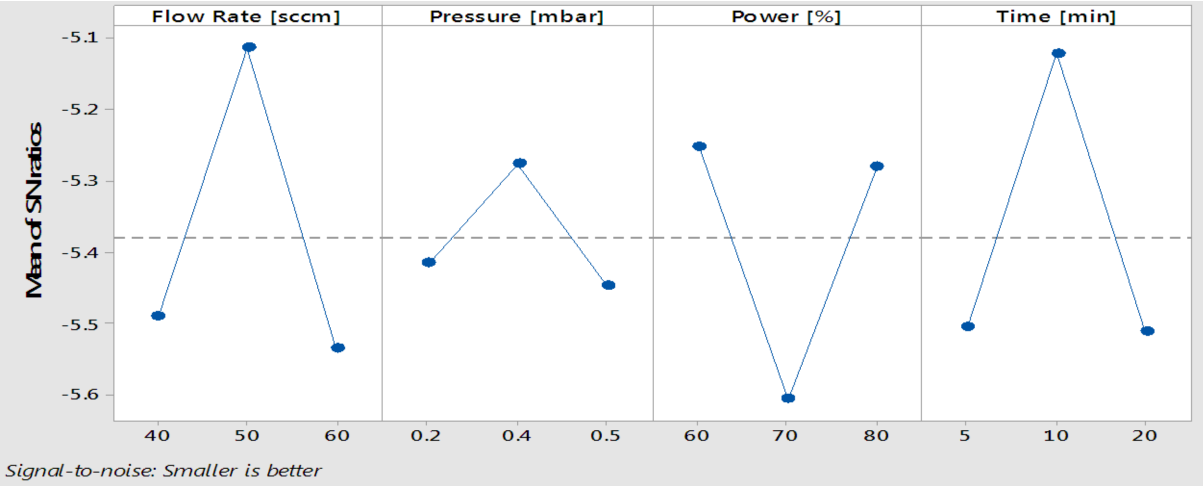

Figure 5: Main effects for S/N ratio of treated fabric water vapour resistance

3.6 Thermal resistance

According to the results in Table 3 (column 7), the thermal resistance decreased on average by 33.3% compared to the untreated fabric sample after plasma treatment. The thermal properties of the blended fabric depend mainly on the passage of air. The cleaning effect of the oxygen plasma treatment increased the porosity and wettability of the fibres and yarns. The trapped air and the removal of heat by evaporating water are the most important factors for heat transfer and thermal insulation. Therefore, the thermal resistance of the plasma-treated blended fabric has lower insulation properties compared to the untreated fabric. Water vapour permeability and air permeability increased after plasma treatment, as shown in 3.3 and 3.4. When the thermal resistance of clothing decreases in a hot climatic environment, the thermal energy is more easily dissipated and the body is cooled. Therefore, this type of treatment is good for summer clothing.

The optimum parameters and the greatest influence of the parameters on the thermal resistance of a blended fabric are described in Table 9 and Figure 6. According to the delta value, the power had the greatest influence on the thermal resistance of the P/C blended fabric. Both also most effectively influenced the increase in air and relative water vapour permeability.

TABLE 9: RESPONSE TABLE FOR S/N RATIO OF TREATED FABRIC THERMAL RESISTANCE

Level		Flow Rate (sccm)	Pressure (mbar)	Power (%)	Time (min)
Average S/N, Db	1	-11.85	-12.25	-13.68*	-11.75
	2	-11.14	-11.16	-11.37	-12.24*
	3	-12.79*	-12.38*	-10.73	-11.79
Delta		1.65	1.22	2.95	0.49
Rank		2	3	1	4

Note: *: Optimum parameter level.

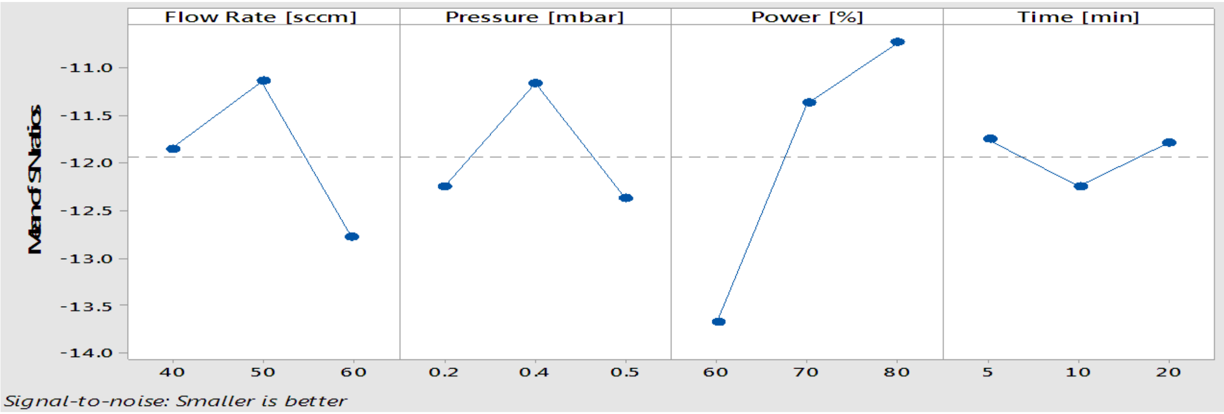

Figure 6: Main effects plot for S/N ratio of treated fabric thermal resistance

3.7 Surface Morphology and Topography

The surface morphologies of cotton and polyester fibres found in the blended fabric can be seen in Figure 7. The images of 2.0 um x 2.0 um x 10.0 nm were taken by AFM from the blended fabric before and after low-pressure oxygen plasma treatment. The images clearly show the topographic surface modification of the fibres. The surfaces of the fibres were changed from smooth (Figure 7 a) & c)) to rough (Figure 7 b) & d)) due to oxygen plasma treatment. The quantitative measurement of the nanotopography and the surface properties of the fibres in the blended fabric is given in Table 10.

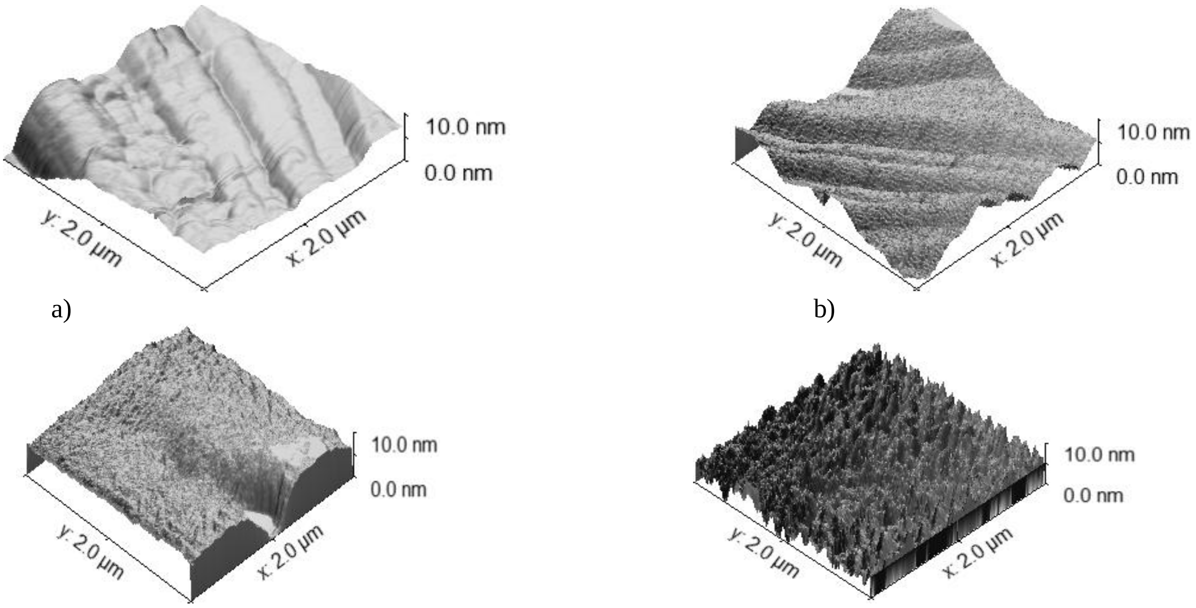

Figure 7: AFM images were taken from P/C blend fabric: a) untreated cotton. b) treated cotton, c) untreated polyester, d) treated polyester fibres. Blend fabric was treated at 40sccm, 0.2mbar, 5min and 600W with oxygen plasma.

TABLE 10: SURFACE PARAMETERS TAKEN BY AFM (AVERAGE OF 3 SAMPLES FOR EACH)

PET/Cotton blend fabric		A(pm^2)	Sa(nm)	Sq(nm)	Sy(nm)	Sp(nm)	Sv(nm)
Untreated	Cotton	4.03	11.65	14.59	89.47	50.19	-39.29
	PET	4.03	8.17	11.02	94.73	44.66	-51.08
Treated	Cotton	4.03	15.65	19.03	100.18	57.63	-42.55
	PET	4.03	8.99	12.29	95.99	45.57	-49.42

Note: A - area, Sa - average roughness, Sq - root mean sq. roughness, Sy - peak-valley height, Sp - peak height, Sv - valley depth.

The AFM analysis showed that the average roughness (Sa), the mean square roughness (Sq) and the peak roughness (Sy) of the fibres increased after low-pressure oxygen plasma treatment at 40 sccm, 0.2 mbar, 600 W and 5 min. The change in the shape of the surface features is obvious. The calculated Sa and Sq values obtained after the same plasma treatment were higher for cotton than for polyester fibres. As shown in Figure 7, b) and b), the treated specimens showed some wells and craters distributed almost uniformly on the surface. According to various studies, the fibril structure of the fibre surface changes to pit formation after plasma treatment [17]. In addition, the etching effects of the plasma increase in the amorphous region of the fibres and not in the crystalline areas [37].

IV. CONCLUSION

This study focused on the development of an economic and ecological textile process using plasma technology. The purpose of this research is to investigate the effects of low pressure oxygen plasma treatment on the various comfort properties of a polyester/cotton blend fabric (65/35%) by using the Taguchi method for experimental design.

The results showed that the oxygen plasma treatment had a positive effect on the air permeability, the relative water vapour permeability, the water vapour resistance and the heat resistance of the blended fabric. The results depend mainly on the oxygen gas flow rate, operating pressure and discharge performance of the plasma parameters. The Taguchi analysis confirmed that the pressure had the greatest influence on the wicking and the air permeability during treatment, the flow rate on the relative water vapour permeability and the water vapour resistance, whereas power showed the greatest influence on the thermal resistance. After plasma treatment, thermal resistance decreased by 34.3% and wicking properties increased by 49.8% and 45.3%, in the warp and weft directions, respectively. Minor changes with a positive comfort effect were observed with regard to air permeability (2.9%), relative water vapour permeability (2.3%) and water vapour resistance (-10%). The AFM analysis showed the extent of fibre functionalization in the blended fabric from smooth to rough surface after treatment. This research has shown the potential benefits of plasma technology in combination with the design of experiments to investigate optimized combinations of process parameters and to improve important variables responsible for the thermophysiological comfort of blended fabrics.

V. ACKNOWLEDGMENT

This work has been fully supported by the Engineering Education Capacity Building Program of Ethiopia (EECBP) together with the German Academic Exchange Service (DAAD) by providing scholarship under section ST32 and Dire Dawa University. Authors are very grateful to Asst. Prof. Dr. L. Hari Gopalakrishnan and Mr. Ziad Heilani (Albstadt-Sigmaringen University) for their precious help in realizing this research work.

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