Influence of Various Temperatures on the Drying Time of 132 KV Transformer Insulations in Vapour Phase Drying Process

Mohd. Tareq Siddiqui, Jayant T. Pattiwar, Avinash P. Paranjape, Ashok J Keche

Abstract: Transformers are required to handle very high levels of voltage and hence proper insulation is very important in transformers. As of now, the most preferred form of insulation in transformers is cellulose based. The state of cellulose insulation materials like paper & pressboards determines the life end of a transformer. Paper with 1.5% moisture content ages 10 times faster than with only 0.3% moisture. For obvious reasons, it is very important that the moisture is removed from transformer insulation. Vacuum drying has been conventionally used in industries for insulation drying but, as of today the latest technology available is the vapour phase drying process. This paper evaluates the influence of temperatures at various locations on the drying time of the 132kv transformer insulations in vapour phase drying process.

Keywords: Temperature, drying time, moisture, transformer

I. INTRODUCTION

Transformer is required to withstand high voltages during the process of power transfer from primary to secondary. For this purpose, it is required to have adequate insulation. Due to long and positive experience, cellulose based insulation is widely used in transformer manufacturing & it has a significant role in its life & performance characteristics [1]. However, cellulose based insulation being a hygroscopic material, may contain 8 to 10% of moisture by weight at ambient temperature [2]. This moisture is injurious to the health of the transformers since it reduces the dielectric strength, raises the dielectric power factor, increases the risk of thermal breakdown of solid insulation, lowers the lowest hot-spot temperature range for possible bubble formation, accelerates thermal aging of paper insulation, and can be the root cause of a catastrophic failure [3]. It is therefore imperative to remove this moisture from the insulation. In the drying processes used for insulation drying, temperature attained in the insulation is one of the most important factors [4].

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This paper presents a statistical analysis and evaluates the effects of temperatures at various locations viz., outer, middle & innermost layers of insulation in transformer insulation drying using vapour phase drying process for two 132/27 KV, 45 MVA transformer coil with 2 ton insulation.

II. VAPOUR PHASE DRYING OF 132KV (I)

For the process of vapour phase drying, the 132/27 KV, 45 MVA transformer coil with 2 ton insulation was loaded into the vacuum chamber. The vacuum chamber has a provision of thermic fluid heating. Initially the chamber is evacuated for about 2 hours. The vacuum pressure of 19.17 mbar was observed at this point. Thereafter, the vacuum chamber is heated through thermic fluid for about 17 hours. It was observed at this point that the temperature of the outermost layer of insulation was 73ºc while that of the middle layer was 67ºc and that of the innermost layer was 62 ºc. Also, during this heating, the pressure in the vessel increased to 95mbar. The reason for this increase in pressure is the vapourisation of moisture form the outer layers of insulation. Then, the vacuum chamber is subjected to further pressure reduction for about 2 hours before kerosene vapours are introduced in the vacuum chamber. Kerosene vapours are introduced in the vacuum chamber for about 8 hours. As a result of injection of kerosene vapours, the temperature of the insulation increases such that the temperature of the outermost layer reaches up to 107ºc, while that of the middle layer is 103ºc and that of the innermost layer is 99ºc. The final vacuum achieved at the end of the cycle was found to be 0.1 mbar. Also, the total amount of moisture removed was about 30 litres at the end of cycle.

The following tables illustrates the readings of temperatures and the moisture removal per hour during the drying cycle.

In the table, t1 is the temperature of the outermost layer of the insulation, t2 is the temperature of the middle layer of insulation & t3 is the temperature of the innermost layer of the insulation which is nearest to the core. It may be clearly seen from the table that the temperatures in the insulation are not the same throughout. Maximum temperature is observed on the outermost layer while, minimum temperature is observed on the innermost layer. The different temperatures at different locations in the insulation have different effect on the drying time of the insulation.

Table- I: Vacuum Chamber Readings (I)

Time in Hrs.	Total Water/ Hr	t1	t2	t3	Vacuum Level (mbar)
0	0.27	33	33	33	975.42
1	0.38	31	30	30	139.88
2	0.45	37	31	29	19.17
3	0.6	38	33	32	33.62

4	0.71	40	35	34	35.97
5	0.88	42	37	34	40.86
6	0.97	46	40	35	39.56
7	1.09	46	41	36	45.49
8	1.28	48	43	36	50.42
9	1.51	52	45	39	54.78
10	1.73	54	47	42	62.56
11	1.95	55	49	43	68.44
12	2.15	58	51	45	76.77
13	2.22	62	55	48	84.52
14	2.54	65	59	53	90.78
15	2.74	68	63	57	94.41
16	2.89	71	65	60	94.36
17	3.01	72	66	60	94.46
18	3.12	72	67	62	95.49
19	3.2	73	67	62	95.25
20	3.08	77	70	65	71.76
21	14.33	86	79	70	24.62
22	25.17	95	85	77	12.97
23	27.25	98	88	81	13.53
24	27.25	101	90	83	2.3
25	28.65	105	95	89	0.1
26	29.46	103	98	91	0.1
27	29.46	105	98	91	0.1
28	29.46	107	101	97	0.1
29	29.46	108	102	98	0.1
30	29.46	107	103	99	0.1

In the drying processes used for insulation drying, temperature attained in the insulation is one of the most important factors [4]. However, to establish temperature at which location in the insulation, will have the maximum influence on the drying time, Taguchi & Regression analysis were performed using Minitab software between temperatures and drying time and temperatures & rate of moisture removal.

III. TAGUCHI ANALYSIS BETWEEN TEMPERATURES & TIME (I)

While maintaining the quality standards, it is always desirable to have lower drying times. Here quality pertains to the amount of moisture removed. Taguchi analysis between temperatures & drying time was therefore performed by taking temperatures as input factors & drying time as response variable. Signal to noise ratios were also evaluated for "Smaller the Better" (drying time). The values obtained from the analysis may summarized in tables 2 & 3.

Table- II: Response Table for Signal to Noise Ratios "Smaller Is Better" (I)

Level	t1	t2	t3
1	0	0	-6.0206
2		-6.0206	0
3	-6.0206	-9.5424	-9.5424
4	-9.5424	-12.0412	
5	-12.0412	-13.9794	-13.0103
6	-13.9794	-15.563	-15.563
7	-16.2325	-16.902	-17.4819
8	-18.0618	-18.0618	-19.0849
9	-19.0849	-19.0849	-20
10	-20	-20	-20.8279
11	-20.8279	-20.8279	-21.5836
12	-21.5836	-21.5836	-22.2789
13	-22.2789	-22.2789	-22.9226
14	-22.9226	-22.9226	-23.5218
15	-23.5218	-23.5218	-24.3457
16	-24.0824	-24.0824	-25.3403
17	-24.8572	-24.609	-26.0206
18	-25.5751	-25.3403	-26.4444
19	-26.0206	-26.0206	-26.8485
20	-26.4444	-26.4444	-27.2346
21	-26.8485	-26.8485	-27.6042
22	-27.2346	-27.2346	-27.9588
23	-27.6042	-27.6042	-28.4634
24	-28.2995	-27.9588	-28.9432
25	-28.293	-28.4634	-29.248
26	-29.2428	-28.9432	-29.5424
27	-29.248	-29.248	
28		-29.5424	
Delta	29.248	29.5424	29.5424

Rank	3	1.5	1.5

Table- III: Response Table for Means (I)

Level	t1	t2	t3
1	1	1	2
2	0	2	1
3	2	1.5	3
4	3	4	0
5	4	5	4.5
6	5	6	6
7	6.5	7	7.5
8	8	8	9
9	9	9	10
10	10	10	11
11	11	11	12
12	12	12	13
13	13	13	14
14	14	14	15
15	15	15	16.5
16	16	16	18.5
17	17.5	17	20
18	19	18.5	21
19	20	20	22
20	21	21	23
21	22	22	24
22	23	23	25
23	24	24	26.5
24	26	25	28
25	26	26.5	29
26	29	28	30
27	29	29	
28		30	
Delta	29	29	30
Rank	2.5	2.5	1

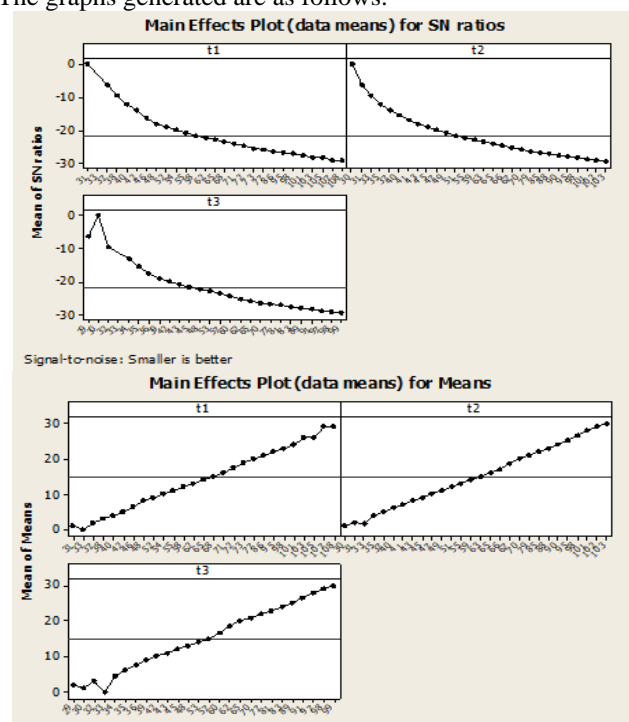The graphs generated are as follows.

Fig. 1. Temp. Vs Time, Taguchi Graphs (I)

IV. REGRESSION ANALYSIS BETWEEN TEMPERATURES & TIME. (I)

To further asses which temperature has the maximum influence on the drying time, regression analysis was performed. Drying time was taken as the response & temperatures was taken as the predictor. The regression equation obtained is as follows.

Time in Hrs. = - 8.85 - 0.009 t1 + 0.682 t2 - 0.321 t3
(1)

Regression in tabular form can be illustrated as follows.

Table- IV: Regression Analysis of Temperatures Vs Time (I)

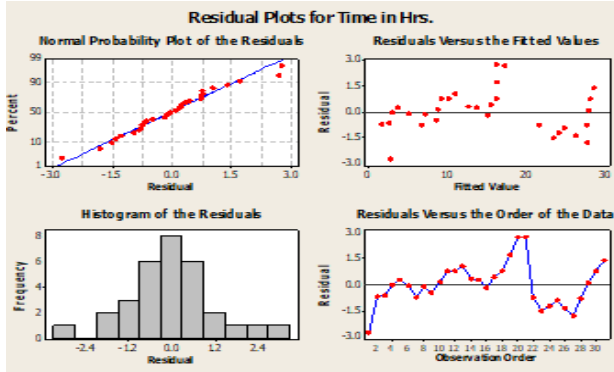| Predictor	Coef	SE Coef	T	P
Constant	-8.8506	0.7524	-11.76	0
t1	-0.0089	0.1459	-0.06	0.952
t2	0.6818	0.2627	2.6	0.015
t3	-0.3213	0.1498	-2.15	0.041

The regression graphs are as follows.

Fig. 2. Temp. Vs Time, Regression Graphs (I)

V. TAGUCHI ANALYSIS BETWEEN TEMPERATURES & MOISTURE REMOVAL RATE. (I)

By taking temperatures as input factors & moisture removal rate as response variable Taguchi analysis between temperatures & moisture removal rate was performed to further determine the effect of different temperatures on the moisture removal rate and by extension on the drying time. Signal to noise ratios were also evaluated for "Larger the Better" (moisture removal rate). The values obtained from the analysis may summarized in tables 5& 6.

Table- V: Response Table for Signal to Noise Ratios "Larger Is Better" (I)

Level	t1	t2	t3
1	-8.4043	-8.4043	-6.9357
2	-11.3727	-6.9357	-8.4043
3	-6.9357	-7.9048	-4.437
4	-4.437	-2.9748	-11.3727
5	-2.9748	-1.1103	-2.0426
6	-1.1103	-0.2646	-0.2646
7	0.242	0.7485	1.4464
8	2.1442	2.1442	3.5795
9	3.5795	3.5795	4.7609
10	4.7609	4.7609	5.8007
11	5.8007	5.8007	6.6488
12	6.6488	6.6488	6.9271
13	6.9271	6.9271	8.0967
14	8.0967	8.0967	8.755
15	8.755	8.755	9.3946
16	9.218	9.218	9.993
17	9.7272	9.5713	9.771
18	10.103	9.993	23.1249
19	9.771	9.771	28.0177
20	23.1249	23.1249	28.7073
21	28.0177	28.0177	28.7073
22	28.7073	28.7073	29.1425
23	28.7073	28.7073	29.3847
24	29.3847	29.1425	29.3847
25	29.2636	29.3847	29.3847
26	29.3847	29.3847	29.3847
27	29.3847	29.3847	
28		29.3847	
Delta	40.7574	37.789	40.7574
Rank	1.5	3	1.5

Table- VI: Response Table for Means (I)

Level	t1	t2	t3
1	0.38	0.38	0.45
2	0.27	0.45	0.38
3	0.45	0.435	0.6
4	0.6	0.71	0.27
5	0.71	0.88	0.795
6	0.88	0.97	0.97
7	1.03	1.09	1.185
8	1.28	1.28	1.51
9	1.51	1.51	1.73
10	1.73	1.73	1.95
11	1.95	1.95	2.15
12	2.15	2.15	2.22
13	2.22	2.22	2.54
14	2.54	2.54	2.74
15	2.74	2.74	2.95
16	2.89	2.89	3.16
17	3.065	3.01	3.08
18	3.2	3.16	14.33
19	3.08	3.08	25.17
20	14.33	14.33	27.25
21	25.17	25.17	27.25
22	27.25	27.25	28.65
23	27.25	27.25	29.46
24	29.46	28.65	29.46
25	29.055	29.46	29.46
26	29.46	29.46	29.46
27	29.46	29.46	
28		29.46	
Delta	29.19	29.08	29.19
Rank	1.5	3	1.5

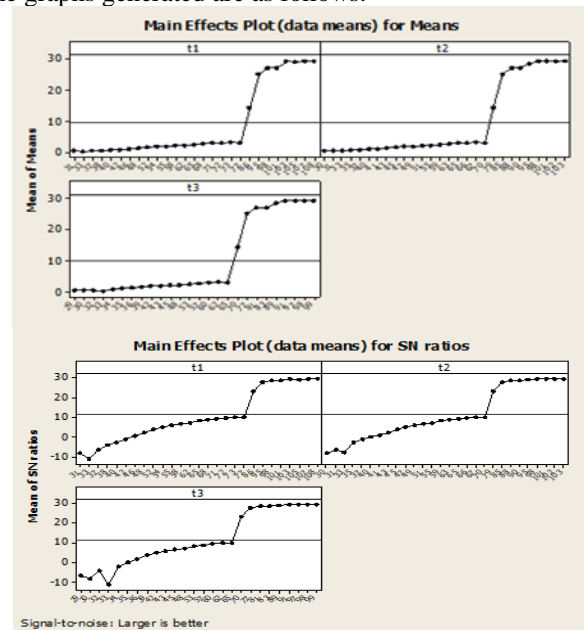The graphs generated are as follows.

Fig. 3. Temp. Vs Moisture Removal Rate, Taguchi Graphs (I)

VI. REGRESSION ANALYSIS BETWEEN TEMPERATURES & MOISTURE REMOVAL RATE. (I)

Regression analysis was performed with moisture removal rate as the response & temperatures as the predictor. The following regression equation was obtained.

Total Water = - 19.5 + 0.926 t1 - 1.86 t2 + 1.42 t3
(2)

The following tabular form of regression was also obtained.

Table- VII: Regression Analysis of Temperatures Vs Moisture Removal Rate (I)

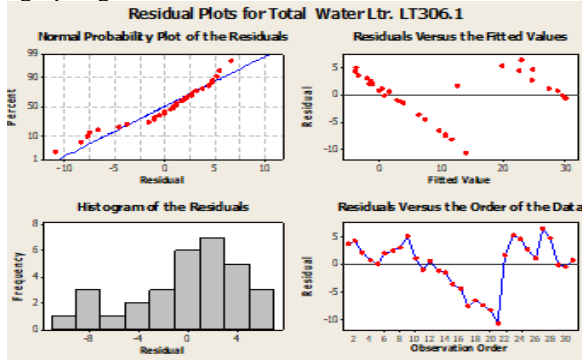| Predictor	Coef	SE	T	P
Constant	-19.514	2.78	-7.02	0
t1	0.9257	0.5391	1.72	0.097
t2	-1.8583	0.9707	-1.91	0.066
t3	1.4192	0.5534	2.56	0.016

The graphs generated are as follows.

Fig 4.Temp. Vs Moisture Removal Rate, Regression Graphs. (I)

VII. VAPOUR PHASE DRYING OF 132KV (II)

For the process of vapour phase drying, the 132/27 KV, 45 MVA transformer coil with 2 ton insulation was loaded into the vacuum chamber. Initially the chamber is evacuated for about 3 hours. The vacuum pressure of 20.81 mbar was observed at this point. Thereafter, the vacuum chamber is heated through thermic fluid for about 10 hours. It was observed at this point that the temperature of the outermost layer of insulation was 64°c while that of the middle layer was 60°c and that of the innermost layer was 54 °c. Also, during this heating, the pressure in the vessel increased to 56.8mbar. The reason for this increase in pressure is the vapourisation of moisture form the outer layers of insulation. Then, the vacuum chamber is subjected to further pressure reduction for about 3 hours. Next, a second heating cycle is taken for 2 hours during which the temperature of the outermost layer reaches 90 °c while that of the middle layer reaches 84°c and that of the innermost layer reaches 77°c. the pressure observed at this point is 61.15mbar. Kerosene vapours are introduced in the vacuum chamber for about 10 hours. As a result of injection of kerosene vapours, the temperature of the insulation increases such that the temperature of the outermost layer reaches up to 108°c, while that of the middle layer is 102°c and that of the innermost layer is 101°c. The final vacuum achieved at the end of the cycle was found to be 0.1 mbar. Also, the total amount of moisture removed was about 24 litres at the end of cycle. The following tables illustrates the readings of temperatures and the moisture removal per hour during the drying cycle.

Table-VIII: Vacuum Chamber Readings (II)

Time in Hrs.	Total Water/ Hr	t1	t2	t3	Vacuum Level (mbar)
0	0.38	37	37	37	971.06
1	0.47	37	37	37	971.1
2	0.69	37	36	36	96.71
3	0.88	43	42	40	20.81
4	1.08	44	43	43	29.4
5	1.15	44	44	43	35.77
6	1.21	45	44	43	38.99
7	1.38	54	50	47	41.87
8	1.44	60	55	50	47.73
9	1.59	61	56	52	50.93
10	1.63	61	55	53	52.3
11	1.69	62	56	52	53.41
12	1.72	64	60	54	56.8
13	1.74	68	62	57	55.22
14	2.65	75	69	63	52.16
15	4.04	84	75	70	39.16
16	4.05	85	77	72	53.77
17	4.05	90	84	77	61.15
18	5.14	94	90	84	38.69
19	8.5	99	95	88	27.26
20	13.53	100	96	92	10.63
21	15.36	103	98	93	11.65
22	18.67	105	99	95	0.16
23	20.58	107	100	95	0.1
24	23.49	107	100	96	0.1
25	23.55	106	103	99	0.1
26	23.57	106	102	100	0.1
27	23.62	108	102	101	0.1

VIII. TAGUCHI ANALYSIS BETWEEN TEMPERATURES & TIME. (II)

Taguchi analysis between temperatures & drying time was performed by taking temperatures as input factors & drying time as response variable. Signal to noise ratios were also evaluated for "Smaller the Better" (drying time). The values obtained from the analysis may summarized in tables 9 & 10.

Table- IX: Response Table for Signal to Noise Ratios "Smaller Is Better" (II)

Level	t1	t2	t3
1	-1.505	-6.021	-6.021
2	-9.542	3.01	3.01
3	-13.01	-9.542	-9.542
4	-15.563	-12.041	-13.861
5	-16.902	-14.771	-16.902
6	-18.062	-16.902	-18.062
7	-19.542	-19.031	-19.956
8	-20.828	-19.956	-20
9	-21.584	-21.584	-21.584
10	-22.279	-22.279	-22.279
11	-22.923	-22.923	-22.923
12	-23.522	-23.522	-23.522
13	-24.082	-24.082	-24.082
14	-24.609	-24.609	-24.609
15	-25.105	-25.105	-25.105
16	-25.575	-25.575	-25.575
17	-26.021	-26.021	-26.021
18	-26.444	-26.444	-26.444
19	-26.848	-26.848	-27.042
20	-28.129	-27.419	-27.604
21	-27.822	-28.299	-28.293
22		-28.293	-28.299
Delta	26.624	31.31	31.31
Rank	3	1.5	1.5

Table- X: Response Table for Means (II)

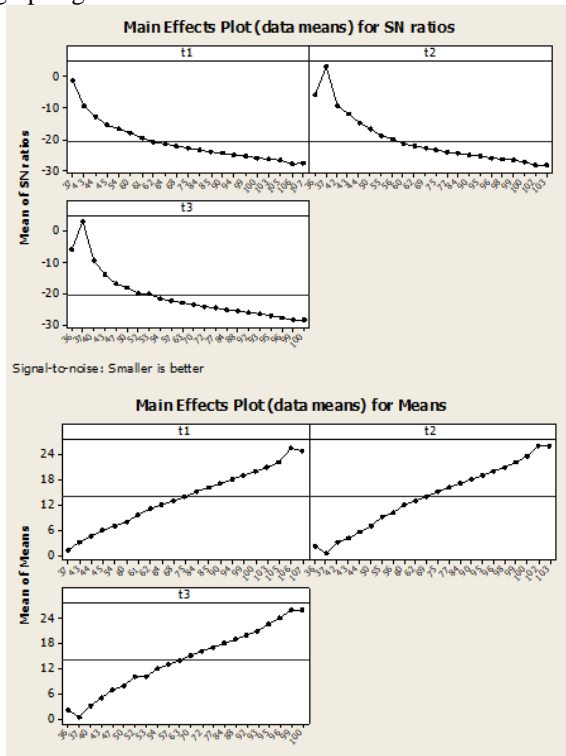| Level	t1	t2	t3
1	1.25	2	2
2	3	0.5	0.5
3	4.5	3	3
4	6	4	5
5	7	5.5	7
6	8	7	8
7	9.5	9	10
8	11	10	10
9	12	12	12
10	13	13	13
11	14	14	14
12	15	15	15
13	16	16	16
14	17	17	17
15	18	18	18
16	19	19	19
17	20	20	20
18	21	21	21
19	22	22	22.5
20	25.5	23.5	24
21	24.6667	26	26
22		26	26
Delta	24.25	25.5	25.5
Rank	3	1.5	1.5

The graphs generated are as follows.

Fig. 5. Temp. Vs Time, Taguchi Graphs (II)

IX. REGRESSION ANALYSIS BETWEEN TEMPERATURES & TIME. (II)

To asses which temperature has the maximum influence on the drying time, regression analysis was performed. Drying time was taken as the response & temperatures was taken as the predictor. The regression equation obtained is as follows.

Time in hrs = - 9.83 + 0.343 t1 - 0.263 t2 + 0.245 t3 (3)

Regression in tabular form can be illustrated as follows.

Table- XI: Regression Analysis of Temperatures Vs Time (II)

Predictor	Coef	SE Coef	T	P
Constant	-9.8316	0.8624	-11.4	0
t1	0.3426	0.1678	2.04	0.052
t2	-0.2633	0.3324	-0.79	0.436
t3	0.2448	0.2067	1.18	0.248

The regression graphs are as follows.
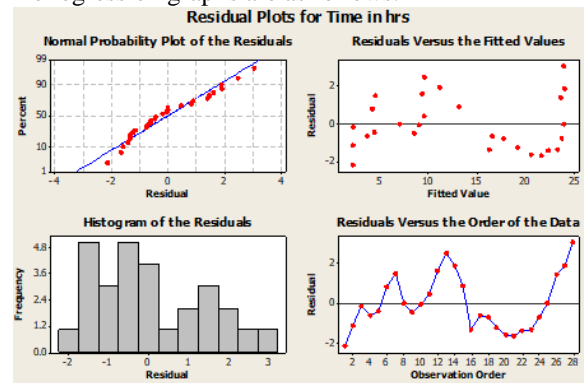
Fig. 6. Temp. Vs Time, Regression Graphs (II)

X. TAGUCHI ANALYSIS BETWEEN TEMPERATURES & MOISTURE REMOVAL RATE. (II)

By taking temperatures as input factors & moisture removal rate as response variable Taguchi analysis between temperatures & moisture removal rate was performed to determine the effect of different temperatures on the moisture removal rate and by extension on the drying time. Signal to noise ratios were also evaluated for "Larger the Better" (moisture removal rate). The values obtained from the analysis may summarized in tables 12 & 13.

Table- XII: Response Table for Signal to Noise Ratios "Larger Is Better" (II)

Level	t1	t2	t3
1	-5.4008	-3.223	-3.223
2	-1.1103	-7.5786	-7.5786
3	0.9412	-1.1103	-1.1103
4	1.6557	0.6685	1.1794
5	2.7976	1.4348	2.7976
6	3.1672	2.7976	3.1672
7	4.1358	3.7055	4.2928
8	4.5577	4.2928	4.2438
9	4.7106	4.7106	4.7106
10	4.811	4.811	4.811
11	8.4649	8.4649	8.4649
12	12.1276	12.1276	12.1276
13	12.1491	12.1491	12.1491
14	12.1491	12.1491	12.1491
15	14.2193	14.2193	14.2193
16	18.5884	18.5884	18.5884
17	22.626	22.626	22.626
18	23.7278	23.7278	23.7278
19	25.4229	25.4229	25.8459
20	27.4435	26.8433	27.4177
21	27.0507	27.4472	27.4527
22		27.4472	27.4527
Delta	32.8443	35.0313	35.0313
Rank	3	1.5	1.5

Table- XIII: Response Table for Means (II)

Level	t1	t2	t3
1	0.5575	0.69	0.69
2	0.88	0.425	0.425
3	1.115	0.88	0.88
4	1.21	1.08	1.1467
5	1.38	1.18	1.38
6	1.44	1.38	1.44
7	1.61	1.535	1.64
8	1.69	1.64	1.63
9	1.72	1.72	1.72
10	1.74	1.74	1.74
11	2.65	2.65	2.65
12	4.04	4.04	4.04
13	4.05	4.05	4.05
14	4.05	4.05	4.05
15	5.14	5.14	5.14
16	8.5	8.5	8.5
17	13.53	13.53	13.53
18	15.36	15.36	15.36
19	18.67	18.67	19.625
20	23.56	22.035	23.49
21	22.5633	23.57	23.585
22		23.57	23.585
Delta	23.0025	23.16	23.16
Rank	3	1.5	1.5

The graphs generated are as follows.
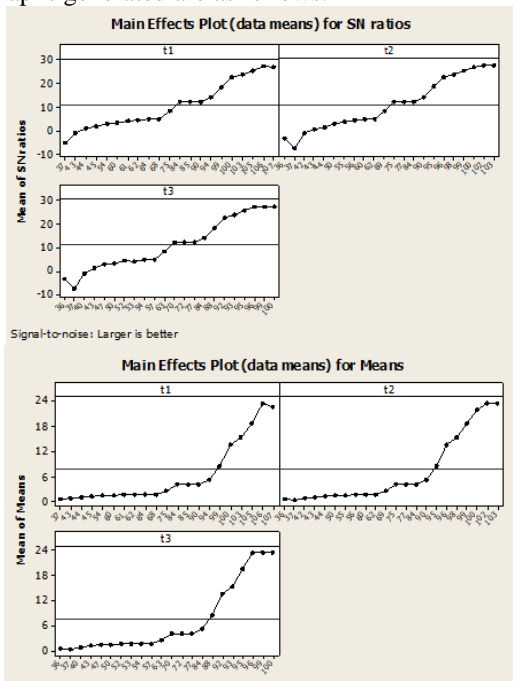
Fig. 7. Temp. Vs Moisture Removal Rate, Taguchi Graphs (II)

XI. REGRESSION ANALYSIS BETWEEN TEMPERATURES & MOISTURE REMOVAL RATE. (II)

Regression analysis was performed with moisture removal rate as the response & temperatures as the predictor. The following regression equation was obtained.

Total   Water = - 14.8 + 0.000 t1 - 1.64 t2 + 2.07 t3
(4)
The following tabular form of regression was also obtained.

Table- XIV: Regression Analysis of Temperatures Vs Moisture Removal Rate (I)

Predictor	Coef	SE Coef	T	P
Constant	-14.791	1.576	-9.39	0
t1	0.0004	0.3066	0	0.999
t2	-1.6444	0.6073	-2.71	0.012

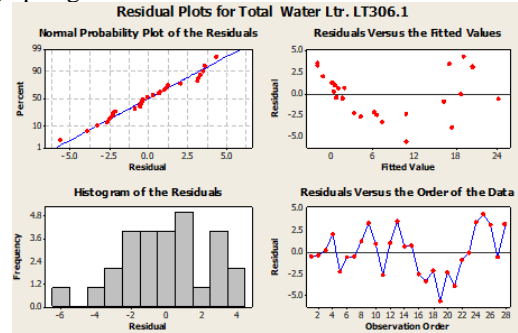| t3 | 2.0661 | 0.3775 | 5.47 | 0 |

The graphs generated are as follows.

Fig. 8. Temp. Vs Moisture Removal Rate, Regression Graphs (II)

XII. RESULTS & DISCUSSIONS

Since the delta value and rank in Taguchi analysis (I) between temperatures and drying time is the highest for the innermost layer temperature as can be seen in tables 2 & 3, it is clearly evident that, of all the temperatures, the innermost layer temperature of insulation has maximum influence on the drying time.

As can be clearly seen in table 4 for regression analysis (I) between temperatures and drying time that, P value for temperature of the innermost layer of insulation is minimum after the P value for temperature of the middle layer. It can therefore be concluded that the temperature of the innermost layer is one of the most influential temperature for drying time.

As can be clearly seen in tables 5 & 6 for Taguchi analysis (I) between temperatures and moisture removal rate that the delta value & rank of the innermost layer temperature i.e t3 is highest, it can therefore be concluded that, of all the temperatures, the temperature of the innermost layer of insulation will have maximum influence on the moisture removal rate as the temperature of the outermost layer cannot be exceeded after a certain limit.

It is clearly evident from table 7 for regression analysis (I) between temperatures and moisture removal rate that, P value for temperature of the innermost layer of insulation t3 is minimum & hence it is the most influential temperature on the moisture removal rate.

The delta value and rank in tables 9 & 10 for Taguchi analysis (II) between temperatures and drying time is the highest for the innermost layer temperature i.e t3. Therefore, it is clearly evident that, of all the temperatures, the innermost layer temperature of insulation has maximum influence on the drying time.

As can be clearly seen in table 11 for regression analysis (II) between temperatures and drying time that, P value for temperature of the innermost layer of insulation is minimum. It can therefore be concluded from regression analysis that the temperature of the innermost layer is the most influential temperature for drying time.

As can be clearly seen in tables 12 & 13 for Taguchi analysis (II) between temperatures and moisture removal that the delta value & rank of the innermost layer temperature i.e t3 is highest, it can therefore be concluded that, of all the temperatures, the temperature of the

innermost layer of insulation will have maximum influence on the moisture removal rate.

In table 14 it can be seen that the P value in regression analysis (II) between temperatures and moisture removal rate is minimum for temperature of the innermost layer of insulation t3 & hence it is the most influential temperature on the moisture removal rate.

XIII. CONCLUSION

Form the results of the Taguchi and Regression analysis obtained for vapour phase drying, it is clearly seen that, the temperature of the innermost layer of the insulation which is nearest to the transformer core is the most decisive temperature in reducing the overall drying time and increasing the moisture removal rate. The innermost layer temperature is predominant in positively influencing to reduce the drying time and increasing the moisture removal rate. It can therefore be concluded that if the temperature of the innermost layer of insulation is increased, the overall drying time may be reduced as, this increase in temperature will serve to increase the moisture removal rate.

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