Journal of the Korea Society of
Tobacco Science Vol. 21, No. 2, 109~118 (1999)
Printed in Republic of Korea

Practical modeling of cigarette ventilation rate

Young-Hoh Kim*, Moon-Yong Lee, Kyu-Seo Rhee and Dong-Wook Lee

Korea Ginseng and Tobacco Research Institute, Taejon 305-345, Korea

(Received October 5, 1999)

ABSTRACT : A model predicted describing the effect of cigarette making materials on the level of filter ventilation was developed and evaluated. The developed model was expressed in terms of a linear and quadratic relationship which was validated with experimental measurements for different porosity of plug wrap and tipping paper, unencapsulated pressure drop of filter plug and cigarette column and vent position.

Forty-six experimental frequencies were determined as a result of using three levels with five factors Box-Behnken design and analyzed by the multiple regression analysis with backward stepwise in STATISTICA/PC under restricted conditions. The four factors, except filter pressure drop variable, were statistically significant at the level of 0.05 but most of all linear by linear interactions were comparatively lower significant.

By the analysis of linear and quadratic regression coefficient, filter ventilation of the cigarette was affected by porosity of plugwrap (5.87, -4.25), porosity of tip paper (5.68, -1.00), vent position (-3.87, 3.08), tobacco column pressure drop (2.56, 0.66), and filter pressure drop (1.50, 0.58) in the decreasing order. It should be emphasized that the major conclusion of this study was not that any particular parameter was linear or quadratic on any limit scale, but that there were highly significant relationships among factors involving linear, quadratic and their interaction and perhaps even linearity between and within factors. While, there is also quite strong evidence that vent position from mouth end and cigarette making materials are reverse relationship on this experimental model.

On the basis of the result, it can be concluded that the porosity of the plug wrap and tipping paper has a marked effect on degree of filter ventilation rate. The F-value of plug wrap and tipping paper porosity among five factors were 39.2 and 36.8 respectively with *P*-value of 0.000 indicating higher significant for both factors. According to the analysis of variance, the model fitted for filter ventilation was significant at 5% confidence level and the coefficient of determination (R^2=0.84) was the proportion to variability in the data well fitted for by the model.

Key words : Box-Behnken design, Interaction effect, *P*-value, Linear & quadratic

Introduction

In recent years, health authorities and smokers to reduce the tar in their cigarettes have prescribed cigarette manufactures. These requirements initially led to the cigarette designers to develope more efficient filters. However, these filters which have higher pressure drop and increases cigarette encapsulated pressure drop to some extent if smoking acceptability is to be

---

Corresponding author : *Korea Ginseng and Tobacco Research Institute, P. O. Box 7, Yusung-Gu, Daeduk Science Town, Taejon 305-345, KOREA*

maintained. Therefore, ventilated filter cigarette have been used for long period to increase the degree of ventilation while maintaining appropriate cigarette unencapsulated pressure drop. it was well known that the variability of a ventilated filter cigarette depends on the details of its construction and on the variability of its ventilation in filter cigarette caused by many factors, like fluctuations in tipping paper, plug wrap porosity, pressure drop of tobacco column, and vent position from mouth end etc. (Selke, 1978) So many articles to derive a theoretic (Keith, 1979, Mathews, 1978,) and empirical prediction model (Baskevitch, 1994, Parker, 1979) of the filter pressure drop and ventilation rate for the cigarette design have been published. Schneider et *al.* (1984) presented a mathematical model for a ventilated filter cigarette to predict effects of this model.

Prediction models can be used to examine the relationships of component variability to the cigarette performance and to study the expected variability of alternative cigarette design. At the point of these mathematical calculation is a routine which uses a detailed understanding of the effect of tipping materials on cigarette ventilation level and tar delivery(Broune, 1990; Kiefer, 1980). Curran(1982) reported that selecting the optimum cigarette design to achieve specific filter cigarette ventilation requires the simultaneous solution of several complicated polynomial equations. Therefore, this study was carried out to elucidate their interrelationships of ventilation affected parameters. The specific objective was to provide a means of estimating the effects of cigarette making materials on the degree of ventilation. To perform this objective, we had to clarify the effect of the wrapping materials including draw resistance of filter and tobacco rod, porosity of plug wrap and tip paper, and vent position from mouth end on the amount of cigarette ventilation.

Materials and Methods

A study for air dilution was conducted to determine the effect of wrapping materials with filter plugs on the ventilation level. Independent variables chosen in this study were three levels of filter pressure drop with 3.0 filament deiner, 37,000 total denier restricted circumference and filter length, and porosity of tipping paper and plug wrap. Permeability of tipping paper which was punched by microlaser in 4 rows with 18 holes at each perforating line was selected at three levels of 700, 900, and 1,100 CORESTA UNIT(CU), plug wrap porosity were of 6,500, 9,500, and 12,000 CU. draw resistance of tobacco column were of 45, 55, 65mmH_2O with 60mm length, and vent positions from mouth end were of 9, 13 and 17mm. Because any variation in the permeability of the plug wrap has a major impact on the uniformity of filter ventil- ation, the air permeability of porous plug wrap must not only specify to the target but must also be as uniform as possible. The ISO method using 4Cm^2 measuring head of *Heiner Borgwaldt* porosimeter is generally adopted measuring method of air permeability of porous plug wrap and tipping paper.

Hand-made cigarette

A Box-Behnken design for five independent factors was used for filter tip pressure drop, tipping paper permeability, pressure drop of the tobacco rod, vent position from mouth and plug wrap permeability. Dependant variable(Y) was selected as cigarette ventilation levels. Cigarette which was 84mm in overall length including 24mm filter section and was wrapped with cigarette paper at a permeability of 60 Cm/min. measured at 1. The tipping paper had four rows of micro laser perforation at the position of 9, 13, 17mm from mouth and the width between rows of perforation was 1mm. In order to minimize the fluctuation of the analysis results, tobacco column weight, length, cigarette circumference were remained unchaged as a consistent factor. Test cigarette was prepared for each pressure drop of filter plug at three permeability targets of plug wrap with three levels of permeability of tipping paper.

Table 1 showed coded five independent factors with three levels for the cigarette ventilation rate experiment. For the purpose of verifying the graphical method, three types of cigarettes were tested. Test cigarettes were all hand made and selected for weight and draw residence after conditioning at 20°C and 65% relative humidity (Futamura,1988) and experimented by ISO method. That is, the depth of insertion in the holder was 8mm and the airflow leaving the cigarette was constant and mean volumetric flow of 17.5 Cm^3/s.

Statistical analysis

A $3^{(k-p)}$ design, so-called Box-Behnken(1960), was used to reduce the experimental frequency and to increase the significance determination through statistical data analysis. Mathematical models which relate properties of cigarette components to filter ventilation were employed with a three levels and five factors fractional factorial analysis to study the expected variability of alternative cigarette designs. The lower significant data, which was gained by statistical analysis with their interactions among independent factors, were pooled to get a higher significant value by backward stepwise. This study induced to review the Pareto chart of the factor effects as a quick way to compare the 5 independent factors. The levels of the factors in the analysis of variance (ANOVA) were internally recoded so that we tested the linear, quadratic and interaction components in the relationship between five independent factors and the dependant, filter ventilation, variable. Thus, regardless of the original metric of factor settings (e.g., 300, 340, 380 mmH_2O), it will always recode those values to -1, 0, +1 to perform the computations. Regression coefficients, R-square value and its accuracy (t-test) for polynomial equations were determined to make predictions of the dependent variable, based on the coded value of the factors by *STATISTICA/PC* statistical software.

Results and Discussion

Avoiding trial and error combinations of the various choice available require understanding of effects the component materials on smoke yields, resistance to draw, burn rate and other characteristics important to product acceptability among smokers. We need to determine exactly which one of the independent factors significantly affected the dependant variable of interest. It was desired to learn which one of the factors including the tipping material, that is, permeability of plugwrap paper and tipping paper, pressure drop for filter plug affected the level of cigarette ventilation except filter ventilation. We determined 46 trial numbers for ventilation model and the experimental layout and treatment combinations were drawn out based on the table 1. In the quick reviewing of the effects to filter ventilation, first of all, the Pareto chart are sorted from the largest absolute value of upper position to the smallest absolute value of lower position. A horizontal column represents the magnitude of each effect, and the dotted lines show how the statistically significant at the level of 0.05. Note that the plot shown here was stretched to accommodate the twenty factors along the vertical axis.

A simple way to present 20 independent or

Table 1. Coded five major independent factors with 3 levels for filter ventilation rate using Box-Behnken design

Independent factors (variables, unit)	Code levels		
	low (-1)	medium (0)	high (+1)
Filter pressure drop (FPD, mmH_2O)	300	340	380
Plug wrap porosity (PWP, CU)	6,500	9,500	12,000
Tip paper porosity (TPP, CU)	700	900	1,100
Tobacco column pressure drop (TCPD, mmH_2O)	55	65	75
Vent position from mouth end (VEPO, mm)	9	13	17

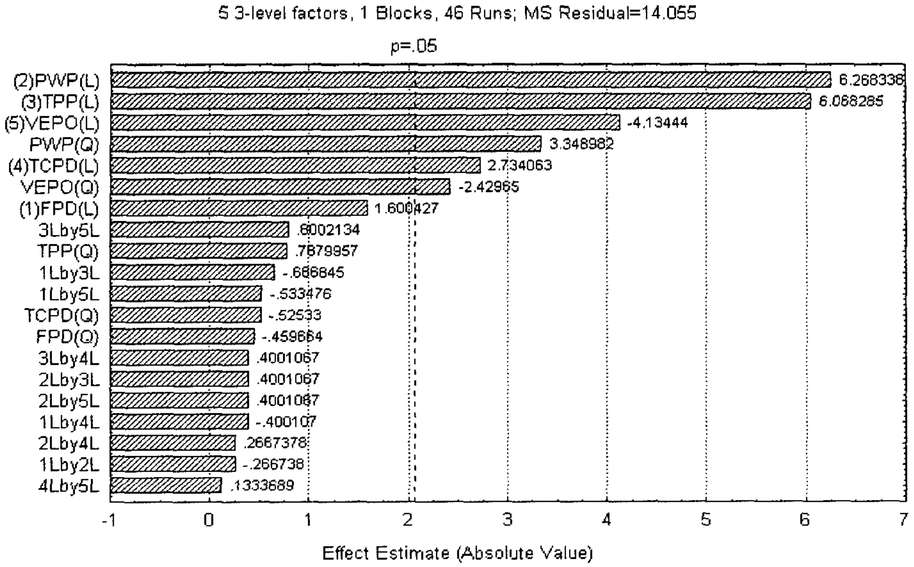

Fig 1. Pareto chart of standardized effects for filter Ventilation rate

interaction factors in this experiment for the five major independent factors except filter pressure drop (FPD) and interaction variables (X by Y) was statistically significant as a absolute value at the level of 0.05(p-value), and permeability of tipping paper and plug wrap paper clearly had a much larger effect than the other effects; permeability of tipping paper and plug wrap paper parameter value were positive. Thus, we could estimate the higher the permeability of the tipping paper and plug wrap paper, the higher filter ventilation through the filter tip circumference. Whereas, linear and quadratic effect of vent position parameter (VEPO) was negative, and so, also assume the higher the code value from the mouth end, the lower filter ventilation rate. No significant were shown among X by Y type interaction parameters (Fig. 1).

The analysis of variance and the regression coefficients for the filter ventilation data is shown in Table 2 and 3. The 45 treatment combinations had 26 degree of freedom. The main effect of each has 1 degrees of freedom and the sums of squares have been computed by usual methods. Table 2 indicates that the permeability of plugwrap and tipping paper significantly affected the level of filter ventilation. but interaction *F* ratio (2L by 3L) of both parameters had a 0.160 at the *P*-value of 0.692, indicating lower interaction between both factors. While linear and quadratic effect of vent position (VEPO) much effect on filter ventilation unexpectedly. It is notice that one of five main variables had negative effects in Table 3, increasing the variable moves the average deviation from the filter ventilation target downward.

As prediction in filter ventilation was directly related to the types and characteristics of filter tipping materials. Variation in filter ventilation at constant filter length and circumference and tobacco rod length was also related to the types and characteristics of filter tipping materials. Maximum filter ventilation occurred when the permeability of tipping paper and plug wrap paper was the highest to code +1 at the center point of the other independent factors exception of the code -1 of vent position parameter. We knewthat the five all factors were statistically significant at the level of 0.05. Most of all linear by linear interactions showed also low significant. While in

Table 2. Analysis of variance for filter ventilation data from Box-Behnken design

		SS	df	MS	F	p
(1)FPD	(L)	36.000	1.000	36.000	2.561	0.122
FPD	(Q)	2.970	1.000	2.970	0.211	0.650
(2)PWP	(L)	552.250	1.000	552.250	39.292	0.000
PWP	(Q)	157.636	1.000	157.636	11.216	0.003
(3)TPP	(L)	517.563	1.000	517.563	36.824	0.000
TPP	(Q)	8.727	1.000	8.727	0.621	0.438
(4)TCPD	(L)	105.063	1.000	105.063	7.475	0.011
TCPD	(Q)	3.879	1.000	3.879	0.276	0.604
(5)VEPO	(L)	240.250	1.000	240.250	17.094	0.000
VEPO	(Q)	82.970	1.000	82.970	5.903	0.023
1L by 2L		1.000	1.000	1.000	0.071	0.792
1L by 3L		6.250	1.000	6.250	0.445	0.511
1L by 4L		2.250	1.000	2.250	0.160	0.692
1L by 5L		4.000	1.000	4.000	0.285	0.598
2L by 3L		2.250	1.000	2.250	0.160	0.692
2L by 4L		1.000	1.000	1.000	0.071	0.792
2L by 5L		2.250	1.000	2.250	0.160	0.692
3L by 4L		2.250	1.000	2.250	0.160	0.692
3L by 5L		9.000	1.000	9.000	0.640	0.431
4L by 5L		0.250	1.000	0.250	0.018	0.895
Error		351.375	25.000	14.055		
Total SS		2183.935	45.000			

the case of ANOVA and regression coefficients of ventilation, no significant interaction of those factors was shown (Table 2, 3). Filter ventilation of the cigarette was affected by porosity of plugwrap (5.87), porosity of tip paper (5.68), vent position (-3.87), tobacco column pressure drop (2.56), and filter pressure drop (1.50) in the decreasing order.

Table 3 shows these linear regression models for filter ventilation rate. The regression coefficients for each independent factor in these models were estimated using a standard linear regression computed program. Variables were coded to the level -1, 0, +1 as discussed previously, Each regression equation was tested lack of fit. Based on the analysis of variance, the model fitted for dependent variables, filter ventilation (Y) was significant at 5% confidence level and the coefficient of determination (R square=0.84) was the proportion of variability in the data well fitted for by the model. According to the results Fig 2, an ideal making paper for a low variation of filter ventilation will have a high level of porosity of plug wrap and tipping paper, preferably in the 9,500 to 12,000 CORESTA range for plug wrap with any porosity range of tip paper

Table 3. Regression coefficient and its significance for filter ventilation Rate(%)

	Regressn Coeff.	Std. Err.	t(25)	p	-95% Cnf.Limt	+95.% Cnf.Limt
Mean/Interc.	61.167	1.531	39.965	0.000	58.014	64.319
(1)FPD (L)	1.500	0.937	1.600	0.122	-0.430	3.430
FPD (Q)	0.583	1.269	0.460	0.650	-2.030	3.197
(2)PWP (L)	5.875	0.937	6.268	0.000	3.945	7.805
PWP (Q)	-4.250	1.269	-3.349	0.003	-6.864	-1.636
(3)TPP (L)	5.688	0.937	6.068	0.000	3.757	7.618
TPP (Q)	-1.000	1.269	-0.788	0.438	-3.614	1.614
(4)TCPD (L)	2.563	0.937	2.734	0.011	0.632	4.493
TCPD (Q)	0.667	1.269	0.525	0.604	-1.947	3.280
(5)VEPO (L)	-3.875	0.937	-4.134	0.000	-5.805	-1.945
VEPO (Q)	3.083	1.269	2.430	0.023	0.470	5.697
1L by 2L	-0.500	1.874	-0.267	0.792	-4.361	3.361
1L by 3L	-1.250	1.874	-0.667	0.511	-5.111	2.611
1L by 4L	-0.750	1.874	-0.400	0.692	-4.611	3.111
1L by 5L	-1.000	1.874	-0.533	0.598	-4.861	2.861
2L by 3L	0.750	1.874	0.400	0.692	-3.111	4.611
2L by 4L	0.500	1.874	0.267	0.792	-3.361	4.361
2L by 5L	0.750	1.874	0.400	0.692	-3.111	4.611
3L by 4L	0.750	1.874	0.400	0.692	-3.111	4.611
3L by 5L	1.500	1.874	0.800	0.431	-2.361	5.361
4L by 5L	0.250	1.874	0.133	0.895	-3.611	4.111

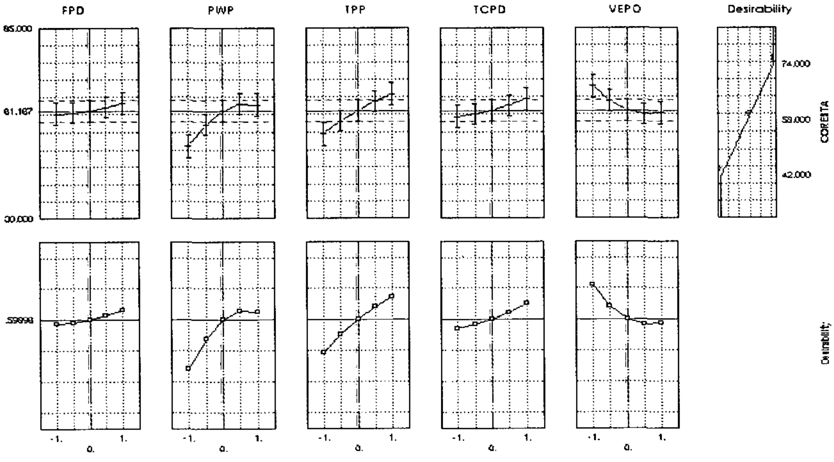

Fig. 2. A comparison of Pattern distribution of each independent variables on filter ventilation rate

(refer to second column at the left in Fig. 2).

This combination will optimize the stable filter ventilation rate and assure a uniform smoking taste to the smokers. Because slope angle of plug wrap porosity (PWP) increases drastically following to the increase the code value start from -1 to 0 and then no more variation of that slope angle of the solid line was shown. It assumed that ultra high porosity of wrapping paper has no more affect to filter ventilation than lower porosity around 9,000CU or more of plug wrap paper. Wrapping paper may also have a very strong influence on filter ventilation (Baskevitch, 1997). That also may affect to puff number resulting from the interaction between static burn rate (puff number decreases as increase of static burn rate) and filter ventilation (the higher the ventilation, the higher the puff number). So it is clear that cigarette quality is not only influenced by the chemical composition of the tobacco leaf, but also by the physical characteristics such as tobacco rod density, vent position and wrapping paper characteristics such as porosity.

Fig. 3 shows normal probability plot of the effect estimates. In the normal probability plot of the residuals, first the effect estimates are rank odered, and then a normal expected score is computed based on the assumption that the estimates are normally distributed on the Y-axis; the observed estimates are plotted on the X-axis. Note that in this plot all two-way interactions were also included, three main independent variables, TPP, PWP, and VEPO, were clearly distinguishable in the upper right-hand corner for TPP and PWP, in the lower left-hand corner for the VEPO of the plot. Thus, the Pareto chart (Fig.1), ANOVA table (Tab.1), parameter estimate (Fig.2) and this plot (Fig.3) all agree on which factors are most important for cigarette design, that is, had greatest effect on filter ventilation rate.

Fig. 4 represented the response surface contour plots of dependent filter ventilation as a function of natural porosity of plugwrap (PWP) at X axis and tipping paper permeability (TPP) for Y axis (left Fig.), and tobacco column pressure drop (TCPD) at horizontal axis versus vent position from mouth (VEPO) at vertical axis(right Fig.). Note that these contour graphs also contained the prediction equation in terms of the original metric of factors that produces the respective response surface on the bottom of the graphs. These two

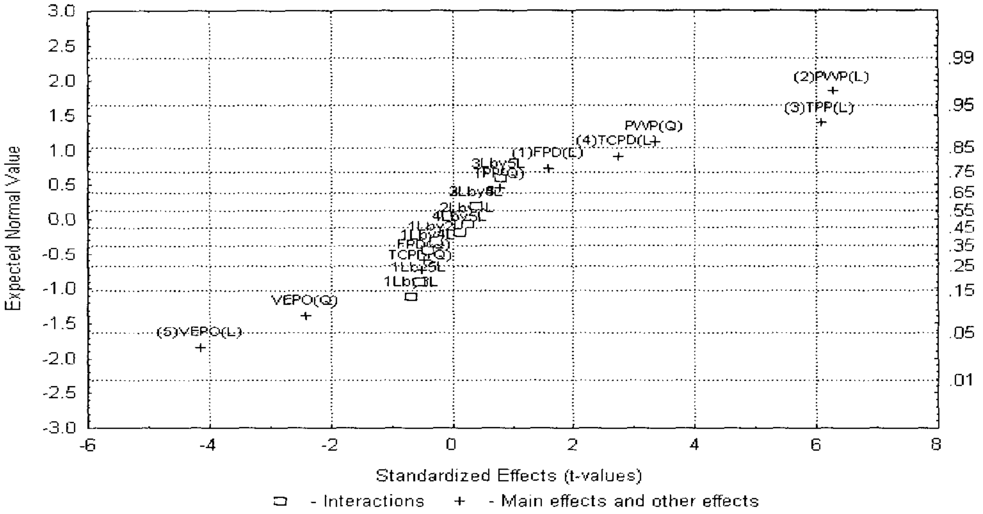

Fig 3. Normal probability plot of effects for filter ventilation

contour plots reveal considerable useful information about the performance of this filter ventilation and so we can be used to minimize trial and error for designing new cigarette brand as a key information. According to these 3-dimentional contour graphs, the other three variable should be maintained at the center point value (code 0) and and then the level of ventilation rate was plotted as a function of the main factors ranging from code -1.2 to +1,2. All five major factor variables affected the filter ventilation simultaneously. Among those factors, tip paper permeability and

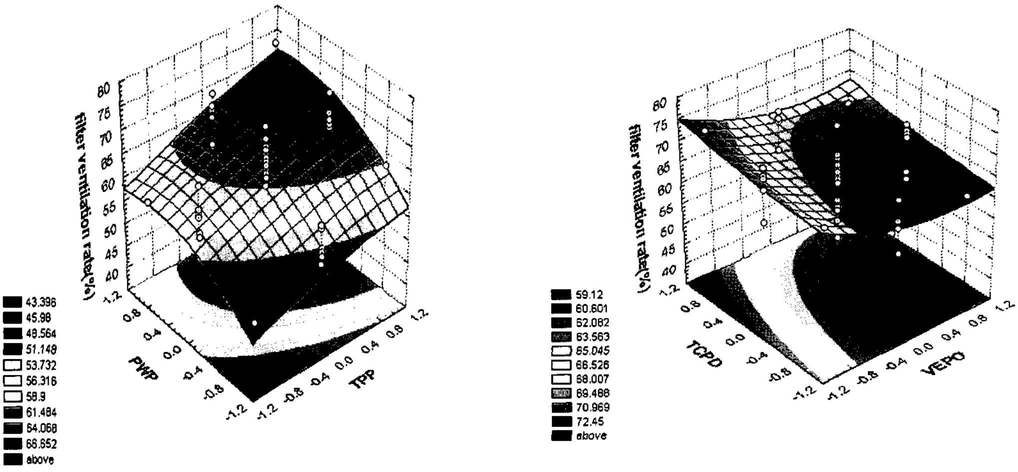

Fig. 4. A three-dimensional response surface showing the expected filter ventilation yield as a function of porosity of plug wrap (PWP) and permeability of tipping paper (TPP) on the left and tobacco column pressure drop (TCPD)and perforating hole position from mouse tip (VEPO) on the right.

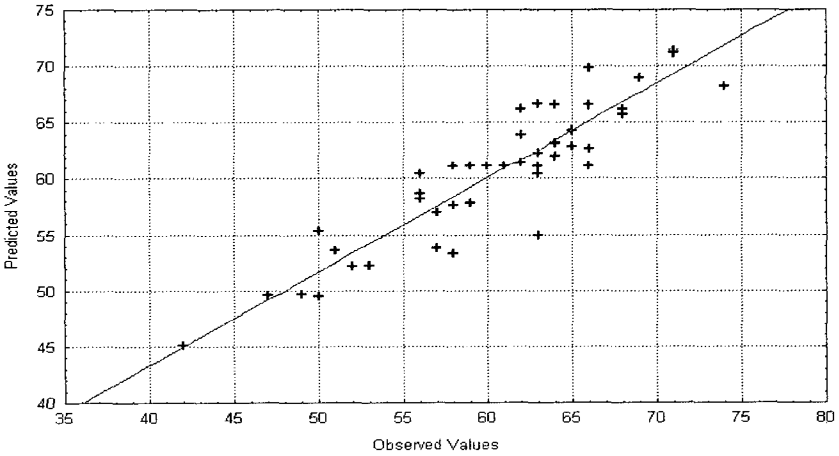

Fig. 5. Distribution of predicted and observed values of the response following the changed conditions.

plug wrap porosity especially had the highest impact to dependent variables, ventilation. Since the affectivity of tipping paper permeability with plug wrap porosity to ventilation is the highest, we came to the point that the air permeability of tipping paper and plug wrap must not only specify to the target but must also be as uniform as possible.

Fig. 5 illustrated comparison of observed and predicted filter ventilation for this model. The observed values were plotted as a cross symbol along a common solid line, and this was a technique how closely a set of observed values follow a theoretical distribution.

The plot revealed that there was a good distribution the observed data exception of some outliners as a plus symbol is plotted near around a predicted solid line. Such close agreement between calculated and observed values demonstrates that the proposed filter ventilation model is useful to describe ventilation and to evaluate the factors governing the ventilation. Baskevitch(1997) reported that 4 main parameters influencing the level of filter ventilation are a) Air permeability of tipping, b) Air permeability of plug wrap, c) Effective area of plug wrap submitted to ventilation, d) Pressure drop of upstream rod. And so we also suggested that the degree of ventilation could be controlled either by the tipping or the plug wrap, or both. The worst situation occurs when both papers control in part ventilation. Only one paper should control the flow of air at the other being permeable enough so it has no influence. The best combination occurs when ventilation is controlled by the very precisely perforated tipping like laser perforated tipping rather than of porous plug wrap.

Conclusion

A model has been developed to elucidate the physical factors affecting filter ventilation rate. Fourty-six trial numbers were obtained as a results of using a three levels with five factors Box-Behnken design and it is analyzed by the multiple regression analysis with backward stepwise in STATISTICA/PC under restricted conditions. The four factors except filter pressure drop variables were statistically significant at the level of 0.05 but most of all linear by linear interactions were comparatively low significant.

Following the linear and quadratic regression coefficients analysis, filter ventilation of cigarette was affected by porosity of plugwrap (5.87, -4.25), porosity of tip paper (5.68, -1.00), vent position (-3.87, 3.08), tobacco column pressure drop (2.56, 0.66), and filter pressure drop (1.50, 0.58) in the decreasing order. It should be emphasized that the major conclusion of this study is not that any particular parameter is linear or quadratic on any limit scale, but that there are highly significant relationships among factors involving linear, quadratic and their interaction and perhaps even linearity between and within factors. While, there is also quite strong evidence that vent position from mouth end and wrapping materials are in reverse relationship on this experimental model.

On the basis of results obtained, it can be concluded that the porosity of the plug wrap and tipping paper have a marked effect in degree of filter ventilation rate. The F-value of plug wrap and tipping paper porosity among five factors has a 39.2 and 36.8 each, *P*-value of 0.000 indicating higher significant both factors. According to the analysis of variance, the model fitted for filter ventilation was significant at 5% confidence level and the coefficient of determination (R^2=0.84) is the proportion of variability in the data well fitted for by the model.

References

Baskevitch, N. (1993); "Reducing tar in cigarette," Papetries De Mauduit.

Baskevitch N. (1997); One mg tar cigarette from the component point of view, symposium at korean society of tobacco science

Box, G. E. P. and D. W. Behnken (1960); Some new three level designs for the study of quantitative variables; Technometrics, vol. 3, 311-352

Browne, C. L., C. H. Keith and R. E. Allen;" The effect of Filter Ventilation on the

Yield and Composition of Mainstream and Sidestream Smokes, " Celanese Fibers Co.

Curran J. G. (1982); Curves that relate filter pressure drop, filter efficiency, denier per filament, and total denier, Eastman Kodak Co. Published, USA, FTR-44.

Futamura Y., K. Takeda, A. Tokida and M. Muramatsu (1988); A ventila-tion model of cigarette (I) one-dimensiomal mathematical model of tobacco rod ventilation (II) one-dimensional mathematical model of filter ventilation, Japan Tobacco report.

Keith C. H. (1978); physical mechanism of smoke filtration, 32nd Tobacco Chemists' Researcher conference, Montreal, Canada; 25-45.

Keith C. H. (1979); The use of pressure drop measurements for estimating ventilation and paper porosity, Beitrage zur Tabakforschung international, 10(1); 7-16

Kiefer J. E. (1980); Effect of vents on the performance of filter cigarette, Eastman Kodak Co. Published, USA, FTR-22.

Parker, J. A., R. T. Montgomery (1979); "Design Criteria for Ventilated Filters," Celanese Fibers Company, Beitrafe zur Tabakforschung international, Vol. 10, No. 1.

Schneider, W., A. Schluter and F. Seehofer (1984); Beitrafe zur Tabakforschung international, Vol. 12,123-136.

Selke W.A. and J. H. Mathews (1978); The permeability of cigarette papers and cigarette ventilation Beitrage zur Tabakforschung international, 9(4)