Design Criteria for Ventilated Filters*

by James A. Parker and Robert T. Montgomery

Celanese Fibers Company, Charlotte, North Carolina, U.S.A.

INTRODUCTION

There is great interest in the effects of ventilation on the chemistry of cigarette smoke. Filter ventilation, using porous plug wrap and perforated tipping paper, decreases condensate delivery and this is important in view of the growing consumer preference for "low tar" brands (less than 15 milligrams).

Low condensate cigarettes increased to 34.5% of U.S. sales in 1978, up by 9.6% (relative) from 1977 (1). Although several researchers have studied smoke filtration in ventilated cigarettes (2, 3, 4), it was the purpose of this work to extend these investigations to include a broad range of filter tow items and also several commercially used, ventilated filters. The data showed that ventilation gives a basic design capability for controlling a number of smoke parameters.

MATERIALS AND METHODS

Two studies were performed to measure the effects of air ventilation: one based upon testing filters made from cellulose acetate tows of increasing denier per filament (dpf), and a second using commercial air-ventilated filters. In the first study, six tow items were prepared in conventional filter construction, where the degree of ventilation was varied by size and location of tipping paper perforations. The second study involved smoking a number of commercial filters, all of which incorporated some physical method for air dilution.

Figure 1 shows the construction of the reference cigarette used in the first study. A series of these cigarettes was prepared on commercial equipment using a 64 mm standard tobacco column. Two levels of ventilation were achieved using Malaucène M 1.5 and M 3.0 laser-perforated filter tip papers, where the total area of the holes in the M 3.0 paper was approximately twice the open area of the M 1.5 paper. In addition, control filters using non-ventilated tipping were made. For each of the three tipping configurations, six tow items were tested for which the dpf ranged from less than 1.5 to 5.0 and the total denier varied from 40,000 to 50,000. Filter size, 25.0 mm circumference and 21 mm length, was held constant. The plug wrap was Schweitzer No. 912, having a Coresta

permeability of 26,000 cm per min. Ten percent (w/w) triacetin was used as a plasticizer.

In the second investigation, thirteen commercial filters were hand-tipped to a 64 mm standard tobacco column. For both studies, pressure drop, percent air dilution, puff count, particulate delivery, gas phase delivery of selected components, and filtration efficiency were measured.

Particulate matter delivery was measured by the Federal Trade Commission method (5). Particulate removal efficiencies were derived according to Keith and Newsome (6). CO was measured by gas chromatography (7), and aldehydes were determined colorimetrically (8). The percent dilution was the unlit puff dilution volume, measured by a bubble burette connected through encapsulation to the ventilating perforations [cf. (4)]. The puff-by-puff ventilation and tip pressure drop were assumed constant throughout smoking of a cigarette (4). Standard instrumentation was used for measuring physical parameters (e.g. circumference, pressure drop) and the Coresta standard smoking procedure was employed.

RESULTS

Filter Tow Study

Table 1 shows physical and chemical data for filters with different tow items and air dilution levels smoked with the standard tobacco column. Examining the table shows

Figure 1. Construction parameters for test cigarettes.

	M 3.0	M 1.5
a. Venting hole location	15*	12
b. Filter length	21	21
c. Tipping length	30	30
d. Butt length	33	33
e. Cigarette length	85	85

* Values in millimeters.

* Presented, in part, at the Coresta Technology Study Group meeting held in Munich, Germany, in September 1977.

Received: 29th September 1978 — accepted: 6th July 1979.

Table 1. Physical and chemical data from the filter tow study.

Filter tow	Tipping	Tip pressure drop (mm H ₂ O)	Air dilution (%)	Puff count	Particulate matter (mg/cigarette)			Gas phase		Filtration efficiencies (%)		
					Total particulate matter*	Nicotine	Dry condensate	CO (mg/cig.)	Total aldehydes (µg/cig.)	Wet smoke [SRE]	Nicotine [NRE]	Dry condensate [CRE]
Type A/45 (< 1.5)	Non-perforated	89	—	8.0	40.0	0.8	13.1	15.4	1445	59.0	46.2	52.8
	M 1.5	74	53	9.4	15.2	0.4	4.9	4.2	629	62.5	53.0	62.8
	M 3.0	82	62	9.2	13.3	0.3	4.5	4.1	488	61.5	52.7	61.2
Type B/40 (< 1.5)	Non-perforated	97	—	8.0	39.6	0.7	13.0	16.5	1492	59.8	50.1	53.5
	M 1.5	87	50	9.2	18.1	0.5	5.9	5.8	808	62.0	52.9	60.3
	M 3.0	90	56	9.8	15.9	0.5	5.2	5.1	688	61.6	50.3	61.6
1.6R/50	Non-perforated	99	—	8.2	41.3	0.8	13.4	15.9	1661	60.1	49.3	53.0
	M 1.5	87	55	9.2	19.3	0.5	6.4	6.3	558	61.8	51.7	59.8
	M 3.0	96	57	9.6	15.6	0.4	5.2	5.5	405	61.9	53.1	60.9
1.8Y/42	Non-perforated	90	—	7.8	40.4	0.8	14.2	16.6	1449	56.7	43.9	49.6
	M 1.5	76	50	9.2	19.9	0.5	7.1	6.7	801	58.6	47.7	56.8
	M 3.0	83	59	9.8	17.0	0.5	5.9	5.6	484	59.8	48.1	59.1
2.5Y/48	Non-perforated	90	—	7.8	41.9	0.9	14.6	16.0	1594	57.1	44.4	49.6
	M 1.5	79	59	9.5	16.7	0.5	6.0	4.9	591	58.2	48.3	57.0
	M 3.0	83	62	9.4	14.2	0.4	5.1	4.4	529	59.1	48.6	60.2
5.0Y/40	Non-perforated	49	—	7.1	38.0	1.0	17.4	16.7	1647	43.4	27.8	34.7
	M 1.5	46	45	9.1	22.0	0.7	11.1	7.1	806	41.9	29.0	38.1
	M 3.0	46	51	9.1	20.3	0.7	9.5	6.0	699	41.0	28.6	30.7

* : Wet particulate matter entering the filter.

that puff count increased by 1.5 to 2.0 puffs with air dilution. Overall, particulate matter deliveries decreased monotonically as a function of increasing air dilution. As expected, lower deliveries were measured for the lower dpf tow items (9). These effects are illustrated in Figure 2, which shows a proportional decrease in dry condensate and nicotine delivery as a function of percent dilution. The curves represent composite trends for all filters studied, and illustrate the effect of dpf as well.

Carbon monoxide and aldehyde deliveries are shown in Figure 3. The mainstream delivery of carbon monoxide which is lower than expected from dilution, is related again to diffusion into the sidestream smoke caused by lower gas velocity in the cigarette (3, 10). *Baker* (11) and *Muramatsu* (12) reported detailed studies of diffusion of carbon monoxide and other low molecular weight gases out of cigarettes.

The filtration efficiencies in Table 1 show that at 50% air dilution, wet smoke removal efficiency (SRE) in-

creased by 2–5% (relative). Dry condensate removal efficiency (CRE) increased by about 15% (relative), and nicotine removal efficiency (NRE) increased by 5–10% (relative). The higher filtration efficiencies observed with air dilution were primarily attributed to increased filter effectiveness in trapping slower velocity particles, as previously reported by *Overton* (13) and *Keith* (14).

Commercial Filter Study

Analysis of smoking results for the commercial filters investigation led to the identification of two types of filter performance. One group of eight filters closely fit predictions of smoke characteristics that followed from the first study. These filters were denoted “all-acetate vented”, and Table 2 shows average smoke deliveries and filtration behavior for each. A second group of five commercial filters could not be closely fitted to the data base from the first study, and was called “novel-vented”. Each of these filters had incorporated into the design a plastic mouthpiece or flow chamber which altered filtration behavior in a way that was not predictable based on the results for ventilated, all-acetate tow filters. Smoking results for these filters are also given in Table 2.

In the eight “all acetate” brands tested, the air dilution range varied from 16 to 70% and delivered condensate ranged from 1 to 12 mg/cigarette. Although the methods of ventilation varied greatly, the filtration and delivery characteristics of these filters agreed in all cases with predicted values based on percent air dilution. Gas phase CO also agreed with the dilution curves generated from the previous study.

Comparing the five “novel-vented” brands tested, air dilution ranged from 15 to 46% and delivered condensate varied from 6 to 13 mg/cigarette. Gas phase deliveries of CO were consistent with the “all acetate” filters, but it was observed that plastic mouthpieces and flow channeling devices acted in varying degrees to alter particulate filtration characteristics.

Figure 2. Condensate and nicotine deliveries from ventilated filter cigarettes.

dpf: denier per filament.

Figure 3. Carbon monoxide and aldehyde deliveries from ventilated filter cigarettes.

Table 3. Variability as mean percent relative standard deviation of all filters studied.

Test parameter	Non-vented*	Vented**
Tip pressure drop	4.5	4.5
Tip weight	1.6	1.6
Percent venting	—	8.0
Wet smoke removal efficiency [SRE]	1.1	1.8
Delivered condensate	3.3	4.5
Delivered nicotine	3.4	6.4

*: The data base includes the non-ventilated filters tested in the filter tow study plus eight commercial brands that do not incorporate ventilation in their filter design.

**: The data base sums all ventilated filters tested in the filter tow study plus data taken in the study of commercial vented filters.

Table 2. Physical and chemical data from the study of commercial brands.

Brand identification	Filter description	Physical characteristics						Particulate matter (mg/cigarette)			CO (mg/cig.)	Filtration efficiencies (%)		
		Tip length (mm)	Tip circum- ference (mm)	Tip weight* (mg)	Tip pressure drop (mm H ₂ O)	Air dilution (%)	Puff count	Total par- ticulate matter**	Nicotine	Dry con- densate		Wet smoke [SRE]	Nicotine [NRE]	Dry con- densate [CRE]
"ALL-ACETATE"														
A	monoacetate	25	24.6	201	66	16	8.8	30.4	0.8	11.4	10.4	54.1	38.6	45.8
B	monoacetate	27	24.6	222	83	30	8.4	28.7	0.6	8.9	8.7	62.7	49.9	56.4
C	monoacetate	25	24.8	260	110	70	10.5	8.0	0.1	1.0 ⁺	1.6	80.0	73.3	—
D	monoacetate	25	25.1	233	110	27	8.8	27.7	0.8	8.4	8.0	62.3	52.9	57.2
E	dual acetate	25	24.8	380	71	16	8.8	30.8	0.9	11.6	9.5	54.0	38.8	46.2
F	monoacetate	25	25.0	205	70	41	9.5	22.3	0.7	8.4	—	55.7	47.4	50.4
G	monoacetate	25	25.1	232	110	70	11.2	10.6	0.2	2.0	2.0	77.6	70.1	78.8
H	monoacetate	25	25.0	235	90	45	11.0	23.7	0.5	7.2	6.6	64.2	49.7	58.3
"NOVEL-VENTED"														
V	dual acetate/ mouthpiece	25	24.8	346	70	25	9.2	25.0	0.9	10.6	10.0	47.9	31.7	42.9
W	dual acetate/ with solids	25	25.0	430	50	25	9.8	27.6	1.0	10.6	9.5	53.1	30.3	46.4
X	dual acetate/ mouthpiece	25	24.5	230	58	45	10.5	19.9	0.6	6.1	5.7	62.7	50.3	58.0
Y	dual acetate/ mouthpiece	27	24.5	250	72	15	8.6	31.5	1.0	11.9	11.0	52.3	36.6	46.9
Z	monoacetate/ flow channel	25	24.5	260	69	46	9.0	20.8	0.6	9.1	5.6	48.1	35.8	43.0

* : As cut from finished cigarettes.

** : Wet particulate matter entering the filter.

+ : Estimated value.

Variability

Table 3 shows a comparison of variance between filters which incorporated ventilation, and filters that were not designed with air dilution. Since the magnitudes of these measurements varied greatly, the percent relative standard deviation (rel. S. D.) of grouped data gave a useful way of comparing variability between ventilated and non-ventilated filters. Comparing rel. S. D. for smoke removal efficiency and delivered condensate and nicotine showed the ventilated filter types to have somewhat higher variability than non-ventilated filters. An F-test revealed that the variance of mean rel. S. D. for condensate, nicotine and smoke removal efficiency in the ventilated category was statistically greater than in the non-ventilated filters tested. That no variability difference was observed for ventilated vs. non-ventilated tip pressure drop, was probably due to the relative insensitivity of tip pressure drop to dilution level.

DISCUSSION

From these data, it is seen that delivered smoke composition can be altered in a controlled manner, by careful selection of filter characteristics, including ventilation. Table 4 gives an example that illustrates this capability by comparing selected smoke component deliveries with design criteria for two different ventilated tow filters. Here the principal variables altered were dpf, total denier, and percent ventilation. The original 2.5Y/48 tow was replaced with one having an increased filament size and total denier (5.0Y/65), while maintaining physical characteristics of tip length and tip pressure drop essentially constant. Particulate deliveries of dry condensate and nicotine were maintained constant. The main alteration in smoke composition was a reduction in the delivery of gas phase components as illustrated by the lower level of carbon monoxide resulting from increased air dilution. A second example is shown in Table 5. In this illustration, tip length was increased from 21 to 25 mm for a King size cigarette, and a less efficient (higher denier per filament) filter tow was selected. The new design incorporated 15% air dilution and slightly reduced filter pressure drop. The resultant cigarette was easier to draw, delivered 2.5 mg less condensate and 25% less CO, without significantly changing puff count.

Table 4. Tow design for ventilated filters.

Physical/chemical characteristics	Tow Item	
	2.5Y/48	5.0Y/65
Tip length (mm)	20	20
Tip pressure drop (mm H ₂ O)	87	90
Dilution (%)	30	50
Dry condensate (mg/cigarette)	9.0	8.5
Nicotine (mg/cigarette)	0.6	0.6
Carbon monoxide (mg/cigarette)	12.5	8.8

Table 5. Design parameters for all-acetate, vented filters.

Physical/chemical characteristics	Tow item	
	2.1Y/42	3.3Y/40
Standard rod, encapsulated pressure drop (mm H ₂ O)	380	310
Standard rod, dry weight (mg)	660	663
Weight of tow in standard rod (mg)	584	587
Filter tip length (mm)	21	25
Filter ventilation (%)	0	15
Filter pressure drop (mm H ₂ O)	82	75
Weight of tow in filter (mg)	120	144
Tobacco column length (mm)	64	60
Available condensate (mg/cigarette)	27	25
Condensate removal efficiency (%)	49	47
Delivered condensate (mg/cigarette)	13.8	11.3
Delivered CO (mg/cigarette)	15.5	11.8
Puff count (puff/cigarette)	9.5	9.3

SUMMARY

A number of filters were studied to determine the effect of air dilution on smoke filtration, both in well characterized acetate tow items and also in commercial filters that incorporated air dilution. A direct reduction of condensate and nicotine was observed in proportion to the degree of air dilution. Particulate filtration efficiency increased with air dilution. Gas phase delivery of aldehydes and CO decreased in greater proportion than the amount of air dilution.

The commercial brands tested closely fitted the model developed in the filter tow study, except where mouthpieces or other flow channeling devices altered the filtration characteristics of the cigarette in varying degrees. Significantly, the results of the studies showed that the amount of air dilution, and not the physical means of air mixing, was the defining parameter to predict filter performance. Ventilation gives a useful design capacity that extends control of smoke filtration behavior. By appropriate selection of tow denier per filament, total denier and cross-section shape, filter length and diameter, and the level of air dilution, filter properties can be adjusted to control gas and particulate phase deliveries, and the proportionality between the two.

ZUSAMMENFASSUNG

An einer Reihe von Filtern (sowohl Testfilter mit unterschiedlichen, genau definierten Celluloseacetatkabeln als auch verschiedene handelsübliche ventilierte Filter) wurde die Wirkung der Verdünnung des Rauches mit Luft auf die Retention von Rauchinhaltsstoffen untersucht. Es zeigte sich eine direkte Proportionalität der Verminderung der

Ausbeute an Kondensat und Nikotin zum Grad der Verdünnung. Die Retention der Partikelphase stieg mit zunehmender Luftverdünnung an. Die Ausbeute an Aldehyden und Kohlenmonoxid in der Gasphase verringerte sich bei zunehmender Verdünnung des Rauches prozentual hingegen stärker.

Die untersuchten handelsüblichen Zigaretten entsprachen weitgehend dem von den Autoren für die Testfilter entwickelten Modell, außer wenn das Filtrationsverhalten der Zigarette durch Mundstücke oder andere Vorrichtungen zur Steuerung des Rauchstromes in unterschiedlichem Ausmaß verändert wurde.

Als wesentlich erscheint die Beobachtung, daß die Filterwirksamkeit nicht von der Art der Luftbeimengung, sondern von der Menge der zugesetzten Luft entscheidend bestimmt wird. Die Ventilation bedeutet eine nützliche Möglichkeit, die Filtration des Rauches zu steuern. Durch Auswahl geeigneter Größen für Einzeltiter, Gesamttiter und Querschnittsform, für Länge und Durchmesser des Filters sowie den Grad der Verdünnung des Rauchstromes können die Eigenschaften des Filters auf eine kontrollierte Ausbeute an Inhaltsstoffen der Gas- und Partikelphase sowie deren Verhältnis zueinander abgestimmt werden.

RÉSUMÉ

Un certain nombre de filtres ont été étudiés afin de déterminer l'effet de la dilution sur la filtration de la fumée. Des filtres en câbles d'acétate bien définis ainsi que des filtres commerciaux avec dilution ont été examinés. La réduction du condensat et de la nicotine était directement proportionnelle au degré de dilution. L'efficacité de filtration sur la phase particulaire a augmenté en proportion de la dilution. Les rendements en aldéhydes et CO dans la phase gazeuse diminuèrent plus que proportionnellement par rapport au degré de dilution.

Les cigarettes commerciales examinées correspondaient étroitement au modèle dérivé de l'étude faite avec des câbles d'acétate définis, sauf lorsque des embouts ou d'autres dispositifs de canalisation du flux modifièrent les caractéristiques filtrantes à divers degrés.

Les résultats de ces études démontrent clairement que le degré de dilution, et non la manière de la réaliser, est le paramètre déterminant pour prédire le comportement du filtre. La ventilation ajoute une dimension nouvelle à l'inventaire des moyens de filtration de la fumée. Par une sélection appropriée du denier par fibre, du denier total du câble, du profil de la coupe transversale, de la longueur du filtre et de son diamètre, ainsi que du degré de dilution, les propriétés du filtre peuvent être conçues en fonction du rendement désiré en phases gazeuse et particulaire ainsi que du rapport entre ces deux phases.

REFERENCES

1. Maxwell, John C.: The Maxwell Report, Revised 1978 year-end sales estimates for the cigarette industry; Morgan Stanley & Co., New York, N. Y., February 10, 1979.
2. Mikami, Y., N. Naito and Y. Kaburaki: Effects of some factors on carbon monoxide concentration in

main stream smoke of a cigarette; Jap. Monop. Corp. Centr. Res. Inst., Sci. Paper No. 113, 1971, pp. 99-105.

3. Morie, G. P.: Some factors that affect the diffusion of carbon monoxide out of cigarettes; Tob. Sci. 11 (1976) 51-53.
4. Norman, V.: The effect of perforated tipping paper on the yield of various smoke components; Beitr. Tabakforsch. 7 (1974) 282-287.
5. Ogg, C. L., and E. F. Schultz, Jr.: Collaborative study of the determination of tar and nicotine in cigarette smoke; J. Assoc. Offic. Anal. Chem. 53 (1970) 659-672.
6. Keith, C. H., and J. R. Newsome: Quantitative studies on cigarette smoke, III. Methods of analysis for filter cigarettes; Tob. Sci. 2 (1958) 14-19.
7. Watanabe, M., and Y. Kobashi: Analytical methods in tobacco smoke, I. Determination of CO and CO₂ in cigarette smoke by gas chromatography; Jap. Monop. Corp. Centr. Res. Inst., Paper No. 107, 1965, pp. 177-180.
8. Collins, P. F., N. M. Sarji and J. F. Williams: An automated method for the determination of total aldehydes in gas phase of cigarette smoke; Tob. Sci. 14 (1970) 182-186.
9. Keith, C. H.: Prediction of tobacco smoke filtration from fiber properties, Paper presented at the Symposium on Fibrous Structures for Gas and Liquid Filtration; The Fiber Society, Princeton, N. J., Nov. 9-10, 1976.
10. Newsome, J. R., and C. H. Keith: Variation of the gas phase composition within a burning cigarette; Tob. Sci. 9 (1965) 65-69.
11. Baker, R. R., and R. A. Crellin: The diffusion of carbon monoxide out of cigarettes; Beitr. Tabakforsch. 9 (1977) 131-140.
12. Muramatsu, M., T. Mikami, N. Naito and H. Tomita: A model study on the diffusion and the dilution of low molecular weight gaseous components through cigarette paper during smoking; Beitr. Tabakforsch. 9 (1977) 141-146.
13. Overton, J. Ray: Filtration of cigarette smoke, Relative contributions of inertial impaction, diffusional deposition and direct interception; Beitr. Tabakforsch. 7 (1973) 117-120.
14. Keith, C. H.: Physical mechanisms of smoke filtration; Recent Advances in Tobacco Science 4 (1978) 25-45.

Acknowledgements

The authors thank Dr. Vello Norman (Liggett and Myers Research Department, Durham, N. C.) for his assistance in providing cigarettes used in this study and providing analysis of aldehydes. We are grateful to Dr. R. E. Allen and Mr. E. C. Jones (Celanese Fibers Company) for their assistance with the analytical data.

Authors' address:

Celanese Fibers Company, Box 32414,
Charlotte, North Carolina, 28232, U.S.A.