

# A Model Study on the Diffusion and the Dilution of Low Molecular Weight Gaseous Components through Cigarette Paper during Smoking\*

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## INTRODUCTION

There have been numerous publications dealing with the changes in concentration of mainstream smoke gases along with the distance from the glowing cone to the butt end of the cigarette column (1, 2, 3, 4, 5, 6, 7). These changes have been attributed mainly to the dilution with air entering the cigarette and also to the diffusion of the gases leaving the cigarette through the paper (1, 2, 4, 5). However, the effects of dilution and diffusion on the concentration of gaseous components have not yet been fully elucidated owing to the difficulty in distinguishing them from the effect of gas evolution during the smoking process.

In this study, to make the effects of diffusion and dilution clear, the changes in the concentration of a standard gas mixture passing through an unlit cigarette were measured in place of the usual measurement of mainstream smoke. Results have shown the dependence of the changes in gas concentration by dilution with air on paper porosity and cigarette length, but, at the same time, the substantial independence of diffusion loss on paper porosity.

## MATERIALS AND METHODS

### Standard Gas Mixture

The standard gas mixture, which was manufactured by Takachiho Chemical Industrial Company, contained nitrogen, hydrogen, methane, carbon monoxide and carbon dioxide in the ratio of 72.57 : 6.81 : 7.23 : 6.52 : 6.87.

### Cigarettes

Three types of cigarette paper, i.e. ordinary non-perforated cigarette paper [porosity<sup>†</sup> 80] and two types of perforated paper differing in porosity [180, 260], were used. The average diameter of the perforation holes

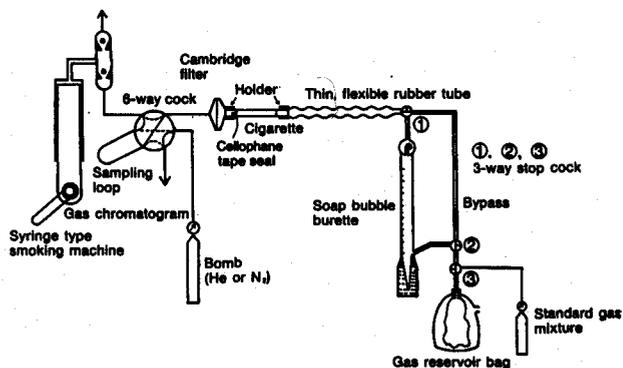
was 24–26  $\mu$  irrespective of the level of porosity. Burley tobacco cut into 0.65 mm shreds was rolled up in these papers to cigarette rods of 8 mm diameter. The rods were cut into cigarettes of 2.0, 2.5, 4.0, 5.5, 7.0, 8.5 and 10.0 cm length. The cigarettes were selected for filling density after conditioning at 20 °C and 60% relative humidity. Both ends of the cigarette paper were sealed to the width of 1 cm each with adhesive cellophane tape. Such sealing was effective in keeping the length of the cigarette paper exposed to the atmosphere at a given length regardless of the positional deviation of the cigarette in the holder. Subsequently, the cigarette length refers to the length of the paper exposed to the atmosphere. The cigarette cut into a 2 cm length, all the paper surface of which was sealed with the tape, was used as the blank.

### Smoking System and Procedures

The measuring system is shown in Figure 1. This smoking system consists of three major parts. The first is for puffing, the second is to measure the volume of the standard gas mixture drawn into an unlit cigarette at the front end, and the third is to measure the concentration of the standard gas mixture after it has passed through a cigarette.

The suction port of a syringe type smoking machine is connected to a cigarette holder with Cambridge filter

Figure 1. Apparatus for measuring diffusion and dilution through cigarette paper during the puff.



\* Received for publication: 2nd May, 1977.

† The porosity was defined as the air volume (ml) which passed through the 10 cm<sup>2</sup> cross-sectional area of the cigarette paper a minute, under the pressure of 100 mm water gauge at 25 °C.

through a 6-way cock equipped with a 1 ml stainless sampling loop for gas chromatographic measurements. The smoking machine was adjusted to a 4-second puff cycle with a suction period of a 2-second duration and a 35 ml puff volume.

The volume of the standard gas mixture drawn into an unlit cigarette at the front was measured with a soap bubble burette. The upper and lower ends of this burette are connected to a cigarette holder by means of a thin, flexible rubber tube and to a gas reservoir bag made of polyvinylidenechloride film, respectively. The reservoir bag, with a capacity of about 700 ml at the maximum, is set inside a bottle.

Both ends of a sample cigarette were mounted in the cigarette holders. After evacuation to remove air, the reservoir bag was filled with a standard gas mixture. The flow system was charged with the standard gas mixture by successive puffs just before measuring. Soon after the reservoir bag was again filled with the standard gas to half or three quarters full, mechanical puffs were repeated 5 times without any measurement in order to recharge the system with the standard gas, and on the 6th puff, either volumetric or gas chromatographic measurements were made. The latter measurements were carried out by turning the 3-way cocks ① and ② through 90° before measuring, so as to connect the bypass with both the gas reservoir bag and rubber tube, and by introducing the gas mixture trapped in the sampling loop into the gas chromatograph at the time when the 6th puff was just completed.

Attention was paid to the inside pressure of the reservoir bag being equivalent to that of the outside.

## Gas Chromatography

The gas chromatographic measurements were made with a Hitachi Model K-53 equipped with a thermal conductivity detector. The detector output was fed into a Hitachi QPD-33 recorder with a full scale sensitivity of 1 millivolt and into a digital integrator, Model TR-2213, manufactured by Takeda Riken Industry Co. Ltd. A stainless column (length 2 m, outside diameter 3 mm) packed with a Linde 5A molecular sieve was used for measuring nitrogen, oxygen, methane and carbon monoxide. The molecular sieve packed in the column was activated at 350 °C for 3 hours under a flow of helium before use. The column and the detector were both maintained at 100 °C and helium, at a flow rate of 20 ml per minute, was used as the carrier gas. The same column and conditions were also used for measuring hydrogen, except for the use of nitrogen as the carrier. Carbon dioxide was measured separately on a stainless column (length 2 m, outside diameter 3 mm) packed with Carbosieve-B (Sapelco Co.). The column was maintained at 150 °C, while the detector was maintained at 100 °C. Helium, at a flow rate of 20 ml per minute, was used as the carrier. The experiments were always repeated at least six times.

## RESULTS AND DISCUSSION

The volume of the standard gas drawn into the cigarette at the front end and the changes in the concentration of gaseous components within the cigarette column during the puff were measured varying the cigarette paper and length. The results are shown in Table 1.

**Table 1. Volume of a standard gas mixture drawn into a cigarette at the front end and concentration of gases at the butt end.**

Cigarette	Cigarette length (cm)	Volume drawn into cigarette at front end (ml/puff)	Concentration of gases at butt end (%)					
			N <sub>2</sub>	O <sub>2</sub>	H <sub>2</sub>	CH <sub>4</sub>	CO	CO <sub>2</sub>
Blank	0	35.0	72.6	0	6.81	7.23	6.52	6.87
With non-perforated paper (porosity: 80)	0.5	35.0	72.9	0.96	6.00	6.87	6.23	6.64
	2.0	35.0	74.0	3.16	4.70	6.09	5.51	6.07
	3.5	34.8	74.3	5.17	3.48	5.45	4.91	5.66
	5.0	33.9	75.1	7.22	2.69	4.74	4.18	5.21
	6.5	33.3	75.7	8.39	2.02	4.28	3.78	4.77
	8.0	32.3	75.6	10.29	1.56	3.62	3.18	4.25
With perforated paper (porosity: 180)	0.5	34.9	73.2	1.06	5.98	6.82	6.19	6.60
	2.0	33.8	73.6	3.68	4.57	5.94	5.32	5.99
	3.5	32.2	74.4	6.23	3.38	5.03	4.50	5.39
	5.0	30.4	75.1	8.48	2.31	4.36	3.79	4.98
	6.5	27.6	75.3	10.37	1.60	3.56	3.12	4.33
	8.0	25.1	76.2	11.79	1.16	2.91	2.63	3.67
With perforated paper (porosity: 260)	0.5	34.5	72.9	1.32	5.75	6.75	6.10	6.59
	2.0	32.4	73.3	4.34	4.27	5.68	5.06	5.81
	3.5	28.5	74.9	7.08	2.81	4.67	4.23	4.99
	5.0	26.5	76.0	9.65	2.03	3.79	3.45	4.32
	6.5	22.5	76.3	12.06	1.26	2.90	2.62	3.57
	8.0	19.1	76.3	14.55	0.71	2.08	1.85	2.87

The concentration of nitrogen and oxygen at the butt end increased with the cigarette length and paper porosity, while the levels of hydrogen, methane, carbon monoxide and carbon dioxide, which are essentially absent in air, decreased in the same manner as the volume of the standard gas drawn into the cigarette at the front. Hydrogen gas showed the highest decrease among the constituents of the standard gas mixture. These results are in good agreement with those obtained by using lit cigarettes (1, 2, 3, 4).

The proportion of the decrease in the volume,  $P_{dv}$ , of the standard gas mixture drawn into the cigarette at the front and that in the concentration,  $P_{dc}$ , of a gaseous component  $i$  between the front and butt end during the puff can be calculated by the following equations:

$$P_{dv} = (V_0 - V_1) \times 100 / V_0, \quad [1]$$

$$P_{dc} = (C_{0i} - C_{1i}) \times 100 / C_{0i}, \quad [2]$$

where  $V_0$  is the puff volume of 35 ml,  $V_1$  the volume of the standard gas drawn into at the front,  $C_{0i}$  the con-

centration of the gaseous component  $i$  in the standard gas mixture, i.e. the concentration of the component  $i$  at the front, and  $C_{1i}$  the concentration of the component  $i$  measured at the butt end. Furthermore, the volume,  $V_{ei}$ , of the component  $i$  which actually effuses out of the cigarette through the paper during the puff, and the proportion of the volume effused,  $P_e$ , can be calculated according to the following equations:

$$V_{ei} = C_{0i}V_1 - C_{1i}V_0, \quad [3]$$

$$P_e = (C_{0i}V_1 - C_{1i}V_0) \times 100 / C_{0i}V_1. \quad [4]$$

Calculated results are listed in Table 2. Since the decrease in the volume of the standard gas drawn into the cigarette at the front would be accounted for by the air coming into the cigarette column through the paper, the proportion of the decrease in the volume,  $P_{dv}$ , should represent the extent of dilution with air through the paper. On the other hand, the proportion of the volume of gaseous components effused out of the cigarette,  $P_e$ ,

**Table 2. Changes in gas volume drawn into cigarette at the front, concentration of gases and gas volume effused out of cigarette through the paper during the puff.**

Cigarette	Cigarette length cm	$P_{dv}^*$ %	H <sub>2</sub>			CH <sub>4</sub>			CO			CO <sub>2</sub>		
			$P_{dc}^+$ %	$V_e^{++}$ ml/puff	$P_e^{+++}$ %	$P_{dc}$ %	$V_e$ ml/puff	$P_e$ %	$P_{dc}$ %	$V_e$ ml/puff	$P_e$ %	$P_{dc}$ %	$V_e$ ml/puff	$P_e$ %
With non-perforated paper (porosity: 80)	0.5	0	11.9	0.28	11.9	5.0	0.13	4.0	4.4	0.10	4.4	3.3	0.08	3.3
	2.0	0	31.0	0.74	31.0	15.8	0.40	15.7	15.5	0.35	15.5	11.6	0.28	11.6
	3.5	0.5	48.9	1.15	48.6	24.6	0.61	24.2	24.7	0.55	24.3	17.6	0.41	17.1
	5.0	3.1	60.5	1.37	59.2	34.4	0.79	32.3	35.9	0.74	33.8	24.1	0.51	21.7
	6.5	4.7	70.3	1.56	68.8	40.7	0.91	37.8	42.0	0.85	39.0	30.6	0.62	27.0
8.0	7.7	77.1	1.65	75.2	49.9	1.07	45.7	51.2	0.99	47.1	38.1	0.73	33.0	
With perforated paper (porosity: 180)	0.5	0.1	12.2	0.29	12.1	5.7	0.14	5.6	5.1	0.11	5.0	3.9	0.09	3.9
	2.0	3.4	32.9	0.70	30.5	17.8	0.36	14.9	18.4	0.34	15.5	12.8	0.22	9.7
	3.5	8.0	50.4	1.01	46.1	30.4	0.57	24.4	31.0	0.52	23.0	21.5	0.33	14.7
	5.0	13.1	66.1	1.26	60.9	39.7	0.67	30.6	41.9	0.66	33.1	27.5	0.35	16.5
	6.5	21.2	76.5	1.32	70.2	50.8	0.75	37.5	52.1	0.71	39.3	37.0	0.38	20.1
8.0	28.3	83.0	1.30	76.2	59.7	0.80	43.9	59.7	0.72	43.8	46.6	0.44	25.5	
With perforated paper (porosity: 260)	0.5	2.1	15.6	0.34	14.3	6.6	0.13	5.3	6.4	0.11	5.1	4.1	0.06	2.7
	2.0	7.4	37.3	0.71	32.2	21.4	0.35	15.1	22.4	0.34	16.2	15.4	0.19	8.6
	3.5	18.6	58.7	0.96	49.3	35.4	0.43	20.7	35.1	0.38	20.3	27.4	0.21	10.8
	5.0	24.2	70.2	1.09	60.6	47.6	0.59	30.7	47.1	0.52	30.1	37.1	0.31	16.9
	6.5	35.7	81.5	1.09	71.2	59.9	0.61	37.6	59.8	0.55	37.5	48.0	0.30	19.2
8.0	45.5	85.3	1.05	80.8	71.2	0.65	47.2	71.6	0.60	48.0	58.2	0.31	23.4	

\*:  $P_{dv}$  = The proportion of the decrease in the volume of a standard gas mixture drawn into a cigarette at the front during the puff, defined as  $P_{dv} = 100 (V_0 - V_1) / V_0$ .

+:  $P_{dc}$  = The proportion of the decrease in the concentration of a gaseous component between the front and butt end during the puff, defined as  $P_{dc} = 100 (C_0 - C_1) / C_0$ .

++:  $V_e$  = The volume of a gaseous component effused out of the cigarette through the paper during the puff, defined as  $V_e = C_0V_1 - C_1V_0$ .

+++:  $P_e$  = The proportion of the volume effused out during the puff, defined as  $P_e = 100 V_e / C_0V_1$ .

$V_0$  = The puff volume of 35 ml.

$V_1$  = The volume of the standard gas mixture drawn into the cigarette at the front.

$C_0$  = The concentration of each component in the standard gas mixture.

$C_1$  = The concentration of each component measured at the butt end.

should represent the extent of diffusion of the gas out of the cigarette column, because the effusion should be principally dependent on diffusion.

As would be anticipated by diffusion loss, the decreasing proportion in the concentration,  $P_{dei}$ , of each gaseous component is much greater than that in volume,  $P_{dv}$ , in each cigarette. Actually, diffusion loss of gases through the paper during the puff can be clearly recognized, as is obvious from the volume effused,  $V_{ei}$ , in Table 2. The effused proportion,  $P_{ei}$ , of each gas depends largely on the diffusion coefficient of respective gases, e.g. the greatest value is observed with hydrogen which has the highest diffusion coefficient into air among the constituents of the standard gas used, but does not appreciably depend on the porosity of the paper. Our observation evidently contradicts *Imazu's* prediction (5) that diffusion loss of smoke gases would hardly occur in the cigarette with perforated paper. On the other hand, the proportion of the decrease in the volume,  $P_{dv}$ , of the standard gas mixture drawn into the cigarette at the front is dependent on paper porosity, and for the cigarette with the non-perforated ordinary paper the dilution effect is so small that it is practically negligible compared with the diffusion effect.

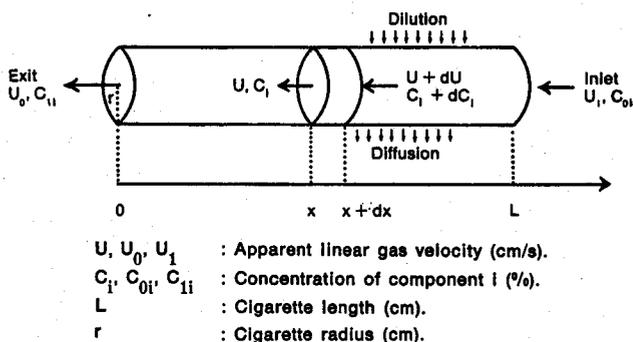
Our interpretation of the results could be summarised as follows: The extent of the decrease in the concentration of gaseous components between the front and butt end increases with cigarette length and paper porosity. This change can be explained mainly by the diffusion loss through the paper in the case of the cigarette with ordinary paper and dilution with air through the paper in addition to diffusion loss in the case of the cigarette with perforated paper, so that the decrease in concentration of gaseous components, such as carbon monoxide, in mainstream smoke during the puff is more significant for the latter cigarette.

Assuming that both the air flow into the burning cone and the concentration of combustion gases produced around the cone are constant and considering that the changes in their concentration during smoking would be accounted for by diffusion loss only, *Owen* and *Reynolds* (2) developed a simplified one-dimensional diffusion model and proposed the following equation which shows that the concentration of the gaseous component  $i$  ( $C_{1i}$ ) at the butt end is related to its concentration produced around the cone ( $C_{0i}$ ):

$$\log C_{1i} = -\frac{2D_i}{\sigma r U} L + \log C_{0i}, \quad [5]$$

where  $L$  is the cigarette length remaining after the puff,  $r$  the cigarette radius,  $D_i$  the diffusion coefficient of the gaseous component  $i$  through the paper,  $\sigma$  the thickness of the paper and  $U$  the apparent linear gas velocity in the cigarette column. This equation 5 may be applicable to cigarettes with ordinary paper, but will not hold for cigarettes with perforated or highly porous paper, because the dilution with air through the paper cannot be neglected, as pointed out above in this paper. We tried briefly to derive an equation, which would account for the changes in the concentration of gases during the puff

Figure 2. A material balance model during the puff.



even in the event of not being able to disregard dilution. Fig. 2 illustrates a one-dimensional material balance model with dilution and diffusion through the paper of a cigarette column. The  $x$ -axis is taken along the axis of the cigarette, and  $x = 0$  at the butt end, and gases flow in the opposite direction to the  $x$ -axis. Assumptions are almost the same as described by *Owen* and *Reynolds* (2), except that the dilution is not disregarded and, consequently, apparent linear velocity of the gas stream is not constant.

The material balance of a component  $i$  in the element of thickness  $dx$  between  $x$  and  $x+dx$  for unit time is given as follows:

$$U \frac{\partial C_i}{\partial x} + C_i \frac{\partial U}{\partial x} = \frac{2D_i}{\sigma r} C_i, \quad [6]$$

where  $C_i$  is the concentration of component  $i$  in the element. If the apparent linear gas velocity,  $U$ , is assumed to vary linearly with the  $x$ -axis,  $U$  at  $x$  cross section must be represented by

$$U = U_0 - \frac{U_0 - U_1}{L} x, \quad [7]$$

where  $U_0$  and  $U_1$  are apparent gas velocities at the butt and the front end, respectively. From equation 7 we have

$$\frac{\partial U}{\partial x} = -\frac{U_0 - U_1}{L}. \quad [8]$$

The following equation ensues from equations 6, 7 and 8:

$$\frac{dC_i}{dx} = C_i \left( \frac{2D_i L}{\sigma r} + U_0 - U_1 \right) / (U_0 L - (U_0 - U_1) x). \quad [9]$$

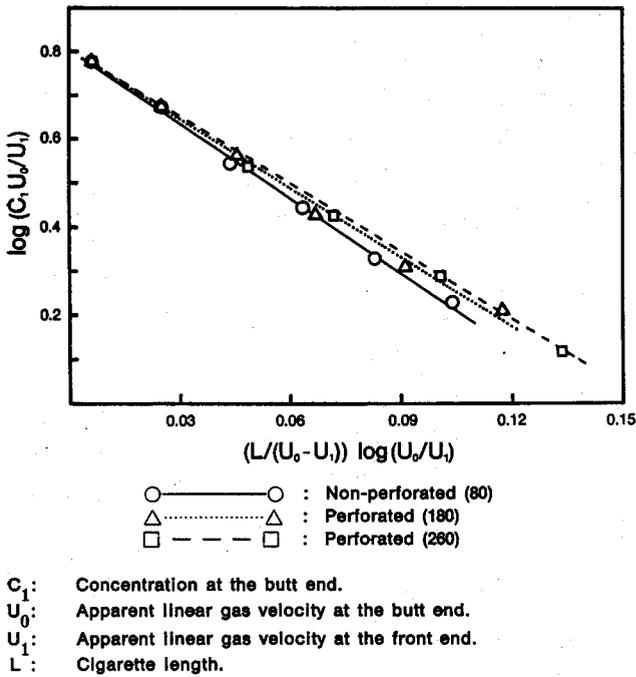
This equation can be written as in equation 10 with the use of the boundary conditions,  $C_i = C_{1i}$  at  $x = 0$ , and  $C_i = C_{0i}$  at  $x = L$ :

$$\log \frac{C_{1i} U_0}{U_1} = -\frac{2D_i}{\sigma r} \left( \frac{L}{U_0 - U_1} \log \frac{U_0}{U_1} \right) + \log C_{0i}, \quad [10]$$

$U_0 \neq U_1.$

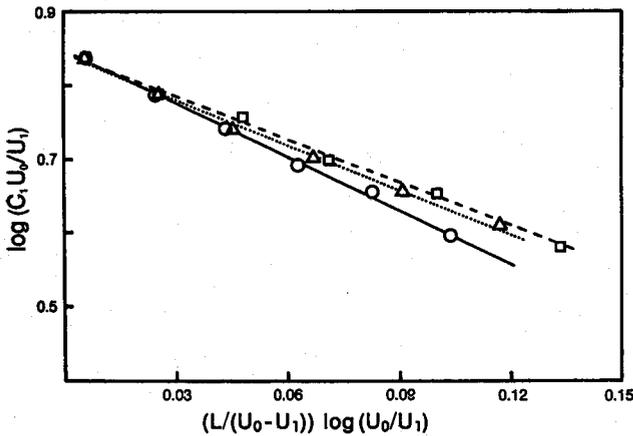
If  $U_0$  is equal to  $U_1$ , this equation becomes the same as equation 5 derived by *Owen* and *Reynolds* (2). Equation 10 suggests that a plot of  $\log(C_{1i} U_0 / U_1)$  vs.  $(L / (U_0 - U_1)) \log(U_0 / U_1)$  gives a straight line with a slope,  $-2D_i / \sigma r$ , and an intercept,  $\log C_{0i}$ .

**Figure 3. Plots of  $\log(C_1 U_0/U_1)$  vs.  $(L/(U_0-U_1)) \log(U_0/U_1)$  for  $H_2$ .**



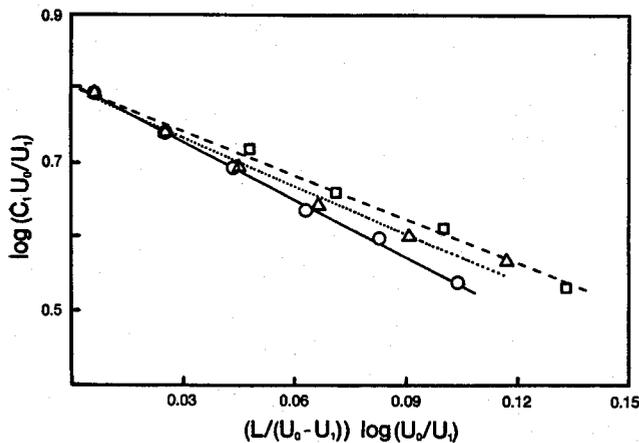
**Figure 4. Plots of  $\log(C_1 U_0/U_1)$  vs.  $(L/(U_0-U_1)) \log(U_0/U_1)$  for  $CH_4$ .**

All symbols are the same as in Figure 3.



**Figure 5. Plots of  $\log(C_1 U_0/U_1)$  vs.  $(L/(U_0-U_1)) \log(U_0/U_1)$  for CO.**

All symbols are the same as in Figure 3.



**Table 3. Comparison of relative diffusion coefficients.**

Cigarette paper (porosity)	$H_2$	$CH_4$	CO	$CO_2$
Non-perforated (80)	1.00	0.43	0.45	0.26
Perforated (180)	1.00	0.39	0.39	0.18
Perforated (260)	1.00	0.39	0.38	0.16
Diffusion coefficient <sup>a</sup>	1.00	0.31	0.30	0.22

a: Diffusion coefficient into air (references: 8, 9).

Such plots for hydrogen, methane, carbon monoxide and carbon dioxide are given in Figures 3, 4, 5 and 6, respectively. The observed plots for respective gases have given good straight lines. The slopes of these plots would depend on the diffusion coefficient of gaseous components through the paper as pointed out by equation 10. From the slopes given in these figures, it has been demonstrated that there is no remarkable difference in the diffusion effect among the cigarette papers used.

Table 3 shows the comparison of relative diffusion coefficients (hydrogen = 1.00), one through the cigarette paper obtained from this experiment, the other into air obtained from references (8, 9). Although some seemingly simple assumptions are made in the derivation of the equation, agreement between two kinds of relative diffusion coefficients is quite good.

The results shown in Figures 3, 4, 5 and 6, and Table 3 suggest that equation 10 can account for the changes in concentration of gases between the cone and the butt end during the puff.

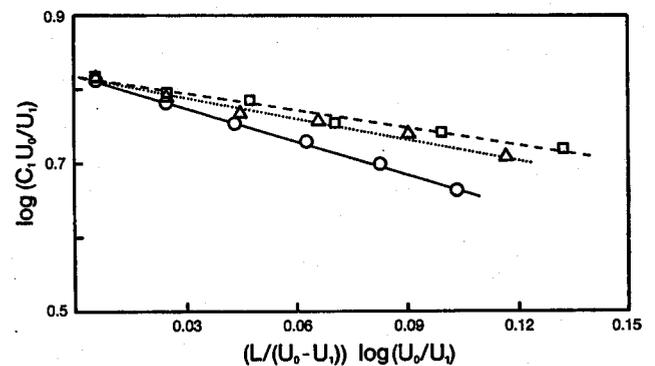
## SUMMARY

The effects of diffusion and dilution on the concentration of gaseous components have been studied by a model consisting of unlit cigarettes differing in paper porosity and length, and a standard gas mixture. Results are as follows:

The difference in the concentration of gaseous components between the front and butt end of the cigarette during the puff increases with cigarette length and paper

**Figure 6. Plots of  $\log(C_1 U_0/U_1)$  vs.  $(L/(U_0-U_1)) \log(U_0/U_1)$  for  $CO_2$ .**

All symbols are the same as in Figure 3.



porosity, and also depends on the diffusion coefficient of respective components through the cigarette paper. These changes could be explained mainly by the diffusion loss through the paper in the case of the cigarette with ordinary paper, but by both dilution with air through the paper and diffusion loss in the case of the cigarette with perforated paper. Subsequently, the levels of gaseous components such as carbon monoxide in the exit stream become lower in the latter cigarette. In addition, the following equation, which can fully account for these changes, has been derived:

$$\log \frac{C_{1i} U_0}{U_1} = - \frac{2D_i}{\sigma r} \left( \frac{L}{U_0 - U_1} \log \frac{U_0}{U_1} \right) + \log C_{0i},$$

where  $C_{1i}$  and  $C_{0i}$  are the concentrations of the component  $i$  at the front and butt end, respectively,  $L$  the cigarette length,  $r$  the cigarette radius,  $\sigma$  the thickness of paper,  $U_0$  and  $U_1$  the apparent linear gas velocities at the butt and front end, respectively, and  $D_i$  the diffusion coefficient of component  $i$  through the paper.

## ZUSAMMENFASSUNG

Die Beeinflussung der Konzentration gasförmiger Bestandteile des Rauchstromes durch Diffusion und Verdünnung wurde in einem Modellversuch an nicht brennenden Zigaretten unterschiedlicher Länge und Papierporosität und einem standardisierten Gasgemisch mit den folgenden Ergebnissen untersucht.

Der während des Zuges zwischen dem Anfang und dem Stummelende der Zigarette zu beobachtende Unterschied in der Konzentration der Gase nimmt mit der Zigarettenlänge und der Papierporosität zu und ist außerdem von dem Koeffizienten der Diffusion des jeweiligen Gases durch das Zigarettenpapier abhängig. Diese Veränderungen könnten bei Zigaretten mit gewöhnlichem Papier vor allem durch Diffusionsverlust durch das Papier erklärt werden, bei Zigaretten mit perforiertem Papier könnten sie hingegen sowohl auf den Diffusionsverlust als auch auf die durch das Papier eintretende Verdünnung mit Luft zurückgeführt werden. Der Gehalt des vom Mundstücksende ausgehenden Stromes an gasförmigen Bestandteilen wie Kohlenmonoxid ist folglich bei Zigaretten mit perforiertem Papier niedriger. Es wurde darüber hinaus die folgende Gleichung entwickelt

$$\log \frac{C_{1i} U_0}{U_1} = - \frac{2D_i}{\sigma r} \left( \frac{L}{U_0 - U_1} \log \frac{U_0}{U_1} \right) + \log C_{0i},$$

die den in Frage stehenden Veränderungen voll Rechnung trägt und in der  $C_{1i}$  und  $C_{0i}$  die Konzentration des Gases  $i$  am Anfang bzw. am Stummelende,  $L$  die Zigarettenlänge,  $r$  den Radius der Zigarette,  $\sigma$  die Papierdicke,  $U_0$  und  $U_1$  die scheinbare lineare Gasgeschwindigkeit am Stummelende bzw. am Anfang der Zigarette und  $D_i$  den Koeffizienten der Diffusion des Gases  $i$  durch das Papier darstellen.

## RÉSUMÉ

On a étudié les effets de la diffusion et de la dilution sur la concentration de composants gazeux au moyen d'une reproduction type composée de cigarettes non allumées différant en longueur et en porosité du papier, et d'un mélange gazeux standard. Voici les résultats:

Durant la bouffée, la différence en concentration des composants gazeux entre l'entrée et l'extrémité côté bouche de la cigarette augmente avec la longueur de la cigarette et la porosité du papier, et cette différence dépend également du coefficient de la diffusion des composants respectifs à travers le papier de cigarette. L'explication de ces changements pourrait en grande partie être la suivante: dans le cas d'une cigarette entourée de papier ordinaire, cela pourrait être la perte par diffusion à travers le papier, mais par contre dans le cas d'une cigarette entourée de papier perforé, cela pourrait être non seulement la dilution par l'air à travers le papier, mais aussi la perte de diffusion. Par conséquent, dans le flux de sortie, les teneurs en composants gazeux comme par exemple le monoxyde de carbone diminuent dans le dernier cas, c'est-à-dire dans la cigarette entourée de papier perforé. En plus, on a pu déduire cette équation permettant de déterminer ces changements:

$$\log \frac{C_{1i} U_0}{U_1} = - \frac{2D_i}{\sigma r} \left( \frac{L}{U_0 - U_1} \log \frac{U_0}{U_1} \right) + \log C_{0i},$$

$C_{1i}$  et  $C_{0i}$  étant les concentrations du composant  $i$  respectivement à l'entrée et l'extrémité côté bouche,  $L$  la longueur de la cigarette,  $r$  le rayon de la cigarette,  $\sigma$  l'épaisseur du papier,  $U_0$  et  $U_1$  la vitesse linéaire apparente du gaz à l'entrée et l'extrémité côté bouche, respectivement, et  $D_i$  le coefficient de la diffusion du composant  $i$  à travers le papier.

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