ST 18 - Colard - Airflow characterization within a cigarette using a permeability-meter

Authors: COLARD S.; JULIEN R.

Airflow characterization within a cigarette using a permeability-meter.

Stéphane Colard and Rémi Julien
ALTADIS Research Center, Experiments and Measurements Department, 4 rue André Dessaux, 45404 Fleury-Les-Aubrais, France.

Abstract

The behavior of a cigarette, during a puff, is strongly determined by the airflow distribution inside. In order to better understand this behavior, a theoretical model has been used which is able to predict the pressure drop as well as the paper and tipping paper ventilation. This model needs to take into account several parameters which influence the flow rate and the pressure drop : cigarette and filter size, paper permeability, coefficients related to the laminar or turbulent airflow within the tobacco rod, the filter and the tipping paper.
Whereas the cigarette sizes can be easily measured, the determination of the other parameters related to the airflow behavior is quite more difficult. In order to make this characterization easier, a permeability-meter commonly used for the paper permeability measurement has been modified. These modifications allow to carry out a quick and easy measurement of the pressure drop versus the flow rate within tobacco rods, filters and tipping paper.

- ✓ Measurements within an encapsulated tobacco or filter rod allow us to calculate the coefficients related to the laminar or turbulent airflow properties.
- ✓ Measurements within an obstructed ventilated filter rod allow us to calculate the coefficients related to the laminar and turbulent airflow within the ventilation zone.

By using the previous determined parameters, we have been able to predict accurately both ventilation and pressure drop after a virtual assembling of a ventilated filter to a tobacco rod.

1. Introduction

The behaviour of a cigarette on puffing is closely linked to the distribution of the air flows. When smokers draw by the end of the cigarette, an air flow enters by the glowing cone, another flow crosses the paper laterally, and when the tipping paper is perforated, an additional lateral flow enters into the filter. The distribution of these air flows depends on the specifications governing the flows in each of the parts making up the cigarette. The behaviour of a cigarette on puffing thus passes via the prior determination of those flow specifications. Such determination is done by analysing the flow rate / pressure curves for each of the parts of the cigarette. For this, the experiments to be used are often long and complex. In order to facilitate carrying them out, we modified a permeability-measuring device normally used for measuring the air permeability of the paper.

2. Theory

2.1. Flow across the cigarette, tipping and wrapping papers

The flow of air across quality and naturally porous cigarette paper is laminar-like. The linear relationship linking the flow rate Q and the pressure drop ΔP across a surface S is thus in the following form:

$$\boxed{Q = S_p \times \omega \times \Delta P} \qquad \textbf{(1)}$$

where: ω: permeability coefficient, flow rate per cm^2 at 1kPa
S_p: flow section across the paper

For perforated cigarette and tipping papers, and for very porous wrapping paper, a turbulent flow is observed more often than not. The two equations generally used to link Q to ΔP are in this case [1,2] :

$$\boxed{Q = S_p \times \omega \times \Delta P^{\alpha}} \qquad \textbf{(2)}$$

or: $$Q = S_p \times \left(\omega_1 \times \Delta P + \omega_2 \times \sqrt{\Delta P}\right)$$

where: $\omega_1 \neq \omega_2$: flow rate per cm^2 at 1kPa
α and ω_2 are specifications for the level of turbulence

It can be shown mathematically that the above two relationships are almost equivalent for the flow rate and pressure levels observed in cigarettes [3].

On a cigarette ventilated by the filter, the ventilation lateral crosses the tipping paper, then the wrapping paper, then the filter. In this case, the physical modelling of the flow rate / pressure relationship across that series of elements proves to be complex and in particular brings into play parameters relating to the quality of assembly of the cigarette. Rather than a complex physical relationship, experimentation shows that a single second degree mathematical law provides an appropriate description of the pressure / flow raterelationship :

$$\boxed{\Delta P = a \times Q + b \times Q^2} \qquad \textbf{(3)}$$

where: a and b: flow coefficients relating to the filter ventilation
b: coefficient specification for the level of turbulence

2.2. Flow across a filter

Experiments have shown [4] that in the large majority of cases the flow across a filter is laminar. The linear relationship which links the pressure drop ΔP to the flow rate Q is thus of the following form :

$$\boxed{\Delta P = \frac{\lambda_F \times L_F}{S_F} \times Q} \qquad \textbf{(4)}$$

where λ_F: flow specification, referred to as the filter impedance
L_F: length of the filter segment
S_F: section of the filter segment

2.3. Flow across a tobacco column

The flow of air across a column of tobacco rolled in porous paper with permeability ω, across which the flow is laminar, is governed by the following differential equation [3] :

$$\left| \begin{array}{l} \dfrac{dP}{dx} = -\dfrac{\lambda_T}{S_c} \times Q \times (1 + \xi_T \times Q) \\ \dfrac{dQ}{dx} = -C \times \omega \times P \end{array} \right.$$

where, λ_T: impedance of the column of tobacco

ξ_T: turbulence coefficient for the column of tobacco

S_c: section of the column of tobacco

C: circumference of the column of tobacco

Where the flow across the paper is turbulent, we have :

$$\frac{dQ}{dx} = -C \times \omega \times P^{\alpha}$$

Taking impermeable paper, the coefficients λ_T and ξ_T which characterise the flow across the tobacco column can be isolated. Indeed, we can then write from the previous differential equation system :

$$\boxed{\Delta P = \frac{\lambda_T \times L_c}{S_c} \times Q \times (1 + \xi_T \times Q)} \qquad \textbf{(5)}$$

where L_c : length of the tobacco column

The relationships (1) to (5) describe the flow in each of the parts of a cigarette. The characterisation of these flows thus passes via the determination of the parameters ω, α, *a*, *b*, λ_F, λ_T and ξ_T.

3. Experiments

The determination of the parameters ω, α, *a*, *b*, λ_F, λ_T and ξ_T. can be long and tedious if a flow rate generator with manual adjustment is used. Indeed several levels of flow rate need to be generated and measured and for each of them the relative pressure drop measured. In order to facilitate this operation, we used a Sodim D23 permeability-measuring device which is normally used to measure paper permeability but which we modified to adapt it to measurements on cigarettes. This equipment has the advantage of being able to generate automatically several levels of pressure from 0.1 to 2kPa and to measure in parallel flow rates of 3 to 20000cm^3/min. The experimental device is represented in figure 1.

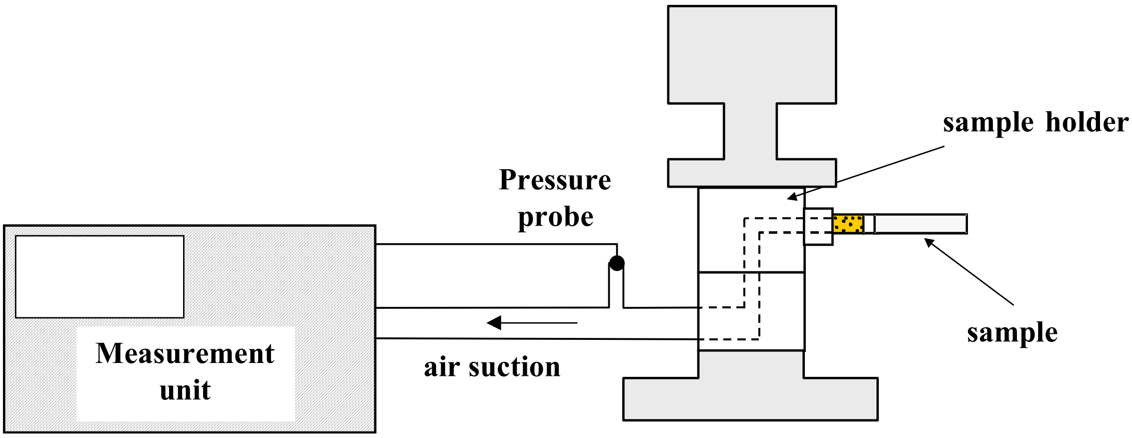

Fig. 1. Experimental device used for the characterisation of flows across a cigarette

The paragraphs which follow describe the experimental protocol and the results obtained relating to the characterisation of flows across a ventilated cigarette.

3.1. Characterisation of the flow across the cigarette paper

The flow across two papers (paper 1 and paper 2) was characterised. For this, the volumetric flow rate across a section S_p of 2 cm^2 was measured according to the pressure difference applied between the two faces, of 0 to 2kPa.

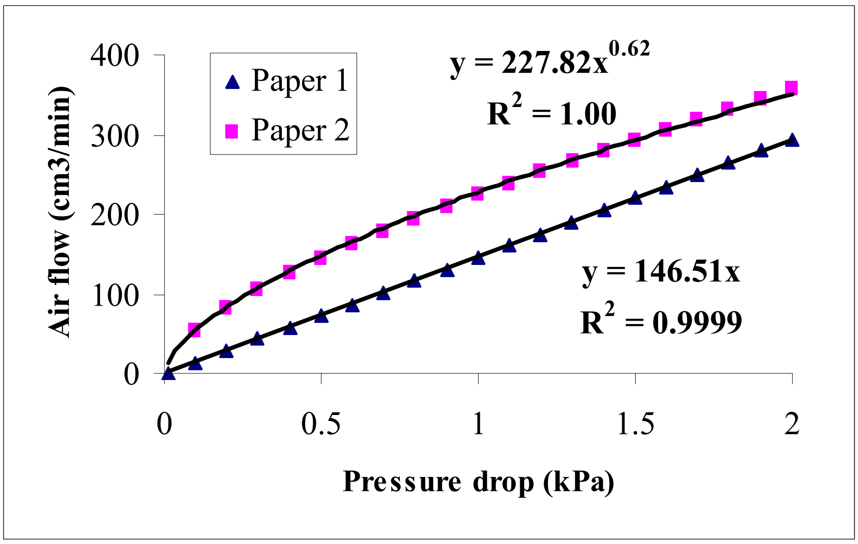

Fig. 2. Flow rate / Pressure curves for cigarette paper

Paper 1 is naturally porous and a type (1) relationship can be used. From the gradient of the flow rate pressure curve and the section S_p, we can calculate the permeability ω. The following is obtained :

$$\omega = \frac{146.5}{2} = 73\,\text{cm.min}^{-1}.\text{kPa}^{-1}$$

Paper 2 is perforated. The nature of the flow which crosses it is thus partly turbulent. Adjustment of a type (2) relationship to the measurements provides the means for calculating the coefficients ω and α. The following is obtained :

$$\omega = \frac{227.8}{2} = 114\,\text{cm.min}^{-1}.\text{kPa}^{-1}$$
$$\alpha = 0.62$$

3.2. Characterisation of the flow across the filter

In order to characterise the flow across the filter by getting rid of the effects of the ventilation and the tobacco column, we separated the filter from the column and covered the tipping paper perforation holes. We then applied negative pressure ranging from 0 to 2kPa to the mouth end and measured the volumetric flow rate induced across the filter.

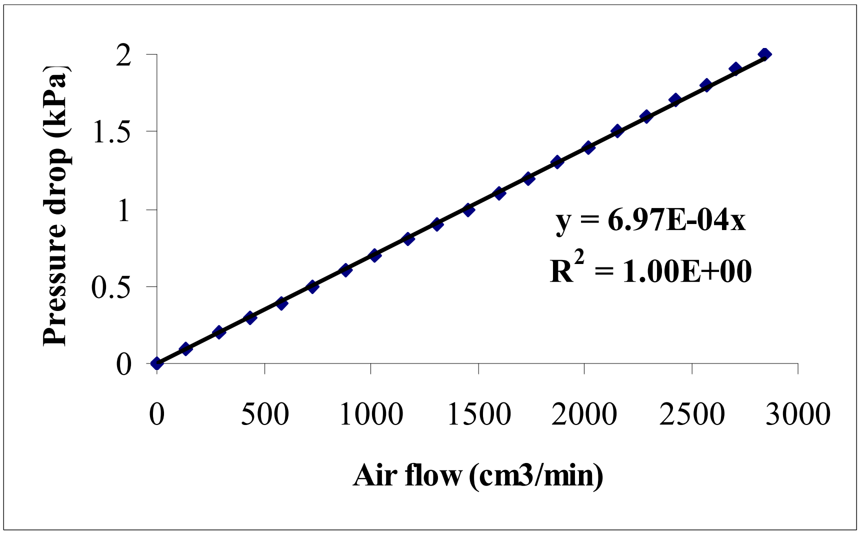

Fig. 3. Pressure / Flow rate curve for an encapsulated filter

The graph above clearly shows a linear Pressure / Flow rate relationship which corresponds to a laminar-type flow. The length L_F of the filter segment is 2.1cm and its section S_F is 0.479cm^2. From the gradient for this relationship, the values of S_F and L_F, and the equation (4), we are able to calculate the impedance λ_F of the filter.

$$\lambda_F = \frac{0.479 \times 6.97 \times 10^{-4}}{2.1} = 1.6 \times 10^{-4}\,\text{kPa.min.cm}^{-2}$$

3.3. Characterisation of the flow across the perforations of the tipping paper

The flow of air coming from the tipping paper perforation holes depends on the permeability of the wrapping paper, the filter and the quality of the rolling. To characterise this flow it thus proved necessary to carry out measurements in situ. In order to get rid of flows resulting from the end of the filter on aspiration across it, we blanked off that end. On aspiration, the only flow observed is thus that resulting from the perforations in the tipping paper.

The pressure drop ΔP measured is the sum of the pressure drop inside the filter and that which appears on each side of the perforations. We have :

$$\Delta P = \frac{\lambda_F \times L_{F1}}{S_F} \times Q + \left(a \times Q + b \times Q^2\right)$$

where L_{F1} : length of the filter between the mouth end and the perforations.

Using the permeability-measuring device, we measured the flow rate across the blocked filter according to the negative pressure applied. By taking the pressure drop across the filter segment of length L_{F1} equal to 1.2cm away from that negative pressure, and by using the relationship (3), we can determine the values of the parameters *a* and *b*.

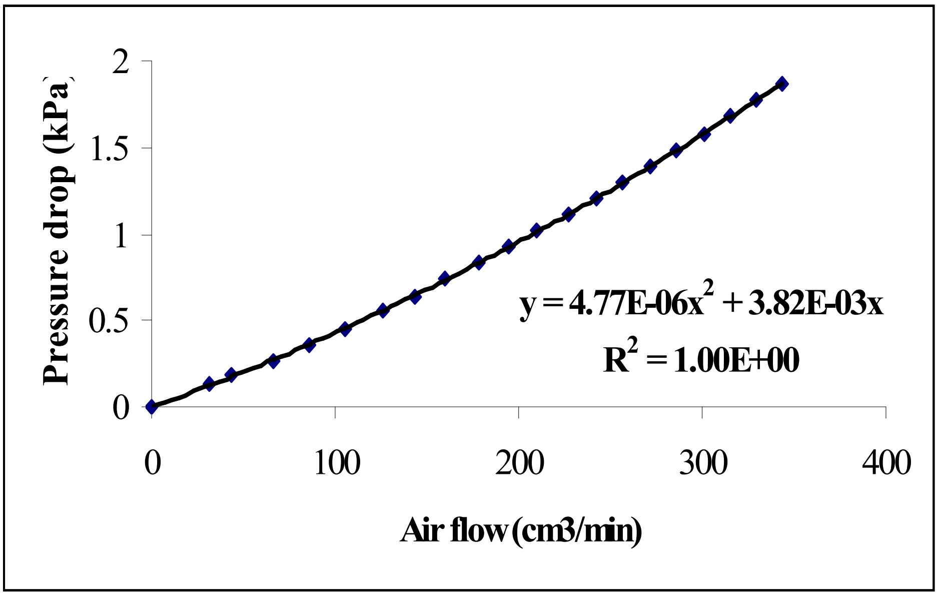

Fig. 4. Pressure / Flow rate curve for the filter ventilation zone

We thus obtained :

$$a = 3.82 \times 10^{-3}\ \text{kPa.min.cm}^{-3}$$
$$b = 4.77 \times 10^{-6}\ \text{kPa.min}^{2}.\text{cm}^{-6}$$

3.4. Characterisation of the flow across the tobacco column

Using the permeability-measuring device, and after having encapsulated the tobacco segment which was first separated from the filter, we measured the flow rate induced by the negative pressure varying from 0 to 2kPa. The use of the equation (5) thus enabled us to determine the flow parameters λ_T and ξ_T over a length L_T of 6.3 cm and a section S_T of 0.491cm^2.

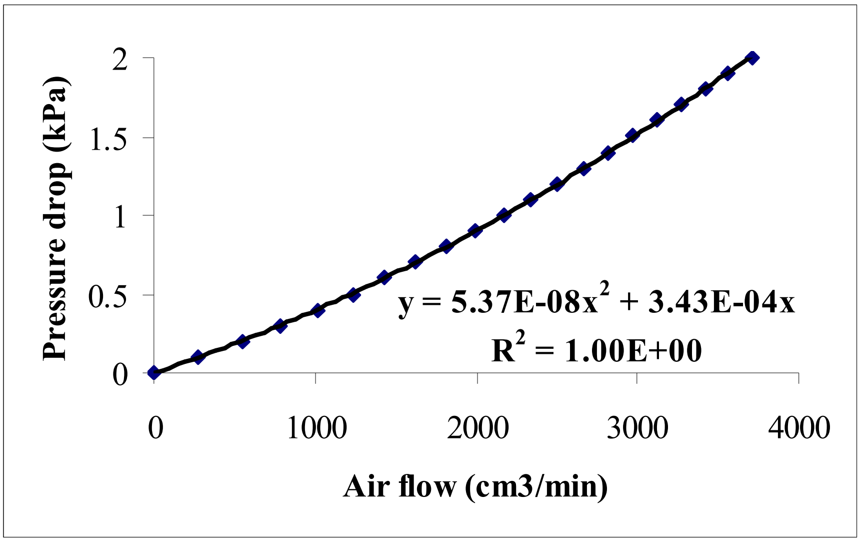

Fig. 5. Pressure / Flow rate curve for an encapsulated tobacco column

We thus obtained :

$$\lambda_T = \frac{0.491}{6.3}\times 3.43\times 10^{-4} = 2.67\times 10^{-5}\,\text{kPa.min.cm}^{-2}$$

$$\xi_T = \frac{0.491}{6.3\times 2.67\times 10^{-5}}\times 5.37\times 10^{-8} = 1.57\times 10^{-4}\,\text{cm}^{-3}.\text{min}$$

4. Conclusion

The permeability-measuring devices are normally used to measure the air permeability of the paper. By simple modification of the sample holder and thanks to the use of a device capable of measuring the flow rates induced at different pressure levels, we were able to determine all the parameters which characterise the air flows across a cigarette:

- the impedance λ_F of the filter and λ_T of the tobacco column
- the turbulence coefficient ξ_T of the tobacco column
- the flow coefficients *a* and *b* at the filter ventilation
- the permeability ω of the paper, and α where required

This modified permeability-measuring device provided a significant time saving to carry out a complete analysis of a cigarette compared with manually adjusted flow rate or pressure devices.

References

[1] W.A. Selke, J.H. Mathews, *The permeability of cigarette papers and cigarette ventilation*, Beitr. Tabakforsch. Int., 9 (1978) 193-200

[2] R.R. Baker, *The viscous and inertial flow of air through perforated papers*, Beitr. Tabakforsch. Int., 14 (1989) 253-260

[3] B. Pitié, *Ventilation equations* [in French], Ann. Du Tabac 18 (1981) 5-40

[4] R.W. Dwyer*, Predicting the pressure drops across Cellulose acetate filters*, Beitr. Tabakforsch. Int., 13 (1986) 157-168