A Multi-purpose, Programmable Smoking Machine*

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SUMMARY

Commercially available cigarette smoking machines are designed to operate at a standard set of smoking parameters and offer little scope for changing the smoking pattern. This paper describes a Programmable Smoking Machine (PSM) which operates in a way that no current commercial machine can. It can smoke cigarettes in a non-standard manner and obtain information useful for the examination of the influence of smoke generation patterns on the smoke yields as an aid to the design of cigarettes.

The PSM consists of a stepper motor driven glass syringe and three-way valve controlled by microcomputer. Suitable programs create the desired smoking patterns and control the operation of the smoking machine via a microcomputer port. Precautions must be taken to prevent stepper motor pulses affecting the puff profiles.

Smoking can be performed in a restricted or open mode with calibrated clearing puffs, and the vapour phase collected is directed on a puff-by-puff basis to a gas analyser or trapping medium at a controlled rate. It is also possible to generate whole smoke should this be a requirement.

ZUSAMMENFASSUNG

Die auf dem Markt befindlichen Rauchmaschinen für Zigaretten sind für bestimmte standardisierte Abrauchparameter eingerichtet, und es besteht nur in geringem Maße die Möglichkeit, diese zu variieren. In der vorliegenden Arbeit wird eine programmierbare Rauchmaschine (PSM) beschrieben, die sich in ihrer Funktionsweise von allen handelsüblichen Maschinen unterscheidet. Die Abrauchparameter sind bei ihr frei wählbar, wodurch sich im Hinblick auf die Entwicklung eines

verbesserten Zigarettendesigns Erkenntnisse darüber gewinnen lassen, inwieweit die Rauchausschüttung von der Art der Rauchbildung bestimmt wird.

Das microcomputergesteuerte Gerät besteht aus einer Glasspritze mit Schrittmotorantrieb und einem Dreifachventil. Über einen entsprechend programmierten Microcomputer wird der Rauchvorgang wie gewünscht angelegt und der Ablauf der Arbeitsgänge überwacht. Einer Beeinträchtigung der Zugprofile durch Stromstöße des Schrittmotors ist durch Vorsichtsmaßnahmen vorzubeugen.

Der Abrauchvorgang ist mit geeichten Leerzügen in geschlossener und offener Weise durchführbar, und die Gasphase der einzelnen Züge läßt sich unter kontrollierten Bedingungen einem Gasanalysegerät oder Aufangmedium zuleiten. Auch Gesamtrauch kann, falls erforderlich, hergestellt werden.

RESUME

Le fonctionnement des machines à fumer les cigarettes à disposition dans le commerce est basé sur une série de paramètres normalisés, et ne permet guère de modifier le schéma de pétunage. Cette étude décrit une machine à fumer programmable (PSM) dont le mode de fonctionnement ne ressemble à aucune des machines du commerce. Elle peut en effet fumer des cigarettes selon un mode non normalisé, et procurer ainsi des renseignements utiles pour l'étude de l'influence des schémas de production de fumée sur le rendement en fumée, ces renseignements venant à l'appui de la conception même des cigarettes.

La machine à fumer programmable (PSM) est équipée d'une seringue en verre entraînée par un moteur à cascade, ainsi que d'une soupape en verre à trois voies commandée par un micro-ordinateur. Des programmes adéquats permettent de créer les schémas de pétunage voulus tout en commandant le fonctionnement de la

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machine à fumer par le biais d'un orifice pratiqué dans le micro-ordinateur. Des précautions doivent être prises afin d'éviter que les impulsions du moteur à cascade n'influencent sur les profils des bouffées.

Le pétunage peut s'effectuer selon un mode restrictif ou ouvert, avec bouffées calibrées au rejet, la phase vapeur recueillie étant orientée bouffée par bouffée, à un rythme réglable, sur un analyseur de gaz ou sur un médium de piégeage. En cas de besoin, il est également possible d'obtenir de la fumée totale.

1. INTRODUCTION

Smoking machines have undergone a steady development since they were first described by BRADFORD in 1936 (1). The commercially available machines prior to 1970 could be placed in one of two general categories: constant flow with the puff volume controlled by time or constant volume by means of syringe displacement. Today, constant volume machines predominate since most laboratories work to an ISO standard (2) for smoke analysis. This standard was written with syringe displacement in mind and specifies a "bell-shaped" puff of 35 cm³ volume, 2-second duration to be taken once every 60 seconds.

However, it is of considerable value to determine the amounts of smoke components produced when a cigarette is smoked in a non-standard manner. Many cigarette parameters such as pressure drop, paper ventilation, etc. will change markedly at the limits of a range of smoking patterns and these changes provide essential information for cigarette design.

Non-standard smoking machines were developed to duplicate the recorded smoking patterns of humans with ADAMS (3, 4) being the first in this field. In 1977 CREIGHTON described some "Instruments to measure, record and duplicate human smoking patterns" (5). CREIGHTON's smoking analyser and smoking duplicator facilitated the smoking of cigarettes to any recorded human smoking pattern.

It should be noted that the scope for changing the parameters of standard smoking machines such as the Filtrona model CSM 300 or Borgwaldt model RM 20/CS are limited to minor adjustments of volume and timing.

2. DISCUSSION

Since 1981 we have used commercially supplied smoking analysers and a smoking duplicator, based on the CREIGHTON design, with considerable success. The smoking analyser makes a record of a smoking pattern by measuring at 50 Hz the flow drawn from the cigarette while a puff is taken. The flow readings and the times when puffs occurred are stored on magnetic disc. The smoking duplicator loads the record from the magnetic disc and attempts to copy the same smoking pattern. It uses an analogue valve to control the flow be-

Figure 1.
A programmable smoking machine.

tween the cigarette and a vacuum source, with sophisticated electronics to sense the obtained flow and apply a feedback correction. Vapour phase products can be collected in a balloon, held within the vacuum tank. However, experience proved that the smoking duplicator requires constant attention if good volume accuracy is to be maintained, and the sampling of vapour phase for analysis is not simple. An imprecise means of taking a clearing puff, when the cigarette is removed from the holder between puffs, further complicates vapour phase analysis.

Our requirements were for an improved, simplified smoking duplicator that would also fulfill the role of an infinitely variable, programmable smoking machine (PSM), with the following features:

- Reliable and simple operation and calibration.
- The PSM should be able to copy smoking patterns from commercial smoking analysers, or smoke to any artificially generated pattern.
- It should be possible to remove the cigarette from the Cambridge filter holder between puffs (open smoking) and take a controlled clearing puff, or leave the cigarette inserted (restricted smoking).
- It should be possible to expel the vapour phase drawn from the cigarette on a puff-by-puff basis and in a controlled manner so that it can be directed to a gas analyser or chemical traps.
- The smoke path length must be short with efficient purging between puffs to permit the manipulation of whole smoke if required (i.e. with the Cambridge filter removed).

- f. Clearly the PSM should be able to smoke to the ISO standard and produce data comparable to the Filtrona model CSM 300 or Borgwaldt model RM 20/CS standard smoking machines.

These requirements were best met with a motor driven glass syringe connected via a three-way valve to the cigarette with Cambridge filter assembly. The syringe smoking method has been well proven on many commercial, analytical smoking machines. The syringe can draw precise volumes of smoke and requires minimal calibration, and the vapour phase can be expelled at a controlled rate. A stepper motor was chosen to drive the syringe via a rack and pinion and provide the scope for programmability. Stepper motors have the advantage of a high torque over a wide range of speeds and of simple control by computer (digital) electronics by virtue of their digital, incremental rotation.

3. CONSTRUCTION DETAILS

The smoking machine is illustrated in Figure 1.

Mechanical

The syringe, rack and pinion, and stepper motor are mounted on an aluminium frame. The connection of stepper motor to syringe is such that one revolution of the motor produces 5 cm of linear movement and displaces approximately 48 cm³ from the 120 cm³ syringe; the largest puff volume is 120 cm³. The connection gear and syringe diameter determine such factors as volume resolution and maximum possible flow.

The three-way solenoid valve, Cambridge filter, cigarette holder and cigarette are mounted on a separate frame which contains a pneumatic actuator to insert and remove the cigarette holder from the Cambridge filter holder labyrinth cigarette seals by means of a vertical bar connecting the holder to the actuator. The cigarette is mounted in the holder and thus moved in and out of a sealed connection with the Cambridge filter.

The amount of design and engineering required for the two frames is minimal and can be simply undertaken by any precision engineering company.

Electrical Control

The electronic hardware is contained in the "interface/drive" cabinet and consists of the following:

- A light emitting diode (LED) interface to receive signals from the computer output port. The LED isolation comprises commercial devices and provides electrical isolation between the computer and stepper motor drive.
- A power supply and relays to drive the three-way solenoid valve and switch the air supply to the pneumatic actuator.

Figure 2.

The computer signal lines required.

- A: reset the stepper motor drive cards (RESET).
 B: stepper motor power on (ON).
 C: stepper motor direction (CLOCKWISE).
 D: pulse to initiate one step (PULSE).
 E: cigarette actuator (IN).
 F: three-way solenoid valve (ENERGISE).

- A stepper motor drive stage comprising a power supply and commercially available translator and amplifier cards.

The translator and amplifier cards are made by The Superior Electric Company* and offer the facility of micro-step drive. Four-pole stepper motors usually have 200 steps per revolution (whole step mode) and a micro-drive provides 16 substeps within each whole step, giving 3200 steps per revolution (micro-step mode). With micro-step drive and a designed syringe displacement of 48 cm³/revolution it follows that the smallest volume increment is 0.015 cm³.

In practice, the maximum flow that can be generated is governed by the maximum pull-in rate of the motor, which in our PSM equates to over 100 cm³/s. It is also limited by the impedance of the lit cigarette and the torque of the motor, since the impedance rises with increased flow while the torque drops with increased rotational speed. The motor used in this case measures only 70 mm long by 55 mm diameter yet is capable of pulling 100 cm³/s through exceptionally high pressure drop cigarettes.

Computer

The microcomputer system was chosen primarily on the grounds of low cost and availability, although good data storage (discs), low level control of an output port and software tools for development are essential; almost any microcomputer could be used. Using a standard, commercially available microcomputer should ensure that repair is not a problem. Writing the software was the most time consuming part of the project, yet should be within the ability of most competent programmers.

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Figure 3. A comparison of the pneumatic noise seen in the puff profiles from the programmable smoking machine and two commercial smoking machines. Each puff is of 35 cm³ volume and 2-second duration.

A: programmable smoking machine. B: Borgwaldt RM 20/CS. C: Filtrona CSM 300.

Figure 4.
An illustration of the distortion of large volume, square-shaped puffs
(70 cm³ volume, 2-second duration).

The software and local smoke records were designed to use the standard smoking analyser data format in which puff profile, pressure and flow values are taken at 50 Hz. This ensured that the PSM was compatible with our existing equipment.

Three programs are used routinely as follows (all are written in interpreted BASIC with machine code subprograms where speed is important):

- a. A *copy* program to read human records from a smoking analyser through an RS232 port, convert these records to a local form and store them to disc.
- b. A *create* program to create artificial smoking records of any shape, volume or time and store them to disc in the same local format.
- c. A *smoke* program to read a disc record (whether human or artificial) and control the interface/drive cabinet through an 8-bit output port. This program contains a machine code written subprogram to enable the output port to be switched at the required speed.

The *smoke* program operates as follows, manipulating the output port control lines shown in Figure 2:

- (i) When a puff is to be taken the cigarette and holder are pneumatically pulled into the Cambridge filter holder seals, the three-way valve is energised for cigarette to syringe connection, and control is passed to the machine code subprogram.
- (ii) The subprogram takes a new flow reading from the smoke record and converts the flow value into a number of steps and a time between each step. The number of steps is calculated by dividing the

volume required in 20 ms by the volume per step syringe/motor constant. The time between each step within the 20 ms period is calculated to give even spacing and smooth operation. In practice, a pre-calibrated look-up table of steps and time between steps, for each flow value, is held in memory to speed up the program operation. The steps are thus signaled to the output port as brief pulses using a clock to keep the correct time between steps. A second clock then permits a repeat of this sequence when a 20 ms flag is signaled.

- (iii) Step (ii) continues until an end of puff flag is found in the smoke record when the cigarette is withdrawn from the holder, the syringe takes a defined clearing puff to flush the Cambridge holder, the three-way valve is de-energised and the syringe exhausts the vapour phase. Control is then returned to the basic program to await the next puff.

The program also receives data from a carbon monoxide analyser, corrects for the clearing puff volume, calculates the mass of carbon monoxide in the puff and prints the results.

4. PERFORMANCE RESULTS

The individual steps taken by the motor, although small, will induce a resonance in the syringe plunger and thus the airflow through the cigarette if some damping is not employed. The resonance is worse if the program timing does not evenly space out step pulses, and will be seen at the slowest step rates when the mo-

Figure 5.
The ability of the programmable smoking machine to copy recorded smoking profiles
(examples).

tor exhibits minimal inertial damping. Serious resonance in the airflow pattern through the cigarette will affect the burn rate and hence all generated products of combustion. Resonance can be minimised by using a flexible coupling between the syringe plunger and motor, combined with the application of an oil of suitable viscosity to the syringe plunger. These modifications are acceptable in the majority of applications of the smoking machine, notably the analysis of smoke particulate phase and gas phase components which are insoluble in the oil used. However, the use of an oil will be unacceptable during the collection of smoke for the analysis of oil soluble vapour phase components. A future modification of the PSM will be to fit an external damper in parallel with a dry syringe which will eliminate contact of smoke with oil.

Figure 3 shows some puff profiles obtained and compares the PSM with the Filtrona model CSM 300 and Borgwaldt model RM 20/CS syringe operated smoking machines, illustrating the type of noise found. It should be mentioned that in all cases the profiles were obtained from instruments that had been in routine use for some time. The flow profiles shown in this paper have been collected by drawing air through a linear flow element of a nominal 5 mm w.g. flow impedance at 83 cm³/s, measuring the differential pressure across the flow element and recording the pressure on a high speed analogue tape recorder. The linear flow element is a very low pressure drop device. An unlit cigarette was fitted to the end of the linear flow element to apply a typical pressure drop to the smoking machine.

It should be noted that a syringe driven in a manner related to a desired puff profile, although reproducing the total puff volume accurately, will not yield the identical profile, since pneumatic delay results in some distortion of profile. This delay is greater at higher rates of increase in flow and is clearly seen on large volume square-shaped puffs where the rate of increase is infinitely large at the start, as shown by Figure 4; however, the use of such puff shapes is limited. A comparison of recorded original puffs and the PSM duplications in Figure 5 gives a more realistic illustration of performance where distortion is minimal. Any small distortions of puff profile shape will cause insignificant changes in concentrations of smoke products. It is much more important to maintain volume accuracy, which this system does.

Although our PSM has been regarded as a prototype, it has been in routine use since September 1983 and proved totally reliable. Once the software has been set for a particular syringe diameter there is no further calibration required and daily checks are limited to leak

testing. The success of the single channel PSM has led to the design and construction of a four-channel PSM with automatic electric lighting. Butt termination detectors could be fitted to allow the smoking of part puffs.

REFERENCES

1. Bradford, J. A., W. R. Harlan and H. R. Hanmer: Nature of cigaret smoke — Technic of experimental smoking; *Ind. Eng. Chem.* 28 (1936) 836—839.
2. ISO 3308-1977 International Standard: Tobacco and tobacco products — Routine analytical cigarette-smoking machine — Definitions, standard conditions and auxiliary equipment; International Organization for Standardization, 1977.
3. Adams, P. I.: Measurements on puffs taken by human smokers; presented at the 20th Tobacco Chemists' Research Conference, Winston-Salem, N.C., 1966.
4. Adams, P. I.: Cigar smoking — Measurement of the human smoking regime and its relationship to smoking machines; in: *Proc. CORESTA (General Assembly) / 26th Tobacco Chemists (TCRC) joint research conference*, Williamsburg, Virginia, 1972.
5. Creighton, D. E., M. J. Noble and R. T. Whewell: Instruments to measure, record and duplicate human smoking patterns; in: *Smoking behaviour — Physiological and psychological influences*, edited by R. E. Thornton, Churchill Livingstone, Edinburgh, London and New York, 1978, pp. 277—288.

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