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Multiple Capillary Pressure Drop Standards*

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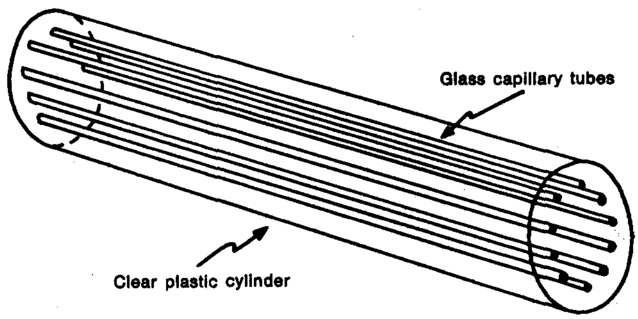
The pressure drop or draw resistance of cigarettes and cigarette filter rods is a quantity of more than usual importance in the tobacco industry. It is a readily measurable quantity which provides a guideline to customer acceptability of the finished product and to the filtration efficiency or "tar" delivery of cigarettes and cigars. Consequently its measurement is widely used as a quality control tool, and with weight measurement, it serves as the basic criterion for acceptance of most filter materials. From a number of studies, including the collaborative tests of the *Coresta* Technology Study Group, adequate methods of measuring pressure drop have been developed. In particular, the critical flow orifice method which was described by *Pullum* and *Tucker* (1) in 1967, has allowed a high degree of standardization of pressure drop measurement by essentially removing the variability of flow measurement. However, there is still a need for a pressure drop standard so that the accuracy of pressure drop measurements can be insured both within a laboratory over a period of time and between laboratories.

A number of pressure drop standards have been developed and utilized. For the most part, these have been simple capillary tubes of metal or glass. More elaborate versions with carefully honed entrance and exit regions have recently been introduced. While these single capillary tube standards are adequate for many purposes, they are not sufficiently constant in pressure drop to serve as a basic, unchanging standard. The reason for this variability is that the flow in these devices may be turbulent or in the ill-defined transition region between laminar and turbulent flow. Under these conditions, variations in atmospheric pressure or the deposition of dust in the capillary passage can significantly affect the pressure drop of the tube. This variability was noted by *Pullum* and *Tucker* who compared the pressure drops of capillary tubes and single filter rods over a period of time. *Haddon* (2) has also noted this effect.

Figure 1. Multiple capillary pressure drop standard.



The purpose of this paper is to describe a multiple capillary tube pressure drop standard which avoids a turbulent flow sensitivity, yet maintains the simplicity and durability of a single tube standard. Essentially what has been done is to distribute the total flow equally among ten very small diameter glass capillaries which are embedded in a clear plastic matrix. Figure 1 illustrates this device.

Before describing the preparation and results obtained with this type of device, we should consider its physical basis. The smooth, laminar flow through a cylindrical tube was described by the French physicist *Poiseuille* (3) by the equation in Figure 2.

Figure 2. Poiseuille's law.

$$Q = \frac{\pi r^4 \Delta p}{8 \eta l} \quad \text{or} \quad \Delta p = \frac{8 \eta l Q}{\pi r^4}$$

where

Q = The volumetric flow rate in cm³/s
r = The tube radius in cm
Δp = The pressure drop in dynes/cm²
η = The fluid viscosity in dyne-s/cm²
l = The length of the tube in cm

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Table 1. Measured and calculated pressure drops (ten .436 mm tube arrays).

Tube length (mm)	Calculated pressure drop (mm H_2O)	Entry and exit correction (mm H_2O)	Total calculated pressure drop (mm H_2O)	Measured pressure drop (mm H_2O)
31	115	30	145	146
65	242	30	272	272
85	315	30	345	342

Since we can determine the flow rate, tube radius, and tube length, and since the viscosity of air is known, we can calculate the pressure drop from these measurable quantities. As indicated in Table 1, these pressure drops have been calculated for a parallel array of ten .436 mm diameter tubes of 31, 65 and 85 mm length. A standard flow rate of 17.5 cm^3/s was used for these calculations and the viscosity of air was considered to be 1.85×10^{-4} dyne-s/cm^2. Since energy must be consumed in channelling the flow of air into and out of the array of capillary tubes, it is not surprising that the pressure drops calculated by *Poiseuille*'s law and those measured should differ by a fixed amount. The difference between the experimentally measured and calculated values, which can be called an entry and exit correction, should be constant for tubes differing only in length. As indicated in Table 1, this appears to be the case. Thus, by a combination of theory and experimentally determined entry and exit corrections, we can determine the pressure drop of a single capillary tube or multiple capillary tubes. The agreement between measured and calculated values is excellent.

One further calculation of interest is a computation of the *Reynolds* number, a dimensionless index used to determine whether flow is laminar or turbulent. For flow in smooth capillary tubes without a sharp entry or exit, smooth or laminar flow can be maintained up to *Reynolds* numbers of 2000. Sharp convergence angles

Figure 3. Calculation of Reynolds numbers.

$$N_{Re} = \frac{d \cdot v \cdot p}{\eta} = \frac{4\,Q\,p}{\pi\,\eta\,d}$$

where

N_{Re} = The Reynolds number (dimensionless)
d = Tube diameter in cm
v = Linear velocity in cm/s
Q = Volume flow in cm^3/s
p = Fluid density = 1.2×10^{-3} g/cm^3 for air
η = Fluid viscosity = 1.85×10^{-4} dyne-s/cm^2 for air

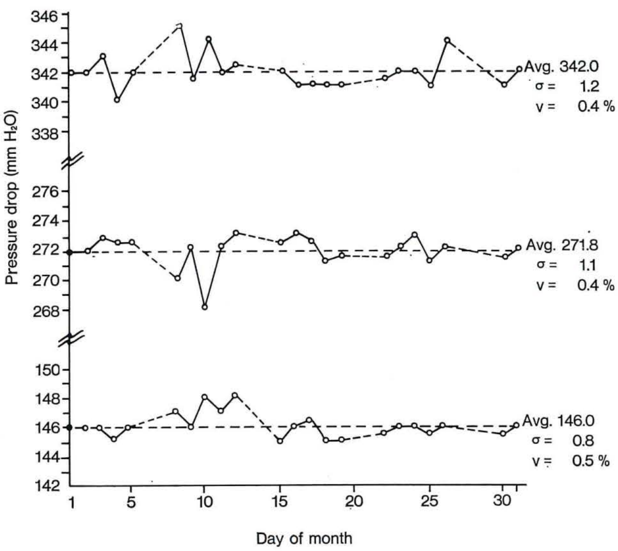
For a single capillary of 5 cm length and 300 mm pressure drop at a flow of 17.5 cm^3/s

$$N_{Re} = 2130$$

For ten parallel capillaries of the same length and pressure drop at the same flow rate

$$N_{Re} = 380$$

Figure 4. Stability of pressure drop standards.



and roughness may reduce this limiting value significantly. As shown in Figure 3, this flow index can be conveniently calculated from the flow rate, tube diameter, and density and viscosity of the fluid.

As indicated, a single tube capillary has approximately five times the *Reynolds* number of a parallel array of ten tubes, and is in the sensitive region where turbulent flow can occur. The *Reynolds* number of the ten-tube array is sufficiently low so that laminar flow should always exist.

The construction of a ten-capillary-tube array is relatively straight forward. Details of the construction and care of these devices are given in the second chapter.

To demonstrate the properties of this type of multiple capillary tube standard, the pressure drops of the three tubes in Table 1 were measured for a period of one month. The pressure drops as measured on each working day are plotted in Figure 4. The average pressure drops for the three tube arrays were 342, 272, and 146 mm. Over this period of time, random variability gave a standard deviation of 1.2 to 0.8 mm about this mean, which is 1/2 % of the mean value or less. Of the 63 values measured during this period, only 8 were more than 1 mm away from the average and only 2 were more than 2 mm away, which is slightly better than the statistically computed 95 % confidence limit of plus or minus 2 mm. It is thought that this very slight variability is entirely random and probably results from measurement error on the part of the two operators making these measurements. Possibly more significant is the fact that the tubes were not cleaned during this period, and were not specially protected during the measurement. Between measurements the tubes were stored in a small plastic box and no microscopically visible dirt or dust contamination was found at the end of the trial period.

Recleaning the tubes and the critical flow orifice in the pressure drop machine at the end of the experiment gave good results. Although no difficulty in cleaning

Table 2. Effect of temperature and humidity on capillary tube array pressure drop standards.

Location	Temperature (°C)	Humidity (% R. H.)	Pressure drop (mm H_2O)			
			#1	#2	#3	#4
Inside	23.3	68	229	342	273	147
Outside	17.2	74	228	340	272	146
Inside	22.8	69	230	344	274	148

the orifice was encountered, it was found that cleaning the capillary tube array could lead to damage of the tubes or deposition of detergent, as indicated by microscopic examination and a change in pressure drop. A satisfactory cleaning procedure, consisting of ultrasonic cleaning in a mild detergent solution followed by a two-hour percolation of distilled water through the tubes, gave no change in pressure drop (see second chapter for a simplified cleaning procedure). A tube array with an initial pressure drop of 330 mm had a pressure drop of 329 mm after one cleaning and 328 mm after two cleanings.

The effects of ambient conditions were also briefly investigated. In one test, summarized in Table 2, four tube arrays were measured inside and outside the laboratory at different temperatures and humidities. Although, as expected, there appears to be a slight temperature effect, this is no greater than the random variability of this range of conditions. In a second test, both sides of the standard and the pressure drop measuring apparatus were subjected to elevated and reduced pressures by commonly connecting them to a tank with a regulated internal pressure. The results of this experiment are given in Table 3. A slight pressure effect was noted, amounting to an increase of .63 mm in pressure drop or .3 % of the base value per 10 mm change in ambient pressure. This effect is not too surprising since the kinetic energy or entry and exit corrections should depend on the density of the air entering. Possibly of more direct interest is the fact that the measured pressure drops did not change more than plus or minus 4—5 millimeters over this pressure range, which encompasses most laboratory pressure levels.

Table 3. Effect of ambient pressure on a capillary tube array pressure drop standard (ambient pressure 772 mmHg).

Difference from ambient (mmHg)		Pressure drop (mm H_2O)
−60		224
−40		226
−20		228
	Start of experiment	229
0	Middle of experiment	228
	End of experiment	229
+20		230
+40		231
+60		232

In summary, a simple multiple capillary tube pressure drop standard has been fabricated. This device gives pressure drops which agree well with theoretically calculated pressure drop values. A one-month test under normal laboratory conditions gave a low statistical variability of 0.5 % or less. Overtly changing the laboratory conditions showed that temperature and humidity had little effect on the pressure drop of the standard but that atmospheric pressure had a slight positive correlation with this quantity.

CONSTRUCTION AND CARE OF MULTIPLE CAPILLARY PRESSURE DROP STANDARDS

1. *Construction*

Clean borosilicate glass tubing of 3 to 6 mm inside diameter was drawn on a Hupe glass drawing machine (Hupe & Busch, D-7501 Grötzingen, Karlsruhe, W. Germany) into 1 meter straight lengths of capillary tubing of .4 to .6 mm/inside diameter. Depending on the initial tube diameter, draw ratios between 14:1 and 21:1 were utilized to achieve the desired diameter. During the drawing operation it is desirable to occasionally check the inside diameter of the drawn capillary by microscopic examination of small segments of the tube. As a guide for the preparation of standards within desired pressure drop ranges, Table 4 lists pressure drop as a function of tube diameter for arrays of ten 120 mm capillary tubes.

After drawing, the capillary tubes were broken into 31-centimeter lengths, the ends sealed off by drawing in a pin point gas flame, and stored for mounting in the plastic matrix.

For casting, ten 30 cm glass capillaries were mounted on 10 tooth brass pinion gear splines [approx. outside diameter 1/4 in. (.64 cm), 48 pitch, 14.5° pressure angle] in a 29 cm length of clean cellulose butyrate tubing [5/16 in. (.79 cm) outside diameter, 1/4 in. (.64 cm) inside diameter]. The plastic tubing is available from

Table 4. Pressure drop vs. capillary tube diameter (ten 120 mm tubes).

Tube diameter (mm)	Pressure drop (mm H_2O)
.40	631
.42	519
.44	431
.46	360
.48	304
.50	258
.52	221
.54	190
.56	164
.58	143
.60	125

Cadillac Plastic and Chemical Co., 3100 South Boulevard, Charlotte, N. C., 28210, USA, and the pinion gear from Boston Gear Division, North American Rockwell, 14 Hayward Street, Quincy, Mass., 02171, USA. The pinion gear stock was cut into 1 cm lengths, and an 1/8 in. (.32 cm) hole drilled axially through each length, and all burrs removed. Two of the pinion gear splines were placed in one end of the plastic tubing, the outer one being secured by a twist of wire squeezing on the outside of the plastic tube. A length of glass capillary was placed in each of the ten teeth of the splines and the free spline was moved to the opposite end of the tube along the inserted capillaries. This end was then capped off with a rubber septum and the array of ten capillaries inside the plastic tube was mounted vertically with the septum downward.

A 25 ml batch of Crystal Clear Polyester Casting Resin containing 6 drops of catalyst was prepared. The resin and catalyst are available from Fibre-Glass-Evercoat Co. Inc., Cornell Road, Cincinnati, Ohio, 45242, USA. The thoroughly mixed but bubble-free resin was injected by a hypodermic syringe with a coarse needle through the septum to fill the plastic tube. After bubbles have risen to the upper surface of the filled vertical tube, the needle is removed and the tube was suspended in an oven at 95–100° C for 15 minutes. After curing the tubes were removed and allowed to cool and examined for flaws such as separation of the resin from the tubes. Tubes without separations or bubble channels or resin cracking are suitable for use as standards.

The cured tubes were cut into 120 mm lengths (or other lengths if desired) on a glass saw and tube ends were slightly beveled. The cut ends were examined for rough cuts on the embedded glass capillary tubes and for separation of tubes from the plastic matrix. Acceptable tubes were cleaned as described below, labelled, and calibrated.

2. *Cleaning and Calibration*

The exterior of the tube assemblies are cleaned by washing in a mild detergent solution (1 to 2 % liquid detergent in distilled water). The capillaries are cleaned by attaching the assembly to a water aspirator or suitably trapped vacuum system and repeatedly dipping the open end of the tube into the detergent solution, thereby drawing cleaning solution through the capillaries. This is immediately followed by a similar repetitive rinsing in distilled water to remove the detergent and allowing clean air to be drawn through to dry the tubes. The exterior is dried with a clean lint-free towel. Organic solvents and corrosive cleaning solutions should not be used as they will attack the plastic exterior of the tube assembly. After cleaning, the tube ends and bores should be examined with a magnifying glass for trash and dirt.

Calibration should be accomplished by placing the tube array in a freshly calibrated pressure drop apparatus providing a corrected flow of 17.5 ± .05 ml/s of air at an atmospheric pressure of 760 Torr at a temperature of 22° C and humidity of 60 ± 3 % relative humidity (R.H.) (*Coresta* Standard Conditions). The pressure drop should be read 10 times (over several hours) with the tube inserted from either end, and the results averaged to provide the calibration value. If the individual values differ by more than 2 to 3 mm from each other, the pressure drop apparatus should be checked for leaks, and the standard recleaned.

Three standards covering a range of pressure drops should be assembled and boxed in a clean, dust-free container which does not touch the tube ends. This will provide a set of standards for checking pressure drop measuring devices.

3. *Normal Care and Precautions*

Because of the high velocity of air flow through the standards, there is little chance that airborne particles will deposit in the capillary tubes. The critical places, which should be examined frequently with a magnifying glass, are the entry and exit of the capillaries as deposition can occur at these points. In use, the standards should be handled without touching the ends to avoid dirt or oil deposits. They should be lightly held to avoid warming the tubes. Excessively dusty or dirty atmospheres should be avoided, and if such usage is necessary, the calibration should be checked frequently in a clean atmosphere. The standards are rugged, and will withstand normal handling and occasional droppage. If such occurs, the standard should be visually examined for damaged tube ends. The standards should be cleaned and the calibration checked at least every six months, and should be protected from exposure to organic and corrosive solvents and vapors.

SUMMARY

This paper describes a simple device, consisting of a collection of glass capillary tubes, which can be used as a stable, pressure insensitive standard for calibrating pressure drop machines.

For air flowing through a single capillary tube of the proper dimensions to give a pressure drop similar to that of a filter rod, the *Reynolds* number is about 2000, the boundary between laminar and turbulent flow. Since turbulent flow gives pressure drops which vary with atmospheric pressure, it is desirable to reduce this quantity to a level where laminar flow is always present. This can be accomplished by distributing the flow among 10 parallel capillaries of very small diameter.

The capillaries were formed by drawing pyrex tubing on a Hupe glass drawing machine to a finished internal diameter of .44 mm. Ten lengths of this capillary were mounted in 8 mm tubing and were encased in a clear resin. After polymerization of the resin, the composite rod was sawed into appropriate lengths and cleaned in an ultrasonic bath. Microscopic examination of the finished tubes showed that each capillary was a clean, smooth-walled tube with a sharp entrance and exit. Calculation of the *Reynolds* number for the composite

capillary gave a value of 314, which is well within the laminar flow region.

The agreement between measured pressure drops of these standards and those calculated using *Poiseuille's* law with an entry and exit correction is excellent.

Daily measurements of the pressure drop of these standard tubes for a period of a month were conducted, and the random variability was found to be 1% or less. Measurements of the pressure drop of these tubes at various pressures and temperatures covering the range of normal laboratory conditions also demonstrated a lack of significant variability. Fouling of the tubes from atmospheric dust was not found to be a significant factor.

ZUSAMMENFASSUNG

Die vorliegende Arbeit beschreibt ein einfaches Gerät, das aus einer Kombination von Glaskapillaren besteht und als stabiler, druckunabhängiger Standard bei der Eichung von Apparaturen zur Messung des Zugwiderstandes dienen kann.

Wenn Luft eine einzelne Kapillarröhre durchströmt, die so bemessen ist, daß der Druckabfall demjenigen eines Filterstabes gleicht, so beläuft sich die *Reynolds*-Zahl auf etwa 2000, dem Grenzwert zwischen laminarer und turbulenter Strömung. Da sich der Zugwiderstand bei turbulenter Strömung mit dem Luftdruck verändert, erscheint es wünschenswert, diese Größe auf einen Wert zu vermindern, bei dem laminare Strömung ständig vorhanden ist. Dies kann dadurch erreicht werden, daß der Strom auf zehn parallele Kapillaren sehr kleinen Durchmessers aufgeteilt wird.

Die Kapillaren wurden mit einem inneren Durchmesser von 0,44 mm aus Pyrexglas auf einer Hupe-Kapillarziehmaschine gezogen. Zehn Längen dieser Kapillaren wurden in ein 8-mm-Rohr eingesetzt und mit durchsichtigem Harz umkleidet. Nach Polymerisation des Harzes wurde der zusammengesetzte Stab in geeignete Längen gesägt und in einem Ultraschallbad gereinigt. Bei mikroskopischer Untersuchung dieser Stäbe erwies sich jede Kapillare als ein reines, mit ebener Wandung und mit scharfkantigem Ein- und Ausgang versehenes Rohr. Die Berechnung der *Reynolds*-Zahl für den Verbundstab ergab den Wert 314, der sich vollauf im Bereich der laminaren Strömung befindet.

Die Werte für den Druckabfall, die sich durch Messung in diesen Standardkapillaren ergaben, stimmen mit jenen sehr gut überein, die unter Benutzung des Gesetzes von *Poiseuille* mit Ein- und Ausgangskorrektur berechnet wurden.

Der Druckabfall wurde in den Standardkapillaren während eines Zeitraumes von einem Monat täglich gemessen, wobei sich eine Zufallsschwankung von 1% oder weniger ergab. Auch wenn bei unterschiedlicher Temperatur und unterschiedlichem Luftdruck über die gesamte Spanne normaler Laboratoriumsbedingungen gemessen wurde, war keine signifikante Schwankung zu beobachten. Die Verschmutzung der Rohre durch atmosphärischen Staub erwies sich als nicht signifikant.

RESUME

On décrit dans cet article un dispositif simple qui consiste en une série de tubes capillaires de verre et peut être utilisé comme étalon stable et indépendant de la pression pour le calibrage d'appareils mesurant la résistance au tirage.

Lorsqu'on fait passer de l'air dans un capillaire unique, de dimensions telles qu'il reproduit la résistance au tirage d'un bâtonnet-filtre, le nombre de *Reynolds* est d'environ 2000, ce qui est la limite entre l'écoulement turbulent et l'écoulement laminaire. Le régime turbulent donnant des différences de pression qui varient en fonction de la pression atmosphérique, il est préférable de réduire cette valeur à un niveau tel que seul le régime laminaire soit présent. On peut obtenir ceci en distribuant le flux sur 10 capillaires parallèles de très faible diamètre.

On a fabriqué ces capillaires sur une étireuse Hupe, en étirant des tubes de pyrex jusqu'à obtenir un diamètre intérieur de 0,44 mm. Un faisceau de dix capillaires a été monté dans un tube de 8 mm, dans lequel on a coulé une résine transparente. Après polymérisation de la résine, le faisceau a été découpé en tronçons de longueur appropriée, et nettoyé aux ultrasons. L'examen microscopique a révélé que chaque capillaire était un net tube aux parois lisses, avec une entrée et une sortie à angles vifs. Le calcul du nombre de *Reynolds* pour le faisceau de capillaires a donné une valeur de 314, ce qui est largement dans la région du régime laminaire.

La concordance entre les différences de pression mesurées avec ces étalons et celles calculées à l'aide de la loi de *Poiseuille* en tenant compte d'une correction d'entrée et de sortie est excellente.

Des mesures quotidiennes de la différence de pression de ces étalons ont été relevées pendant une durée d'un mois, et l'on a trouvé une variation aléatoire égale ou inférieure à 1%. On a également mesuré la résistance au tirage de ces tubes à différentes pressions et températures, dans les zones habituelles au laboratoire. On n'a pas trouvé de variabilité significative. L'encrassement des tubes par les poussières atmosphériques ne joue pas de rôle significatif.

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