The commissioning of a test facility for the calibration of anemometers

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SYNOPSIS

After the erection of a commercially produced open-jet wind tunnel for the calibration of the anemometers used in mine ventilation, the wind tunnel was calibrated for routine use. There is a choice of five orifice plates, which, together with a variable-speed fan, can give a measurable range of air velocities in the test section from about 0,05 to 35 m/s. The orifice plates were calibrated against a standard pitot tube, and it is now necessary only to measure the pressure drop across an orifice plate and to read off, from a set of graphs, the true outlet velocity in the test section. The paper describes the underlying theory and the test results.

SAMEVATTING

Na die oprigting van 'n handels-verskafde oopstraal windtonnel vir die kalibrering van anemometers wat in mynventilasie gebruik word, is dit ge-yk vir roetine gebruik. Daar is 'n keuse van vyf plaatmondstukke wat, tesame met 'n veranderlike spoed waaier, 'n meetbare lugsnelheid in die toets seksie kan gee van tussen ongeveer 0,05 en 35 m/s. Die plaat mondstukke is ge-yk teen 'n standaard pitotbuis en in die praktyk is dit nou slegs nodig om die drukval oor 'n plaat mondstuk te meet om sodoende vanaf 'n stel grafieke diewerklike lugsnelheid indie toets seksie te lees. Die referaat gee die onderliggende teorie asook toets resultate.

INTRODUCTION

The Department of Mining Engineering of the University of Pretoria recently acquired the necessary equipment for the testing of anemometers. This paper describes the work done before this test facility could be put to routine use.

DESCRIPTION OF APPARATUS

The open-jet wind tunnel consists of a single-inlet centrifugal fan driven by a 1,7 kW, 3000 rev/min, shunt-wound, continuously rated motor, wound for 210 V d.c. The motor is controlled by a Neco-Servotec variable-speed controller wound for 220/240 V, 50 to 60 cycles a.c. Air velocities can be varied by variation of the speed. The fan feeds air into a pipe of 0,20 m diameter fitted with a quick-action clamp for the changing of orifice plates. Five orifice plates are supplied with the equipment with diameters of 0,0158 m, 0,0323 m, 0,0721 m, 0,1016 m, and 0,1638 m. These orifice plates, coupled with the speed variation of the fan, produce an extremely flexible test set-up. Inspection of the orifice plates indicated that they complied with the requirements for plate orifices with corner tappings as specified in B. S. 1042[1].

The air passes through a honeycomb air straightener whose main purpose is to eliminate whirling. This causes a velocity distribution on the down-stream side that approaches fully developed pipe flow[2] in a final contraction section and outlet nozzle (see Fig. 1). This section ends in a circular, sharp-edged nozzle through which the air passes at test velocity, maintaining an essentially parallel flow for some distance beyond (see Fig. 2).

A standard N.P.L. pitot tube is supplied with the equipment, and pressure readings are done with the Mk4 high-precision, inclined manometer assembly, which incorporates two adjustable manometers giving the ranges shown in Table I. The manometers are filled with red manometer fluid, which has a specific gravity of 0,787, and are already calibrated to give readings in millimetres water gauge. The anemometer under test is mounted on a rotatable support and can be centralized in the air stream without affecting the discharge from the nozzle.

TEST PROCEDURE AND THEORY

Pitot traverses were done at the outlet concurrently with pressure-drop measurements across the various orifice plates for different velocity settings. The velocity profile across any traverse is sensibly flat with a sharp cut-off at the boundary, thus creating a free air stream of 0,1524 m diameter with an even velocity (see Fig. 3).

The pitot tube is one of the most basic instruments used in the determination of velocity, and hence airflow. It was therefore decided to accept the results obtained by pitot traverses as correct, and to adapt the airflow formula for orifice plates accordingly.

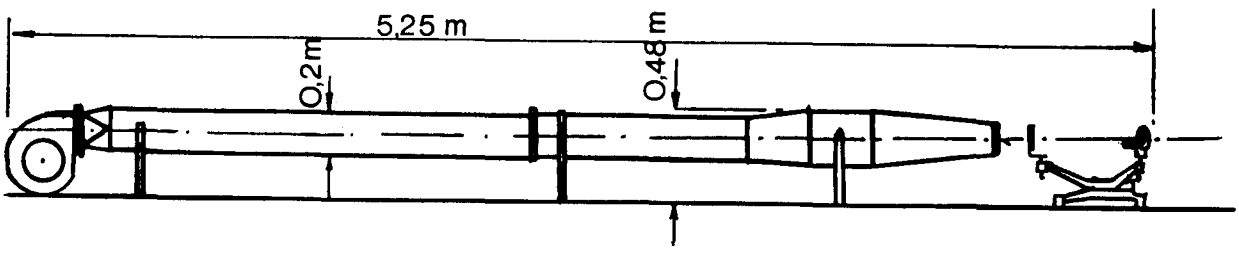

Fig. 1—Arrangement of wind-tunnel assembly

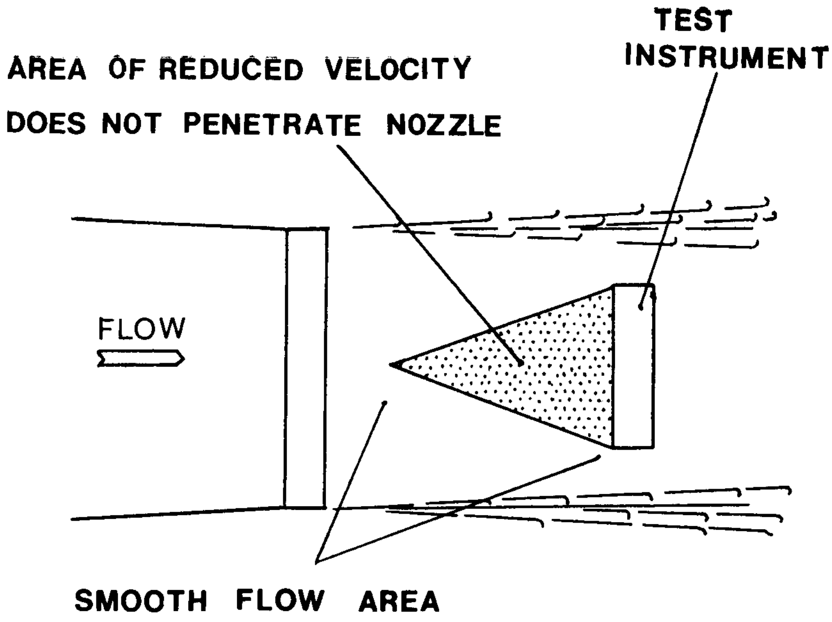

Fig. 2—Substantially parallel flow at outlet

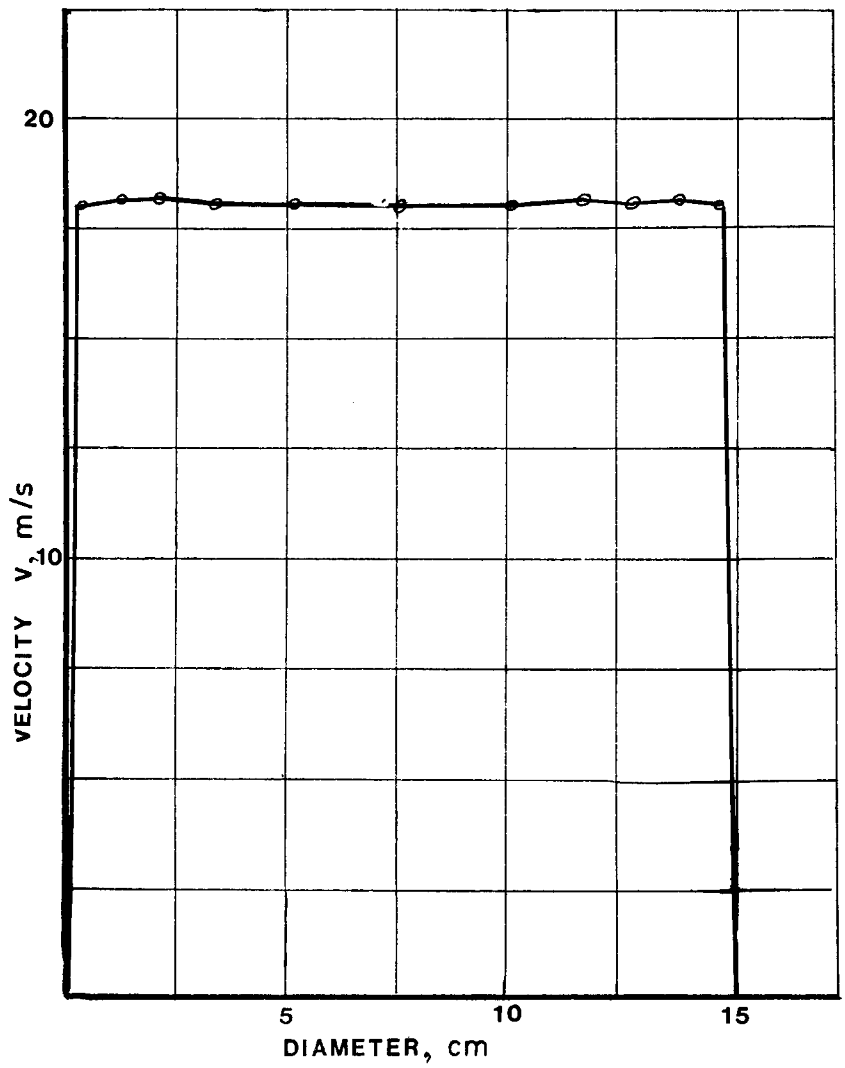

Fig. 3—Typical velocity profile across a diameter

The pitot tube formula is

$$V=\sqrt{\frac{2Pv}{\rho}},$$

where V = velocity, m/s
Pv = velocity pressure, Pa
ρ = density, kg/m³.

In practice, velocity pressure was measured in millimetres watergauge and the appropriate conversion factor was applied.

The formula used for the orifice plate was derived from B.S. 1042[3] as

$$Q=91{,}1951\ C\ Z\ d^2\ E\ \sqrt{h}\ \sqrt{\rho}\ \text{air}. \quad \ldots\ldots\ (1)$$

By substitution of $\rho=0{,}0034837\ \frac{P}{T}$ for dry air and application of a correction factor N for moisture,

$$Q=5{,}38261\ C\ Z\ d^2\ E\ \sqrt{h}\ \sqrt{\frac{P}{T}}\ N, \quad \ldots\ (2)$$

where C = co-efficient of discharge (dimensionless)
Z = combined multiplier incorporating the correction for compressibility ϵ, correction factor for R_D, and the correction for diameter D (dimensionless) see Appendix
d = diameter of orifice plate, m
E = velocity of approach factor $=\sqrt{\frac{1}{1-m^2}}$ (dimensionless, see Table IV)
h = pressure drop over orifice plate in m w.g.,
P = absolute pressure in Pa,
T = absolute temperature in °K, and
N = correction factor for moisture (dimensionless).

The static pressure inside the pipe is not equal to the barometric pressure, P, but is actually $P+P_s$, with P_s the static pressure above or below atmospheric pressure. Because P_1 typically takes a value in the vicinity of 87,5 kPa at the test site and because the square root of the pressure appears in the flow formula, it is clear that P_s can have a value of up to 1,75 kPa (that is 2 per cent of P) without causing an error in Q, as determined from equation (2),

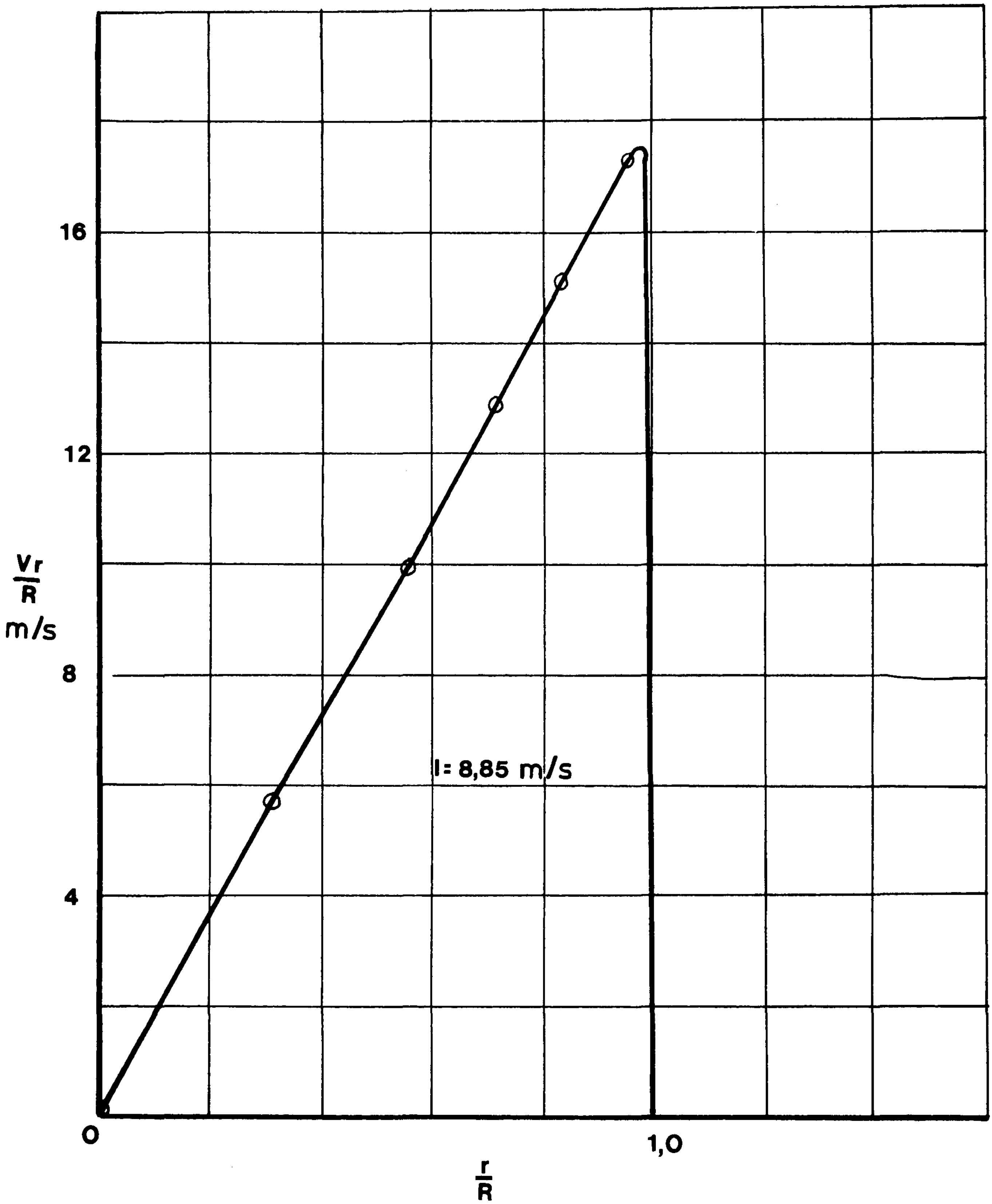

Fig. 4—Determination of I by planimeter integration

of more than 1 per cent[4]. It is therefore satisfactory to regard the static pressure inside the pipe as being the same as the atmospheric pressure.

An advantage of the orifice plate is the large pressure drop across the plate. British and German codes, however, specify that values of $\frac{P_2}{P_1}$ smaller than 0,8 and 0,75 respectively are not to be used, with P_2 the pressure at the downstream side and P_1 the pressure at the upstream side of the orifice plate. The reason for this is that values of the compressibility factor ϵ are not standardized at lower values of $\frac{P_2}{P_1}$. This can be overcome by the use of suitable values for m, where $m = \frac{\text{area of orifice plate}}{\text{area of pipe}}$.

Orifice plates with suitable m values are supplied to cover the entire range from 0 to 35 m/s.

It is necessary when working to a high degree of accuracy that only the effect of moisture and the change in density be taken into account. It will generally be found that the correction for humidity, N, will not exceed 1 per cent, and the error in the velocity, if the effect of humidity on density is neglected, will normally not exceed 0,5 per cent[5].

The airflow, Q, was determined by measurement of the velocity distribution across the open jet and by graphical integration of the velocity profile[6].

With V known, the volumetric flow, dQ, through a ring element can be written as

$dQ = 2\pi \, r \, V \, dr.$

Hence, for the entire jet surface,

$$Q = 2\pi \int_0^R r \, V \, dr$$

$$= 2\pi R^2 \int_0^1 \left(\frac{r}{R}\right) V \, d\left(\frac{r}{R}\right)$$

$$= 2 \text{ x area of jet x } I.$$

Integral I is obtained by the plotting of $V\left(\frac{r}{R}\right)$ against $\left(\frac{r}{R}\right)$ and determination of the area underneath the curve by means of a planimeter (see Fig. 4).

TABLE I

RANGES OF THE ADJUSTABLE MANOMETERS

	Long tube mm	Short tube mm
Vertical position	500	250
Upper inclined position	100	50
Middle inclined position	—	25
Lower inclined position	50	12,5

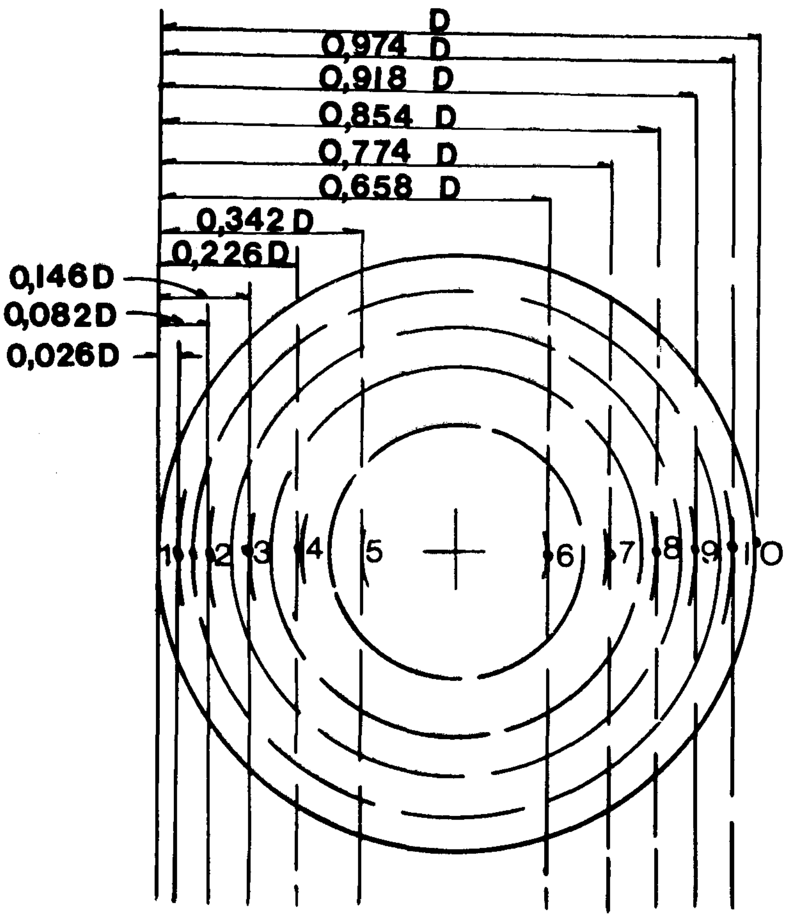

Fig. 5—Equal ring-element areas for velocity measurements

TEST PROCEDURE

In the practical determination of the velocity distribution, the pitot static tube was set systematically on different radii so that a complete profile could be obtained across a diameter of the nozzle. Velocity measurements were taken on equal ring-element areas according to B.S. 1042 (Fig. 5) across the horizontal and vertical diameters.

The barometric pressure was taken at the commencement of each day's experimental work, a whirling hygrometer being placed in the airstream behind the pitot tube so that the wet- and dry-bulb temperatures could be read. The density was read off a chart by use of the appropriate barometric pressure and wet- and dry-bulb temperatures.

During the traverses, the pressure difference across the orifice plate was kept constant by means of the variable-speed controller.

SAMPLE CALCULATION

I_{AV} (as obtained from Fig. 4) $= 8{,}843$ m/s.

$Q_T = 2A \times 1$

$= 2 \times 0{,}018232 \times 8{,}843$

$= 0{,}322451 \; m^3/s.$

V_{AV} according to traverses $=$

$$V_T = \frac{Q}{A} = 17{,}686 \text{ m/s.}$$

V_{AV} in the test section, according to readings on the pitot static tube $= V_r = 18{,}161$ m/s.

$$\frac{V_R}{V_T} = 1{,}0269$$

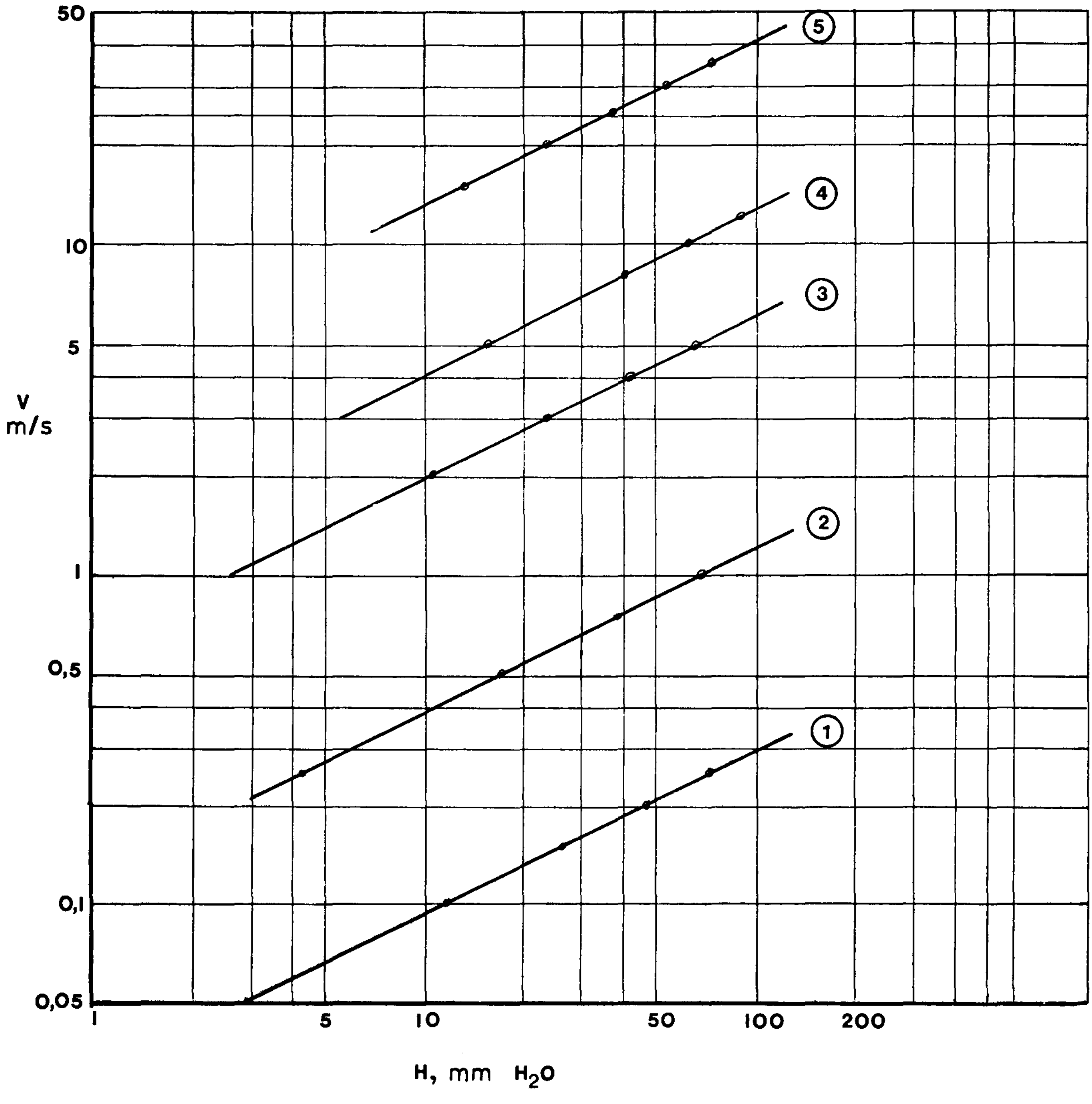

Fig. 6—Final calibration curves for five orifice plates (density 1,03 kg/m³)

Q is determined according to the orifice-plate formula

$$Q_P = 5{,}38261\ C\ Z\ d^2\ E\ \sqrt{h}\ \sqrt{\frac{P}{T} \times N},$$

where $C = 0{,}579$ (dimensionless)
$Z = 1{,}002$ (dimensionless)
$d^2 = 0{,}026830\ m^2$
$E = 1{,}342836$ (dimensionless)
$P = 87370$ Pa
$T = 292{,}4$ K
$N = 0{,}994$ (dimensionless)
$h = 0{,}0198$ m
Q_P = volume flow = 0,272016 m³/s.

Therefore, $\frac{Q_T}{Q_P} = 1{,}1854$.

SUMMARY OF RESULTS

The results are summarized in Tables II and III.

The formula recommended for the specific tunnel thus becomes

$$Q = (1{,}1798)\ (5{,}38261)\left(C\ Z\ d^2\ E\ \sqrt{h} \sqrt{\frac{P}{T}\ N}\right)$$

$$= 6{,}3504\left(C\ Z\ d^2\ E\ \sqrt{h} \sqrt{\frac{P}{T}\ N}\right).$$

However, the purpose is to determine the velocity in the region of the anemometer to be calibrated. If the factor $\frac{V_r}{V_T}$ (=1,024) is taken into account,

$$V = \frac{Q}{A} = 1{,}024 \times \frac{6{,}3504}{0{,}018232}\left(C\ Z\ d^2\ E\ \sqrt{h} \sqrt{\frac{P}{T} N}\right)$$

$$= 356{,}6703\ C\ Z\ d^2\ E\ \sqrt{h}\ \sqrt{\frac{P}{T}\ N}.$$

The calibration process can be simplified considerably if a standard density of air is assumed. An investigation of density values throughout the year has indicated that a value of 1,03 kg/m³ (for the test site in Pretoria) can be assumed to be fairly representative of the air density. If this value is substituted in equation (1) and the factors $\frac{V_r}{V_T}$ and $\frac{Q_T}{Q_P}$, are taken into account,

$$V = 6132{,}877\ C\ Z\ d^2\ E\ \sqrt{h},$$

i.e., for a given orifice plate, V is a constant $\sqrt{h}$. Therefore, the graphs of V versus h for every orifice plate offer a simple method for the calibration of anemometers. A small-scale facsimile of the final set of straight-line calibration curves is reproduced in Fig. 6. In practice only one, or perhaps two, of the curves will be needed to cover the range of a particular anemometer being calibrated.

TABLE II
VOLUME FLOW

I m/s	Q_T m³/s	Q_P m³/s	$\frac{Q_T}{Q_P}$
8,843	0,322451	0,272016	1,1854
11,64	0,424441	0,357875	1,1860
14,72	0,536750	0,457884	1,1702
17,25	0,629004	0,534266	1,1773
6,135	0,223707	0,189435	1,1809
4,753	0,173313	0,146589	1,1823
2,443	0,089082	0,075712	1,1766
1,202	0,043830	0,038323	1,1437
			1,1798 average

TABLE III
VELOCITY

$V_T = V$ average according to traverses	$V_r = V$ average according to pitot readings	Factor $\frac{V_r}{V_T}$
17,686	18,161	1,027
23,280	23,909	1,027
29,440	29,996	1,019
34,500	34,939	1,013
12,270	12,549	1,023
9,506	9,740	1,025
4,886	5,034	1,030
2,404	2,465	1,025
		1,024 average

TABLE IV

Orifice plate	d m	d^2	$m = \frac{d^2}{D^2}$	$E = \sqrt{\frac{1}{1-m^2}}$	C (taken from ref. 1)
1	0,0158	0,000250	0,006219	1,000019	0,596
2	0,0323	0,001043	0,025945	1,000337	0,596
3	0,0721	0,005198	0,129303	1,008466	0,601
4	0,1016	0,010323	0,256778	1,034693	0,604
5	0,1638	0,026830	0,667408	1,342836	0,579

REFERENCES

1. British Standards Institution. *Flow measurement.* B.S. 1042. 1943. p. 7.
2. Ower, E., and Pankhurst, R. C. The measurement of air flow. 4th Edition. London, Pergamon Press. p. 197.
3. British Standards Institution. *op cit.*, p. 24.
4. *Ibid.*, p. 130.
5. *Ibid.*, p. 350.
6. University of Pretoria, Department of Mechanical Engineering. *Yking van plaatmondstuk.* MG. 3/69/1.

APPENDIX

Diameter of nozzle = 0,1524 m
Area of nozzle = 0,018232 m²
Diameter of tunnel = D = 0,2005 m
D^2 = 0,0402003 m²

Determination of R_D

The following formula was used in the determination of R_D:

$$R_D = 15{,}305\ \frac{Q}{d\ \eta},$$

where Q = airflow in m³/s
d = diameter of orifice
η = absolute viscosity of air at room temperature in P $= 180 \times 10^{-6}$ P at 20 °C.

Determination of Z

$Z = \epsilon \times$ factor for $R_D \times$ factor for D. ϵ, R_D, and D are obtained from appropriate graphs[1].