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VISCOSITY OF STEAM AT ATMOSPHERIC PRESSURE

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Abstract—This paper gives the experimental results of the measurement of the viscosity of steam at atmospheric pressure in the temperature range 110–1071 °C. This work was instigated because of the lack of agreement among the results of earlier workers in the range 100–600 °C, the relatively few observations above 600 °C, and the need to obtain reliable atmospheric values for the correlation of the high pressure measurements. It is believed that the results reported here adequately meet these demands.

Two apparatus were designed and developed, both of which were transpiration capillary type viscometers enabling absolute determinations to be made. The design of the apparatus was such that the capillary bores could be checked before and after use and that capillaries of different lengths and bores could be introduced.

The first apparatus, which was a single capillary glass viscometer, was developed as a prototype for the second apparatus. Two different capillaries having approximately the same length, were used used over the temperature range 110–460 °C.

The second apparatus, which was made of quartz, utilized two capillaries in series. Three of which had a different ratio of the lengths of the capillaries in a set, to the other three. The apparatus was used over the temperature range 110–1071 °C.

Over 500 separate observations are reported and the accuracy of the recommended values is thought to be better than 2 per cent. A fifth degree polynomial in the temperature and a Sutherland type equation have been fitted to the results of the present work.

NOMENCLATURE

A,	constant;
B,	constant;
c,	constant in the Sutherland equation;
C,	constant;
d,	diameter [mm];
D,	constant;
E,	constant;
f,	buoyancy correction $= \frac{\{1 - \rho_a/\rho_{wt}\}}{\{1 - \rho_a/\rho_w\}}$;
F,	constant;
g,	acceleration due to gravity [cm/s^2];
K,	Sutherland constant [°K];
l,	length [mm];
L,	mean free path of fluid molecules;
m,	end correction constant;
P,	pressure [kgf/cm^2];
ΔP,	pressure drop [kgf/cm^2];
Q,	mass flow rate [g/s];
Re,	Reynolds number $= v\rho d/\eta = 4Q/\pi d.\eta$;
t,	temperature [°C];
T,	absolute temperature [°K];
v,	velocity [cm/s];
V,	volume flow rate [cm^3/s];
V_s,	specific volume [cm^3/g].

Greek symbols

α,	coefficient of liner expansion [/degC];
ϵ,	coefficient of slip $= cL$;
ρ_a,	density of damp air [g/cm^3];
ρ_{wt},	density of weights on micro balance [g/cm^3];
ρ_w,	density of water [g/cm^3];
η,	coefficient of viscosity [poise-g/cm s].

LITERATURE SURVEY

DETERMINATIONS of the viscosity of steam at atmospheric pressure have been made by Smith [1], Bonilla [2], Braune and Linke [3] and Shifrin [4]. Measurements of the viscosity at high pressures have been made by Schiller [5], Sigwart [6], Speyerer [7], Schugajew and Sorokin [8], Timrot and Khlopkina [10], Jackson *et al.* [11], [12], [13], Kestin *et al.* [14], Hawkins *et. al.* [15], Kjelland-Fosterud [16], Mayinger [17],

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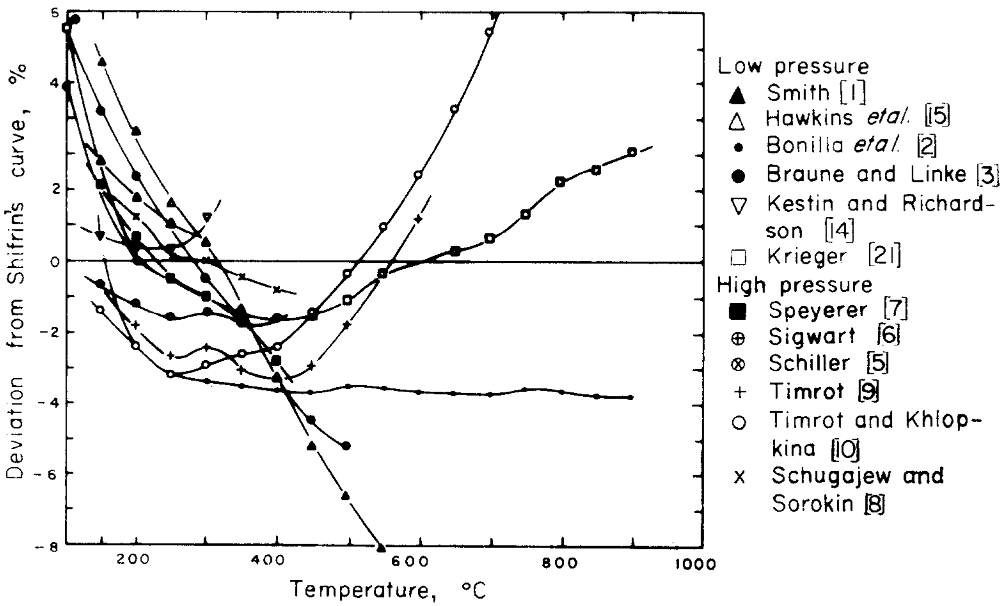


FIG. 1. Deviation plot for relevant results for the 1 atm curve.

Whitelaw [18], Ray [19] and Tanaka *et al.* [20], to mention the more prominent workers. Figure 1 shows the deviation of the atmospheric results from Shifrin's equation, $\eta = (80{\cdot}4 + 0{\cdot}407\ t) \times 10^{-6}$ poise, where t is the temperature in °C, including the more conveniently extrapolated high pressure data. The majority of the high pressure data has not been included because extrapolation to atmospheric pressure could not be achieved with reasonable accuracy. The semi-empircal work of Krieger [21], who used a modified Stockmayer potential equation and computed values for the viscosity of steam at atmospheric pressure, based on the experimental data of Braune and Linke [3], Smith [1], Schugajew and Sorokin [8], Timrot [9] and Keyes [22], is also included in the plot. It is apparent that there is considerable deviation of the present available atmospheric data over the temperature range 100–500°C, even when the more dubious extrapolated high pressure data is excluded the deviation is of the order of 9 per cent. There is also an obvious lack of data for the viscosity at temperatures above 600°C.

DESCRIPTION OF APPARATUS

In the following description apparatus (1) and apparatus (2) will refer to the single capillary and the series capillary apparatus respectively A diagrammatic sketch of the apparatus is given in Fig. 2.

Boiler

The boiler B was a glass cyclone type, having a capacity of about 1 l. for the first apparatus and about 1·5 l. for the second apparatus. In both of the apparatus the boiler control heater was a nichrome spiral wound on a 20 mm o/d glass tube. This type of heater was found to be the most suitable of several types tried in an attempt to reduce the amplitude of the overpressure fluctuations, and increase the fluctuation frequency. Although it was not tried for the work described here, it was noted that Collins and Keyes [23] stated that they obtained good pressure stability using a floating heater. The control heater, used in this present work, was situated in a side arm on the boiler. A mercury-in-glass control manometer, having a probe connected to an electronic relay was used to keep the boiler pressure at a desired value by "switching in or out" of the circuit a rheostat which was in series with the control heater. Using this control system the power to the heater was varied by about 1 per cent which was sufficient to keep the amplitude of the boiler overpressure fluctuation to within 0·5 mm Hg.

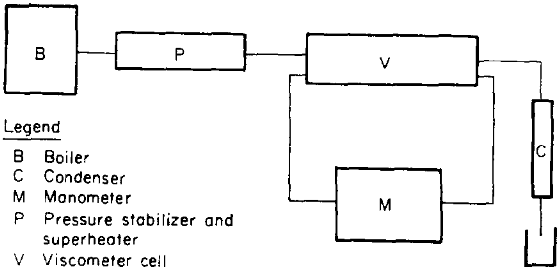


FIG. 2. Diagrammatic sketch of the apparatus layout.

Superheater and pressure stabilizer

The superheater and pressure stabilizer P (see Fig. 3) was connected in series with the boiler and the viscometer. The design was based on suggestions given by Novak [24] who used a similar stabilizer for gas chromotography systems. The stabilizers were made of Pyrex glass for apparatus (1) and quartz for apparatus (2). The design of the stabilizer was such that the damping of the pressure fluctuations was approximately 100:1, i.e. with an overpressure amplitude of 0·5 mm Hg at the boiler the amplitude was expected to be damped to 0·005 mm Hg at the entrance to the viscometer. In practice it was found that the amplitude was very small, in actual fact it was too small to be measured with the manometer.

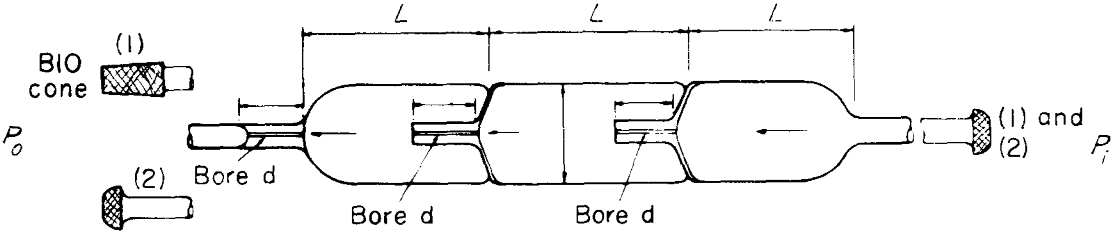
The superheater furnace was tubular and heated electrically using a single winding of Brightray H wire, which approximately covered a 24 inch length of the tube. The temperature of the superheater was measured with a single platinum–10 per cent rhodium platinum thermocouple situated approximately mid-way along the superheater. The electrical power to the furnace was controlled using a Variac.

Manometer

The pressure drop along the capillaries was measured with a three limb mercury-in-glass manometer M situated in an electrically heated box made of Sindanyo. A contact thermometer connected to an electronic relay was used to vary the input power to the box by switching in or by-passing a rheostat in series with the heaters. The temperature controller kept the manometer mercury temperature at approximately 120°C ± 1 degC. All the manometer pressure leads were heated using heating tapes and kept at a temperature slightly above 110°C.

The actual height of the mercury columns were measured with a Swift Utilex precision cathetometer, which was fitted with a Moore and Wright micrometer head (having a sensitivity of 0·004 mm and a range of 25 mm), a vernier (graduated to read to 0·01 mm), and a telescope having a magnification of 10, the sighting being between two fine hair lines. Calibration tests for reading reproducibility and sighting precision indicated that precisions of the order of ±0·025 mm to ±0·028 mm could be expected for the given arrangement.

The pressure measurement procedure was basically the same for both of the systems, however, the procedure for the second system will be described here since all three of the columns were utilized. The level of the mercury in the



	Joint	L(mm)	D(mm)	l(mm)	d(mm)
For single capillary system	(1)	75	1·5	30	0·4
For series capillary system	(2)	130	1·75	25	0·35

$$(P_0/P_i^{l/n} = r^4 g(\Delta P_i + \Delta P_0 + 2P_0)/(16 f n l V)$$

FIG. 3. Pressure stabilizer and superheater.

central column was kept constant, having a fixed telescope sighted on it. A "make up" cylinder, having a coarse and threaded piston and a fine threaded piston, was used to inject or withdraw mercury from the manometer. The level of the mercury in the three limbs could be adjusted to within 0·012 mm per revolution of the fine adjustment differentially threaded piston. Before each series of tests were commenced the three limbs were vented to the atmosphere and the level of the mercury in the central column adjusted to the fixed or zero position indicated by the fixed telescope and the two outer limbs were read with the cathetometer. This was repeated several times to check the datum or zero levels of the outer limbs. The manometer was then switched on to the viscometer and the central limb was re-adjusted to the zero position. After the system had been allowed to settle down again the two outer columns were read, thus giving the pressure drops. The fixed level of the central limb was constantly checked during a run.

Viscometers V

Single capillary viscometer (see Fig. 4). The steam entering the viscometer cell passes via a temperature stabilizing coil to the upstream plenum chamber. The stabilizing coil, which is composed of about 120 cm of 5 mm i/d tubing wound with a 4 cm p.c.d., is concentrically placed about the capillary. The entrance plenum chamber is a 2 cm i/d tube having two coarse grade sintered filters about 2 cm apart centrally placed in it. Tests were carried out with a special rig to check the minimum number of filters required and the most suitable position for them with respect to each other and to the entrance to the capillary, to obtain uniform velocity distribution across the chamber and to stop coring of the fluid flow at the entrance to the capillary. The steam leaving the entrance plenum chamber passes via the capillary to an exit chamber, after which it passes through a nozzle and a sintered disk, designed to stop air diffusing into the system, to a Leibig condenser. The exit chamber is a 2 cm i/d tube having a single coarse grade sintered filter centrally positioned in it. Pressure tappings are made from the entrance and exit chambers. The condensate was collected in pre-weighed test tubes held over the mouth of the condenser. The test tubes were made deep and were raised over the exit of the condenser

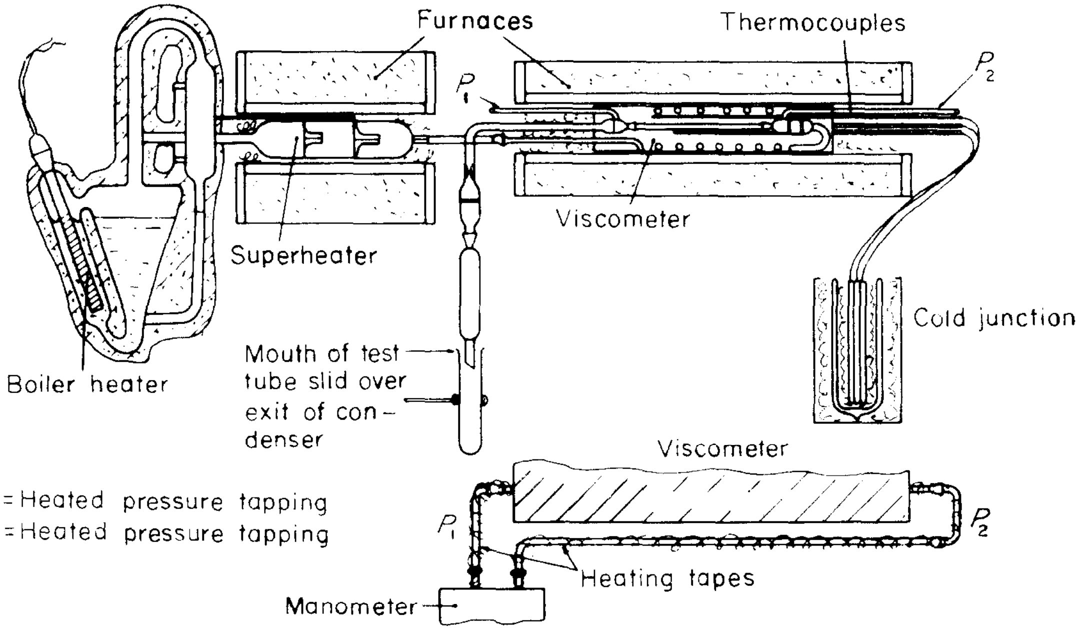


FIG. 4. Layout of the single capillary viscometer apparatus.

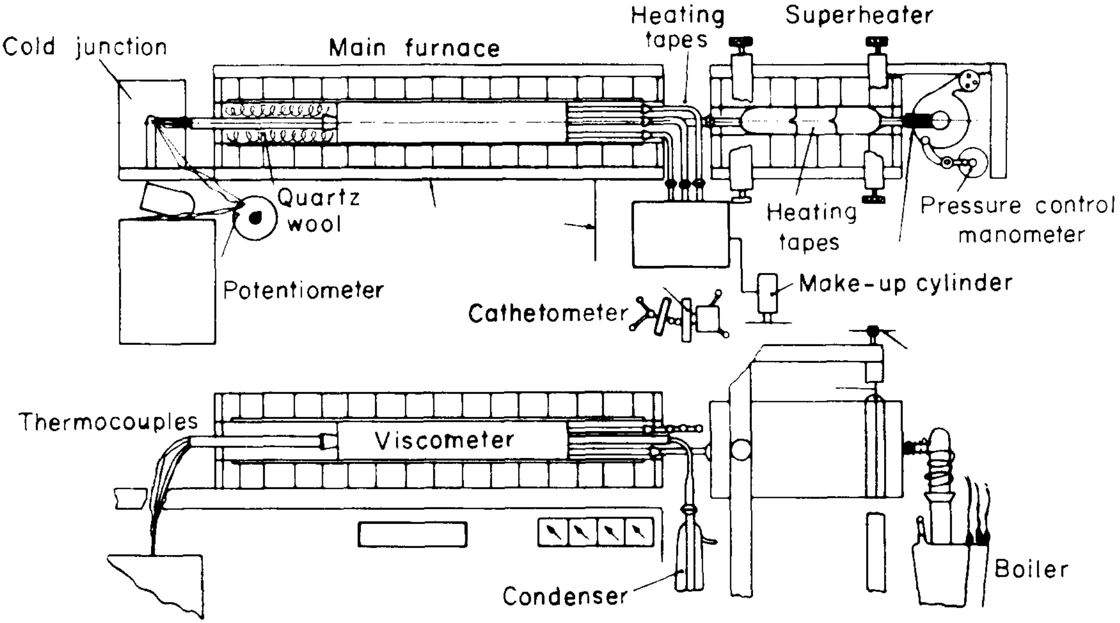


FIG. 5. Layout of series capillary viscometer system.

to reduce the evaporation loss. A microswitch, situated under the condenser, operated a time interval meter, manufactured by Messrs Camerer-Cuss, thus giving condensate collection time. The condensate is weighed on a single pan micro-balance, having a precision of 0·0001 mg.

Series capillary viscometer (see Figs. 5, 6 and 7). The system was basically the same as that required for the single capillary system. The stabilizing spiral which contains about 300 cm of 5 mm i/d of quartz tubing wound with a 75 mm p.c.d. is positioned round the two parallel capillaries. The entrance and exit chambers are basically the same as those used for the first apparatus, however, there is an additional intermediate chamber required. The intermediate chamber, which is situated between the upstream and downstream capillaries, is made annular to allow a thermocouple sheath to pass through it along the axis of the stabilizing spiral. Pressure tappings are made to the entrance, intermediate and exit chambers. Connections in these pressure lines are made with either B.10 standard conical joints or appropriate spherical joints, all of which were outside the very hot furnace zone and could therefore be regularly inspected and greased with silicon stopcock grease. All of the pressure lines were covered with heating tapes to keep them at temperatures above the appropriate saturation value for the steam in them.

The main part of the viscometer is close fitting in a fused silica tube having ground conical end caps. The supply, exhaust and pressure tappings pass out of one of the caps, whilst the thermocouple sheath passes through the other end cap. After assembly, the spaces left within the outer tube are filled with finely ground quartz powder and each end space filled with quartz wool.

The condensing and condensate collection system is basically the same as that used for the first apparatus with obvious modifications to allow for the higher mass flows and temperatures to be used.

Capillaries

All the capillaries had B.5 standard cones ground on their ends, as this was the most convenient size to use. Other arrangements were tried for making the capillaries interchangeable, but ground joints appeared to be the most suitable method. The capillaries for the first apparatus were made of precision bore Pyrex

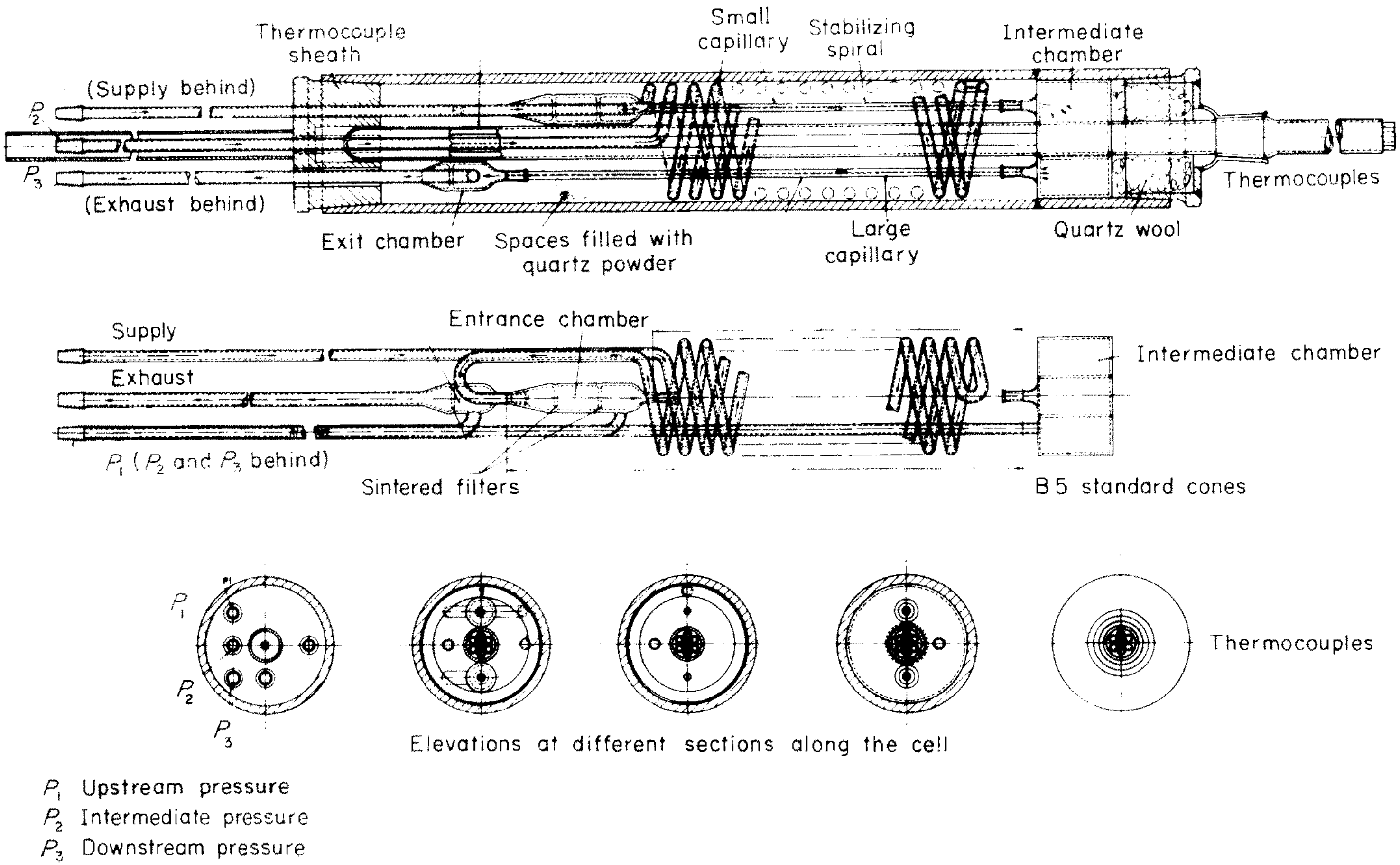


FIG. 6. Viscometer cell assembled.

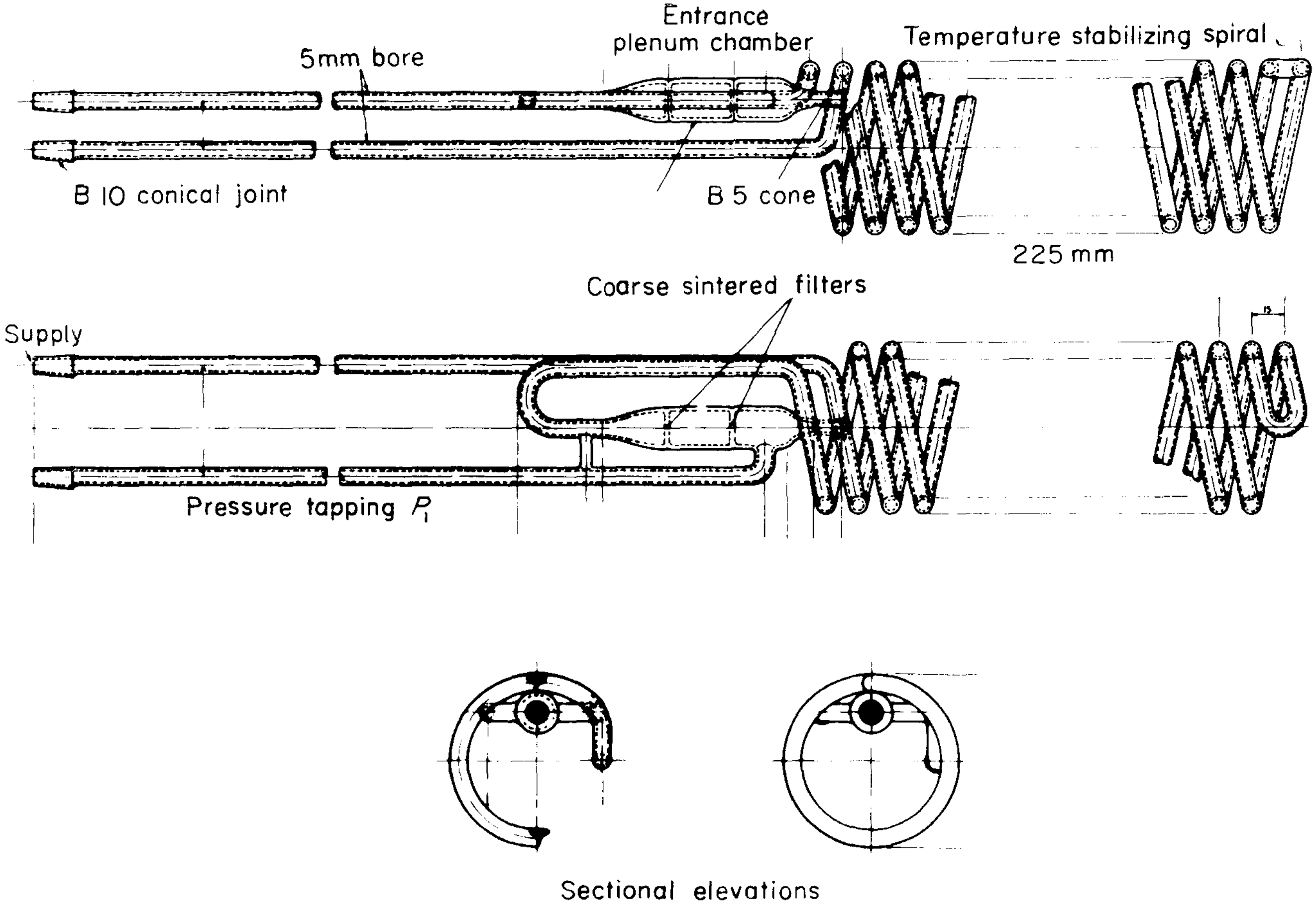


FIG. 7. Temperature stabilizing coil including entrance plenum chamber.

tubing, whilst the capillaries for the second apparatus were made of precision bore quartz tubing. The tubes were square ended, having their ends ground normal to the axis of the tubes. A "small pellet" calibration (i.e. calibrating by passing a small pellet of mercury, about 10 mm in length, along each tube and observing the variation of its length) was carried out initially on a large number of tubes and a short list of the more uniformly bored tubes drawn up. After grinding their ends and thoroughly cleaning the tubes, a further small pellet calibration

Table 1. Capillary diameters obtained from large pellet calibrations

Capillary No.	Before use			After use			Overall mean diameter (mm)	Overall deviation (± %)
	d (mm)	*dm* (mm)	deviation (± %)	*d* (mm)	*dm* (mm)	deviation (± %)		
Quartz.								
8a.	1·70352 1·70321	1·70336	0·009	1·70351 1·70366 1·70343	1·70354	0·007	1·70345	0·005
8b.	1·71804 1·71811 1·71827	1·71814	0·007	1·71838 1·71873 1·71829	1·71848	0·014	1·71831	0·010
Ba.	1·52496 1·52475	1·52485	0·007	broken prior to being dismantled.				
Bb.	1·53365 1·53378 1·53397	1·53380	0·010	1·53388 1·53385	1·53387	0·001	1·53384	0·010
Aa.	0·98462 0·98478 0·98464 0·98475	0·98470	0·008	0·98482 0·98476	0·98480	0·003	0·98475	0·010
Ab.	1·00133 1·00147	1·00140 1·00140	0·007	1·00151 1·00139	1·00145	0·006	1·00142	0·009
Ca.	1·96607 1·96614 1·96643	1·96621	0·009	1·96764 1·96801 1·96807	1·96791	0·011	1·96706	0·051
Cb.	1·95199 1·95208	1·95284	0·002	1·95312 1·95321	1·95317	0·002	1·93260	0·031
1	0·99920 0·99954	0·99937	0·017	0·99882 0·99886	0·99884	0·002	0·99911	0·027
2	1·51041 1·51035 1·51035	1·51037	0·002	1·50885 1·50989 1·50943 1·51005	1·50956	0·040	1·50996	0·052
Quartz.								
3a.	1·05408 1·05488	1·50448	0·038	1·05504 1·05504	1·05440	0·000	1·05476	0·027
4b.	1·02956 1·02958 1·02964	1·02959	0·004	1·03097 1·03908	1·03097	0·001	1·03028	0·067
2a.	1·32482 1·32488 1·32485	1·32485	0·002	1·32452 1·32469	1·32453	0·001	1·32469	0·012
2b.	1·31024 1·31002	1·31013	0·008	1·30971 1·30999 1·30968	1·30979	0·012	1·30996	0·013

was performed and the tubes suitable for use selected. The mean diameter of each tube was then measured several times using a pellet gravimetric calibration method (i.e. weighing a mercury pellet which very nearly occupied the whole length of the capillary). The mercury which was used for the calibrations had been triple distilled and stored in a vacuum. The mercury was not introduced into the capillaries under a vacuum for the large pellet calibrations because of the difficulty encountered when using this method to fill tubes of the large sizes that were used. However, a trial calibration was made using the vacuum filling technique and the diameter obtained agreed with the value obtained using fillings in air, within the expected tolerance, and therefore it was felt that the air filling method was acceptable. The author is of the opinion that vacuum filling would be more important when measuring the diameters of much smaller bore capillaries. The gravimetric method of measuring the diameters was used because of its simplicity when compared with the electrical resistance method or the semi-graphical method put forward by Fisher [25], which the author feels have no obvious advantages over the former method. The diameters and lengths of each capillary were measured, whenever possible, before and after use. Tables 1 and 2 give the diameters and lengths before and after use and the respective deviations. It is apparent that the deviations of the diameters and lengths were within the apparent sensitivity of the measuring technique. It was therefore concluded that there was not any appreciable deterioration of the bore of the capillaries due to the dissolving of the quartz or glass in the steam. The approach was thought to be more reasonable than weighing for obvious reasons.

Two different capillaries were used in the first apparatus. Six different sets of quartz capillaries were used in the second apparatus. Each of the two capillaries in a set had very nearly the same diameter to ensure that the Reynolds numbers in the two tubes were very nearly equal and thereby make the development lengths and the entrance conditions similar. In each case the two capillaries of given set were cut from the same piece of capillary tubing.

The second viscometer was assembled in a vertical position, the joints being thoroughly cleaned, and flooded with alcohol, to ensure that

Table 2. Capillary lengths

Capillary No.	Length before use (cm)	Length after use (cm)	Mean length (cm)	Deviation (± %)
Glass capillaries				
1.	29·785	29·780	29·783	0·017
2.	30·265	30·260	30·263	0·017
Quartz capillaries				
3a.	34·975	34·980	54·978	0·014
4b.	25·010	25·000	25·005	0·020
2a.	35·043	35·046	35·045	0·009
2b.	24·926	24·930	24·928	0·016
8a.	35·045	*	35·045	—
8b.	24·595	*	24·595	—
Ba.	37·515	†	37·515	—
Bb.	23·006	23·004	23·005	0·009
Aa.	37·52[illegible]	37·525	37·523	0·011
Ab.	22·965	22·960	22·968	0·022
Ca.	37·460	‡	37·460	—
Cb.	22·990	‡	22·990	—

* The ends of the capillaries were slightly chipped on dismantling.
† The capillaries were broken before being dismantled.
‡ The ends of the capillaries were broken during dismantling.

no foreign matter got into the joint, whilst being pressed firmly into their respective sockets. After assembly the capillary joints were checked for leaks by connecting a mercury pellet in a drop tube to the system, and observing the rate of full of the mercury pellet. The internal pressure on the joints, which was constant using this method, could be varied by altering the length of the mercury pellet used. With the cell connected into the main system further leak tests were carried out on the relevant joints before and after the use of a given assembly.

Temperature measurement

The temperature in the first apparatus was measured by six platinum 10 per cent rhodium platinum thermocouples situated on a p.c.d. between the temperature stabilizing spiral and the capillary. The actual viscometer is fitted inside a thin copper tube, see Fig. 8. This copper tube had two purposes; (a) to house the viscometer and the thermocouples, and (b) to improve the temperature distribution along the viscometer. The thermocouple sheaths were screwed into the end plate of the copper tube, the actual hot junctions being situated at 7 cm intervals along the capillary. The space between the tube and the glassware was filled with glass wool.

In the second apparatus the temperature was measured using six platinum 10 per cent rhodium platinum thermocouples situated at equal intervals along the axis of the viscometer. The thermocouples are actually on a p.c.d. of about 15 mm with a seventh thermocouple, which is axially moveable, down the centre of the group and used as a check thermocouple.

Apart from the check thermocouple only one of the thermocouples was calibrated, since they were all made from the source of wire, one of the thermocouples being calibrated against a standard N.P.L. calibrated thermocouple. The calibration agreed with the manufacturer's (Messrs Johnson Matthey) recommended values within their given tolerances of ±0·25 degC to 500°C and ±1·0 degC to 1000°C.

Main furnaces

The two main furnaces were tubular and heated electrically using windings of Brightray H wire. The main furnace for the first apparatus had three windings, the two outer ones being 6·5 inches long, and the central one being 15·75 inches long. A temperature distribution, over the central 40 cm, of better than ±0·5 degC up to 500°C was

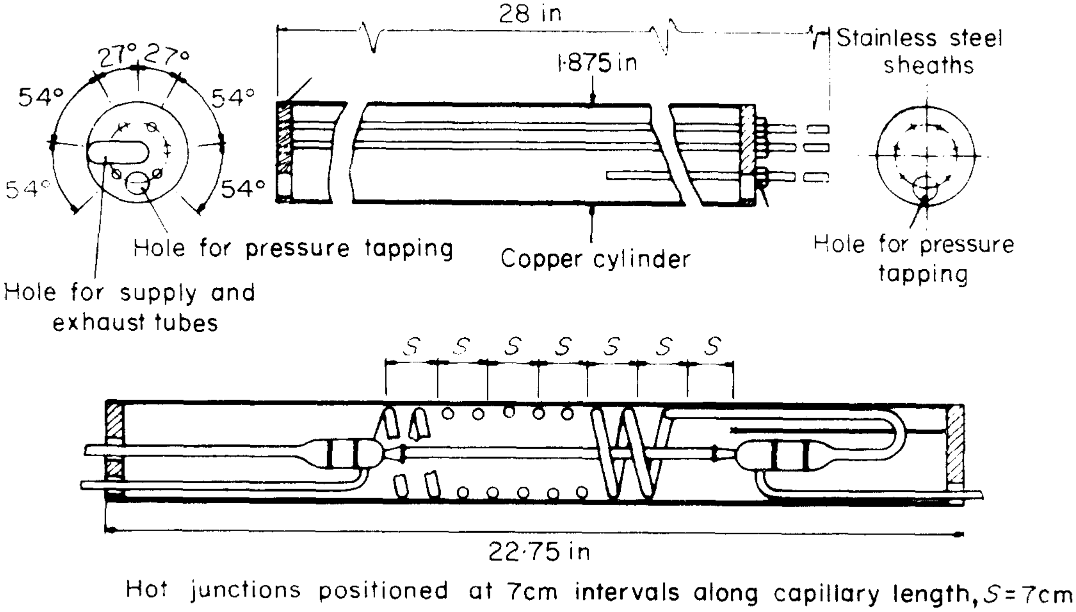


FIG. 8. Radiation shield and thermocouple support for the single capillary viscometer.

attainable with this furnace. The main furnace for the second apparatus originally had five windings but was eventually modified for two reasons, (a) with five variable powers it was very difficult to calibrate and control the temperature distribution of the furnace and (b) the furnace could not be used at temperatures above 940°C since the alumina furnace tube, under the influence of a potential difference of more than 40 V, appeared to combine with the oxide film on the furnace wire to produce a low melting temperature slag, which shorted out the ends of two adjacent windings. The windings were therefore replaced by a continuous variable pitch winding with five electrical tappings at suitable points along it. This made three effective windings, the central two windings being connected in parallel. The lengths of the three windings were 8·5, 27 and 8·5 in. With careful control, the temperature distribution over the central 40 cm could be kept to within ±0·75 degC at a temperature of about 1050°C.

DISCUSSION OF RESULTS

The flow equation for laminar flow of a Newtonian fluid through a tube may be expressed in the form

$$Q = \frac{\pi d^4 \rho}{128} \{-\mathrm{d}p/\mathrm{d}z\}$$

which is the Hagen–Poiseuille equation. Although this equation is adequate for simple capillary flow, it neglects the effect of the acceleration of the flow at the entrance to the tube. At the entrance to the tube the velocity profile may be assumed to be uniform, but at some distance along the tube the velocity profile changes to parabolic. It therefore follows that there must be some drop in the pressure at the entrance due to the fluid gaining kinetic energy. This, in itself, would not effect the equation for the viscosity, if the parabolic profile could be fully converted to a uniformly distributed low velocity at the exit and therefore recover the energy. This cannot be efficiently achieved and allowances must be made for this loss of head. The kinetic energy gained by the fluid at the entrance to the capillary per unit time is

$$\int 1/2\, v_z^2\, (2\,\pi r\, \rho\, v_z)\, \mathrm{d}r = \int \pi\, \rho\, (\mathrm{d}p/\mathrm{d}z)\, [(R^2 - r_2^2)/2\eta]\, \mathrm{d}r = \rho\, V^3/\pi R^4$$

where V is the mean velocity of flow.

The effective loss of head or pressure drop in the transition length therefore is,

$$\Delta p = \rho\, V^2/\pi^2\, R^4 = Q^2/\pi^2\, \rho^2\, R^4$$

where Q is the mass flow rate. This loss of head does not take into accunt the viscous friction in the transition length. In order to allow for this, the correction is assumed to be of the form $mQ^2/\pi^2\rho^2R^4$, where m is the end correction constant. The Hagen–Poiseuille equation with corrections becomes,

$$Q = \frac{\pi\, d^4\, \Delta\, p\, g}{128\, 1\, Q\, f\, Vs} \{1 + 8\, \epsilon/d\}\, (1 + 3\alpha\, \Delta t) - \frac{8\, \pi\, l\, (1 + \alpha\, \Delta t)}{m\, Q\, f}$$

Where m is the end correction constant; $(1 + 8\epsilon/d)$ is the slip correction, ϵ is the slip correction constant; $(1 + 3\alpha\Delta t)$ is the correction for the thermal expansion of the material of the capillaries, α is the coefficient of linear expansion; for the materials of the capillaries; and f is the buoyancy correction for the weighing of the condensate in air.

In order to make absolute measurements with the single capillary apparatus it was necessary to either (1) vary the mass flow rate at a given temperature and obtain the viscosity graphically or (2) decide on a suitable value for the end correction constant m in the flow equation. Although good results can be obtained using method (1), i.e. plotting η_P against mkQ, where η_P is the Poiseuille viscosity and $K = 1/8\ \pi l$. The intercept therefore gives the actual viscosity. Unless the experimental scatter is small and/or a large number of readings are made the final accuracy is no better than that which would be achieved when assuming a value for m. Consequently the latter method was preferred.

There have been a number of investigations into the magnitude and form that the end corrections should take. Values for m in the range of 1·08 to 1·21 have been reported, but in general the agreement is not good. Some investigators are of the opinion that m varies with the density of the fluid being used and the

Reynolds number, but there is no definite proof to substantiate this theory. However, it is reasonably certain that it does depend on the type of entrance that is being used. It was finally decided that a value of 1·12 would be used, based on the work of Boussinesq [28], Langhaar [29] and Riemann [30] amongst others which might be considered to be better than 4 per cent which meant a maximum uncertainty in the value of the viscosity of about $\pm 0{\cdot}4$ per cent, which was an allowable tolerance. It should be appreciated that the importance of the accuracy of m is dependent on the magnitude of the pressure drop across a given capillary, which in turn effects the mass flow rate. When the mass flow rate is high for a given capillary, the end correction can be a large percentage of the actual viscosity and therefore the value of m would be more important than for small mass flow rates.

It was difficult to decide on the exact form that the slip correction should take. Most investigators in this field are of the opinion that it should be a function of the mean free path of the fluid molecules. There appears to be a large diversity of opinion as to the actual magnitude of the function, and consequently it was difficult to make a decision on this matter. It was finally decided that Knudsen's semi-empirical equation for the slip coefficient of the form of

$$\epsilon = cL = \frac{c\,2{\cdot}128}{\sqrt{(P\rho)}} \tag{2}$$

where c is a constant equal to 0·81 would be used in the more general equation for the slip correction. That is, to make the effective diameter of the capillary equal to $d\,(1 + 2\epsilon/d)$ and therefore d can be replaced by the approximation $d\,(1 + 8\epsilon/d)$. The accuracy of the value of the slip correction is not very critical for the present work, since its largest value was of the order of 0·5 per cent of the viscosity and consequently even an uncertainty of 20 per cent in the value of the slip correction factor would only mean an uncertainty of about 0·1 per cent in the value of the viscosity. It would obviously be much more critical for lower density conditions.

RESULTS

Over 550 determinations were made, 109 of which were obtained using the single capillary apparatus. Tables 3 and 4 give the experimental results obtained using the single capillary viscometer. Tables 5–10 give the experimental results obtained when using the series capillary viscometer. In the tables ΔP, ΔP and ΔP_{12} are the pressure drops across the capillaries, Q is the mass flow rate, t is the mean temperature along the viscometer, the graphical mean of the values indicated by the six thermocouples, and V, V_1 and V_2 are the mean specific volumes of the steam at the mean pressure in the capillaries (taken from the 5th edition of the VDI steam tables).

The single capillary apparatus was used primarily as a prototype for the series capillary system. The experimental results obtained with this apparatus were within the tolerance put forward at the report of the Second Meeting of the International Co-ordinating Committee on the Properties of Steam, Munich, July 1962, i.e. ±1 per cent of Shifrin's recommended values between 100°C and 300°C and ±3 per cent between 300°C and 900°C. The experimental measurements were up to about 460°C, the majority of the individual determinations being within a 2 per cent band. The actual trend of the curve was to diverge from Shifrin's and Bonilla's, agreeing more closely with the limited data given by Kestin (up to 300°C). If the present work had been based solely on the results from the single capillary apparatus, the atmospheric line would have been about 2 per cent higher than Shifrin's at 400°C. The scatter of the 109 points was much less than that obtained by Shifrin over the temperature range of 100–450°C.

Having obtained very favourable results from the single capillary glass apparatus, work on the series capillary quartz apparatus was commenced. The anticipated temperature range was 100°C to about 1100°C (the safe temperature ceiling for quartz being about 1050°C, repeated heating to high temperatures tends to produce devitrification of the quartz).

The main object of using two capillaries in series was to remove the need to know an accurate value for the end correction constant m in the capillary flow equation. Making the assumption that the end correction constants m_1 and m_2 for the two capillaries are very nearly

Table 3. Experimental data obtained using the single capillary viscometer

The nominal bore and length of the capillary was 1·0 mm and 300 mm respectively.
The mean Reynolds number in the capillaries was 12·74 Q/η.
The maximum Reynolds number obtained for the given set up 890.

Group	No.	t (°C)	$Q \times 10^2$ (g/s)	ΔP (gf/cm^2)	V (cm^3/g)	$\eta \times 10^4$ (poise)
I	1	112·8	0·88434	26·212	1697·7	1·2769
	2	113·1	0·88431	26·231	1699·1	1·2768
	3	113·7	0·87475	26·221	1701·9	1·2907
	4	113·9	0·87076	25·926	1703·1	1·2808
	5	113·8	0·87031	26·020	1702·6	1·2871
II	6	139·3	0·60200	20·038	1817·6	1·3885
	7	139·6	0·60438	20·136	1818·9	1·3885
	8	139·7	0·60687	20·366	1819·1	1·3988
	9	139·9	0·60853	20·122	1817·2	1·3782
	10	139·9	0·60693	19·970	1817·3	1·3711
	11	140·0	0·60602	20·058	1817·7	1·3796
III	12	155·4	0·58126	21·287	1937·4	1·4395
	13	155·6	0·58172	21·371	1938·3	1·4436
	14	155·9	0·58903	21·371	1939·6	1·4275
	15	156·1	0·57358	21·113	1941·1	1·4455
	16	156·3	0·57979	21·252	1941·8	1·4376
	17	156·4	0·57404	21·059	1942·5	1·4392
IV	18	207·0	0·51635	23·538	2103·1	1·6741
	19	207·4	0·51460	23·285	2105·1	1·6598
	20	207·8	0·51337	23·132	2107·0	1·6512
	21	208·0	0·51207	23·137	2108·5	1·6549
	22	208·2	0·51009	23·137	2109·5	1·6611
	23	208·4	0·50891	23·072	2110·4	1·6597
V	24	250·2	0·40740	22·294	2371·3	1·8043
	25	250·3	0·39971	22·117	2371·8	1·8245
	26	250·5	0·39633	21·965	2373·0	1·8286
	27	250·7	0·39501	21·948	2370·8	1·8354
	28	251·2	0·39345	21·913	2373·1	1·8383
	29	251·5	0·39270	21·872	2373·0	1·8385
VI	30	256·1	0·42387	23·770	2338·6	1·8750
	31	256·1	0·42532	23·768	2338·6	1·8681
	32	256·2	0·42505	23·861	2339·8	1·8759
	33	256·3	0·42433	23·517	2340·4	1·8508
	34	256·3	0·42384	23·535	2340·4	1·8538
	35	256·3	0·42264	23·758	2340·1	1·8786
VII	36	303·1	0·33141	22·210	2547·0	2·0784
	37	303·3	0·32893	22·029	2548·1	2·0765
	38	303·8	0·32740	21·943	2550·5	2·0763
	39	304·2	0·32529	21·870	2552·3	2·0817
	40	304·3	0·32370	21·763	2552·1	2·0821
	41	305·4	0·32378	21·709	2557·2	2·0721

Table 3—continued

Group	No.	t (°C)	$Q \times 10^2$ (g/s)	ΔP (gf/cm^2)	V (cm^3/g)	$\eta \times 10^4$ (poise)
VIII	42	342·9	0·32389	25·340	2788·0	2·2219
	43	343·1	0·32307	25·249	2789·0	2·2189
	44	343·2	0·32119	25·161	2791·1	2·2227
	45	343·5	0·31997	24·990	2792·7	2·2148
	46	343·7	0·32026	25·029	2793·7	2·2155
	47	343·8	0·31987	24·977	2795·7	2·2119
	48	344·2	0·30390	23·929	2798·9	2·2307
IX	49	357·8	0·28155	22·612	2777·3	2·2978
	50	357·5	0·27816	22·460	2776·3	2·3118
	51	357·1	0·27531	22·164	2774·9	2·3065
	52	356·8	0·27474	21·966	2773·8	2·2913
	53	356·5	0·26944	21·810	2772·7	2·3221
	54	356·2	0·26952	21·626	2771·6	2·3024
	55	356·0	0·26749	21·540	2770·8	2·3118
	56	356·0	0·26974	21·579	2770·7	2·2938
X	57	400·5	0·23505	21·968	2981·1	2·5027
	58	400·3	0·23616	21·962	2981·2	2·4900
	59	400·2	0·23666	21·962	2980·8	2·4849
	60	399·9	0·23509	21·906	2979·5	2·4966
	61	399·6	0·23548	21·837	2978·3	2·4854
	62	398·8	0·23318	21·575	2975·0	2·4828
XI	63	441·6	0·19929	21·068	3179·9	2·6627
	64	441·4	0·19821	21·139	3178·9	2·6875
	65	441·2	0·19732	20·969	3178·2	2·6785
	66	441·1	0·19640	20·914	3177·9	2·6844
	67	440·9	0·19677	20·895	3177·0	2·6776
	68	440·9	0·19741	20·820	3177·1	2·6590
	69	440·9	0·19876	21·092	3176·7	2·6758
XII	70	448·8	0·26283	29·394	3312·9	2·6950
	71	448·9	0·26317	29·414	3313·2	2·6931
	72	449·1	0·26311	29·416	3315·7	2·6918
	73	449·5	0·26297	29·389	3316·6	2·6899
	74	449·4	0·26310	29·387	3320·1	2·6856
	75	449·6	0·26189	29·287	3322·4	2·6871

the same,* which they will be since the ends were square cut, and equal to m, and treating the individual flow equations for the capillaries simultaneously to eliminate m, the following equation can be obtained,

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* An estimation of the effect of the uncertainty of the equality of m can be made from the basic flow equation for the two capillaries,

$$\left.\begin{aligned} \eta &= \eta_{P_1} - (m_1 Q)/8\pi l_1 \\ \eta &= \eta_{P_2} - (m_2 Q)/8\pi l_2 \end{aligned}\right\} \qquad (3)$$

where the suffices 1 and 2 refer to the two capillaries and η_{P_1} and η_{P_2} are the Poiseuille viscosities.

Partially differentiating the equations for m and assuming that the uncertainty in the values of m_1 and m_2 from a given value are the same, i.e. $d(m_1) = d(m_2) = d(m)$ then

$$\frac{d\eta}{\eta} = \frac{Q\,d(m)}{16\pi\eta}\left\{\frac{l_1 + l_2}{l_1 l_2}\right\} \qquad (4)$$

Making an assumption that the overall uncertainty between the values of m is about 4 per cent, i.e. $d(m)$ equals 2 per cent, then the maximum uncertainty in the value due to the uncertainty in the equality of m would have been about ±0·15 per cent for the work reported here. This was considered quite reasonable.

Table 4. Experimental data obtained using the single capillary viscometer

The nominal bore and length of the capillary was 1·5 mm and 300 mm respectively.
The mean Reynolds number in the capillaries was 8·43 Q/η.
The maximum Reynolds number obtained for the given set up 670.

Group	No.	t (°C)	$Q \times 10^2$ (g/s)	ΔP (gf/cm^2)	V (cm^3/g)	$\eta \times 10^4$ (poise)
XIII	76	173·0	0·11907	9·837	2021·9	1·5190
	77	173·2	0·11976	9·920	2022·7	1·5218
	78	173·3	0·12115	10·045	2023·0	1·5211
	79	173·4	0·12065	10·035	2023·5	1·5267
	80	173·6	0·12089	10·035	2024·5	1·5222
XIV	81	228·6	0·11634	12·152	2262·1	1·7444
	82	228·9	0·11636	12·150	2263·4	1·7427
	83	229·0	0·11541	12·150	2263·9	1·7594
	84	229·0	0·11550	12·154	2263·6	1·7585
	85	229·3	0·11539	12·136	2264·4	1·7581
XV	86	274·7	0·11186	14·058	2457·6	1·9581
	87	274·8	0·11307	14·058	2458·0	1·9331
	88	275·0	0·11286	14·108	2459·9	1·9431
	89	275·1	0·11337	14·187	2461·5	1·9433
	90	275·1	0·10989	13·649	2461·3	1·9330
XVI	91	345·3	0·10779	17·064	2762·5	2·2218
	92	346·1	0·10848	17·207	2767·3	2·2312
	93	346·2	0·10745	17·210	2768·0	2·2453
	94	346·4	0·10738	17·160	2769·0	2·2393
	95	346·7	0·10715	17·187	2770·3	2·2474
	96	346·8	0·10804	17·255	2770·6	2·2353
XVII	97	406·4	0·10678	20·901	3032·8	2·5253
	98	406·6	0·10645	20·818	3033·8	2·5226
	99	406·8	0·10603	20·770	3035·0	2·5265
	100	406·9	0·10616	20·806	3036·5	2·5263
	101	407·0	0·10551	20·679	3037·1	2·5268
	102	407·1	0·10519	20·627	3037·7	2·5282
	103	407·1	0·10496	20·599	3037·7	2·5307
XVIII	104	454·3	0·10589	23·792	3229·8	2·7370
	105	454·4	0·10585	23·786	3230·3	2·7368
	106	454·5	0·10561	23·718	3230·9	2·7352
	107	454·5	0·10579	23·693	3230·9	2·7268
	108	454·7	0·10595	23·560	3233·2	2·7039
	109	455·1	0·10560	23·534	3235·0	2·7092

$$\eta = \frac{\pi g d_1^4 \{1 + 8\,\epsilon/d\}\{1 + 3a\,\Delta t\}}{128\,Q f (l_1 - l_2)} \left\{\frac{\Delta P_1}{V_{s1}} - \frac{\Delta P_2}{V_{s2}}\left(\frac{d_2}{d_1}\right)^4 K\right\} \tag{5}$$

where suffices 1 and 2 refer to the first and second capillaries respectively, K is the ratio $(1 + 8\epsilon/d_2)$, $(1 + 8\epsilon/d_1)$ which is small and therefore neglected in the actual working equation, f is the buoyancy correction applied to Q and d is the mean value of d_1 and d_2. The mean pressure in each tube was given by

$$\left.\begin{aligned} Pm_1 &= Pa + \Delta P' + \Delta P_1/2 \\ Pm_2 &= Pa + \Delta P' + \Delta P_1 + \Delta P_2/2 \end{aligned}\right\} \tag{6}$$

where Pa is the atmospheric pressure, $\Delta P'$ the pressure drop between the exit plenum chamber and the condenser.

Table 5. Experimental data obtained using the series capillary viscometer

The nominal bore and length ratio of the capillaries was 1·0 mm and 35 mm:25 mm respectively.
The mean Reynolds number in the capillaries 12·22 Q/η.
The maximum Reynolds number obtained for the given set up 810.

Group	No.	t (°C)	$Q \times 10^3$ (g/s)	ΔP_1 (gf/cm^2)	ΔP_2 (gf/cm^2)	V_1 (cm^3/g)	V_2 (cm^3/g)	$\eta \times 10^4$ (poise)
1	110	126·9	8·5653	26·401	21·121	1802·1	1761·6	1·3027
	111	127·1	8·5818	26·042	20·735	1803·4	1763·4	1·3009
	112	127·5	8·3693	25·416	20·176	1805·9	1766·9	1·3131
	113	127·6	8·1893	25·256	20·196	1806·5	1767·3	1·3048
	114	128·1	8·2585	25·366	20·215	1811·0	1771·9	1·3097
2	115	178·0	7·7731	30·557	24·049	2024·7	1944·6	1·4739
	116	177·9	7·7903	30·556	23·928	2024·2	1944·3	1·4929
	117	178·0	7·7809	30·609	24·074	2024·6	1944·4	1·4774
	118	178·0	7·7265	30·141	23·634	2026·9	1948·1	1·4798
	119	178·0	7·7198	30·340	23·966	2026·6	1947·0	1·4574
3	120	268·4	5·1224	28·850	22·446	2432·1	2372·1	1·8971
	121	269·2	5·1255	28·862	22·379	2435·7	2376·4	1·9113
	122	269·6	5·1371	28·862	22·418	2437·5	2378·1	1·8963
	123	272·7	5·0445	28·818	22·362	2451·2	2391·5	1·9227
	124	273·1	5·0344	28·738	22·309	2453·1	2393·5	1·9180
4	125	330·2	3·9693	27·665	21·435	2711·2	2649·0	2·1383
	126	330·1	3·8928	27·464	21·380	2710·9	2648·1	2·1365
	127	330·1	3·9815	27·474	21·271	2711·1	2648·4	2·1200
	128	330·2	3·8738	27·401	21·298	2711·7	2649·1	2·1509
	129	330·3	3·8616	27·348	21·213	2712·2	2649·7	2·1650
	130	330·6	3·9265	27·340	21·217	2713·6	2651·1	2·1247
	131	330·7	3·8958	27·303	21·087	2714·6	2652·3	2·1652
5	132	367·7	3·7082	29·238	22·514	2863·1	2792·2	2·3163
	133	367·9	3·7519	29·531	22·607	2863·7	2792·2	2·3451
	134	367·1	3·7777	29·557	22·584	2860·1	2788·7	2·3456
	135	367·2	3·7610	29·536	22·588	2860·1	2788·8	2·3491
	136	367·2	3·7802	29·341	22·551	2860·4	2789·5	2·2929
	137	367·2	3·7201	29·290	22·633	2860·4	2789·4	2·2940
	138	367·7	3·6877	29·170	22·580	2862·5	2791·6	2·2933
6	139	411·8	3·2915	29·734	22·816	3045·3	2968·4	2·5150
	140	410·9	3·2547	29·549	22·671	3041·6	2965·2	2·5326
	141	410·9	3·2047	29·286	22·646	3042·4	2966·5	2·4987
	142	410·8	3·1860	29·048	22·448	3042·3	2967·0	2·4985
	143	410·0	3·2501	29·289	22·449	3042·7	2967·1	2·5208
	144	410·4	3·2504	29·452	22·612	3039·8	2963·8	2·5254
7	145	473·8	2·5779	28·077	21·547	3328·4	3249·1	2·7850
	146	474·6	2·5622	28·066	21·615	3332·0	3252·6	2·7727
	147	475·6	2·5721	28·107	21·656	3336·5	3256·8	2·7590
	148	476·2	2·5392	28·122	21·670	3334·7	3254·9	2·7964
	149	476·7	2·5790	28·110	21·671	3336·9	3257·1	2·7412
	150	477·0	2·5398	28·125	21·699	3339·2	3259·3	2·7835
	151	477·0	2·5467	27·952	21·579	3339·2	3259·7	2·7555
8	152	515·1	2·5188	30·794	23·528	3541·8	3450·3	2·9557
	153	515·1	2·5878	31·036	23·743	3541·3	3449·0	2·8915
	154	515·0	2·5210	30·649	23·529	3541·5	3450·2	2·9049
	155	515·1	2·4748	30·395	23·448	3540·2	3449·5	2·9006
	156	515·9	2·4802	30·135	22·948	3544·2	3454·7	2·9646
	157	516·4	2·4523	30·218	23·136	3545·1	3455·0	2·9331

Table 5—continued

Group	No.	t (°C)	$Q \times 10^3$ (g/s)	ΔP_1 (gf/cm^2)	ΔP_2 (gf/cm^2)	V_1 (cm/g)	V_2 (cm^3/g)	$\eta \times 10^4$ (poise)
9	158	600·0	1·9004	28·507	21·747	3925·8	3831·4	3·3017
	159	600·2	1·8807	28·458	21·710	3926·5	3832·6	3·3309
	160	601·0	1·8613	28·556	21·849	3929·9	3835·5	3·3483
	161	601·3	1·8853	28·625	21·891	3935·2	3840·5	3·3132
	162	601·5	1·8972	28·512	21·750	3936·3	3842·2	3·3000
	163	601·6	1·8668	28·341	21·818	3946·6	3842·6	3·2292
10	164	633·0	1·8672	30·676	23·303	4128·5	4023·7	3·4630
	165	633·7	1·8563	30·786	23·439	4131·5	4026·2	3·4732
	166	634·3	1·8697	30·240	22·986	4135·3	4031·9	3·4017
	167	634·9	1·8141	30·190	23·042	4137·8	4034·2	3·4630
	168	634·9	1·8449	30·369	23·059	4137·4	4033·5	3·4686
	169	635·0	1·8339	30·514	23·275	4137·5	4032·9	3·4657
11	170	680·9	1·8815	34·062	26·002	4318·1	4195·8	3·5788
	171	681·3	1·8320	34·056	26·177	4319·2	4197·2	3·6087
	172	681·8	1·8437	33·8576	26·032	4320·6	4198·4	3·5632
	173	682·7	1·8119	33·858	25·979	4324·5	4202·5	3·6418
	174	683·5	1·8389	33·752	25·953	4326·2	4204·0	3·5565
12	175	719·9	1·6858	34·182	26·092	4500·4	4372·4	3·8463
	176	720·6	1·7386	34·048	25·932	4503·9	4376·4	3·7341
	177	721·5	1·7124	34·004	25·809	4508·1	4380·9	3·8164
	178	721·8	1·7097	33·615	25·484	4510·2	4384·4	3·7906
	179	722·4	1·7147	33·581	25·588	4513·1	4387·0	3·7263
	180	722·1	1·6761	33·612	25·615	4511·6	4385·5	3·8152
	181	722·5	1·6973	33·758	25·738	4513·6	4386·9	3·7771
13	182	766·0	1·8243	39·181	29·449	4697·8	4545·7	4·0158
	183	768·0	1·8010	39·273	29·821	4706·6	4553·6	3·9666
	184	770·0	1·8280	39·277	29·544	4716·7	4562·8	3·9914
	185	772·9	1·8206	39·609	29·837	4728·1	4573·2	4·0166
	186	773·7	1·8006	39·652	30·038	4726·7	4571·2	4·0089
	187	775·0	1·8142	39·283	29·509	4733·4	4579·7	4·0227
	183	776·2	1·7643	39·177	29·669	4738·5	4584·5	4·0397
14	189	825·2	1·8708	43·602	32·685	4921·7	4742·9	4·1466
	190	825·6	1·8086	43·162	32·657	4924·6	4746·7	4·1496
	191	826·1	1·7885	43·148	32·644	4931·3	4753·3	4·1906
	192	827·1	1·8028	43·070	32·539	4938·6	4761·0	4·1594
	193	827·6	1·7705	42·978	32·552	4944·7	4767·2	4·1948
	194	828·2	1·8138	43·209	32·463	4946·9	4769·0	4·1976
15	195	875·7	1·7184	45·505	34·474	5224·4	5028·3	4·3117
	196	876·2	1·7272	45·425	34·328	5226·9	5031·3	4·3085
	197	876·4	1·6842	45·198	34·261	5228·3	5033·4	4·3631
	198	877·2	1·6831	45·234	34·258	5225·5	5030·5	4·3808
	199	878·0	1·7075	45·127	34·231	5229·5	5034·6	4·2890
	200	878·2	1·6526	45·019	34·230	5227·6	5033·0	4·3956
	201	878·5	1·7178	44·933	33·797	5227·1	5033·7	4·3403
16	202	908·1	1·6112	45·659	34·457	5354·2	5151·8	4·5443
	203	908·7	1·6102	45·076	33·980	5358·4	5158·6	4·5037
	204	909·3	1·5827	45·117	34·008	5361·0	5161·0	4·5849
	205	909·9	1·6109	45·172	33·942	5358·3	5158·3	4·5473
	206	910·0	1·5993	45·145	34·008	5358·9	5158·6	4·5485
	207	909·7	1·6430	44·869	33·758	5358·2	5159·3	4·4170

Table 5—continued

Group	No.	t (°C)	$Q \times 10^3$ (g/s)	ΔP_1 (gf/cm^2)	ΔP_2 (gf/cm^2)	V_1 (cm^3/g)	V_2 (cm^3/g)	$\eta \times 10^4$ (poise)
17	208	234·8	7·6334	37·457	29·005	2244·6	2172·4	1·7750
	209	234·7	7·7085	37·457	29·005	2244·2	2172·0	1·7580
	210	234·9	7·6629	37·442	29·017	2245·1	2172·9	1·7632
	211	234·7	7·5969	37·361	28·949	2246·2	2174·1	1·7751
	212	234·4	7·6958	37·281	29·029	2244·9	2172·9	1·7265
	213	234·2	7·6566	37·361	29·122	2243·9	2171·8	1·7343
	214	234·0	7·5706	37·042	28·909	2244·0	2172·4	1·7344
18	215	569·1	3·1266	43·451	32·725	3731·4	3595·5	3·2177
	216	567·4	3·1391	43·825	33·150	3725·7	3588·5	3·1990
	217	570·0	3·1499	43·914	33·295	3739·5	3601·3	3·1633
	218	570·8	3·1049	43·769	33·336	3743·3	3605·0	3·1588
	219	570·9	3·1363	43·917	33·337	3733·9	3597·0	3·1749
	220	570·8	3·1914	43·597	33·684	3732·2	3594·0	3·2068

Table 6. Experimental data obtained using the series capillary viscometer

The nominal bore and length ratio of the capillaries was 1·3 mm and 35 mm:25 mm respectively.
The mean Reynolds number in the capillaries 9·67 Q/η.
The maximum Reynolds number obtained for the given set up 1130.

Group	No.	t (°C)	$Q \times 10^3$ (g/s)	ΔP_1 (gf/cm^2)	ΔP_2 (gf/cm^2)	V_1 (cm^3/g)	V_2 (cm^3/g)	$\eta \times 10^4$ (poise)
19	221	201·5	18·931	35·187	26·786	2111·3	2048·5	1·6127
	222	201·6	18·653	35·214	26·787	2111·7	2048·9	1·6413
	223	201·6	18·726	35·240	26·759	2111·7	2048·8	1·6447
	224	201·7	18·696	35·173	26·839	2112·2	2049·3	1·6199
	225	201·8	18·628	35·133	26·799	2112·9	2050·1	1·6254
	226	201·9	18·659	35·160	26·786	2113·4	2050·6	1·6298
	227	201·9	18·637	35·133	26·812	2114·1	2051·2	1·6213
20	228	418·4	12·395	48·834	35·950	3083·3	2958·1	2·4983
	229	418·3	12·413	48·817	35·934	3082·8	2957·7	2·4950
	230	418·2	12·402	48·817	35·894	3082·4	2957·4	2·5052
	231	418·1	12·580	48·819	35·962	3081·9	2956·8	2·4574
	232	418·1	12·414	48·965	35·945	3083·7	2958·4	2·5192
	233	418·1	12·431	48·832	35·869	3083·9	2958·8	2·5062
	234	417·9	12·379	48·803	35·880	3083·1	2958·1	2·5095
21	235	453·4	11·847	51·252	37·211	3265·6	3127·8	2·6771
	236	453·4	11·837	51·385	37·278	3265·4	3127·3	2·6911
	237	453·3	11·896	51·439	37·211	3264·8	3126·8	2·7007
	238	453·3	11·968	51·545	37·278	3264·7	3126·4	2·6916
	239	453·3	11·898	51·612	37·238	3263·3	3125·0	2·7284
	240	453·3	12·040	51·703	37·290	3263·2	3124·7	2·7034
	241	453·3	11·993	51·701	37·275	3263·5	3125·0	2·7161
22	242	553·1	8·4230	48·687	35·501	3703·9	3555·1	3·1374
	243	553·2	8·6231	48·621	35·368	3704·5	3556·1	3·0802
	244	553·3	8·7040	48·623	35·370	3704·9	3556·5	3·0515
	245	553·4	8·6090	48·684	35·322	3705·2	3556·8	3·1096
	246	553·4	8·7550	48·684	35·228	3705·6	3557·0	3·0781
	247	553·4	8·6854	48·655	35·320	3705·4	3557·0	3·1366
23	248	651·7	7·2498	51·608	37·311	4147·7	3971·8	3·5082
	249	651·8	7·3995	51·755	37·299	4148·2	3971·6	3·5424
	250	651·8	7·2737	51·688	37·285	4148·0	3971·9	3·5917
	251	651·9	7·2808	51·701	37·325	4148·4	3972·3	3·5120
	252	652·1	7·4330	51·980	37·365	4149·0	3972·1	3·4951

Table 6—continued

Group	No.	t (°C)	$Q \times 10^3$ (g/s)	ΔP_1 (gf/cm^2)	ΔP_2 (gf/cm^2)	V_1 (cm^3/g)	V_2 (cm^3/g)	$\eta \times 10^4$ (poise)
23	253	652·1	7·3770	51·887	37·351	4149·2	3972·5	3·5027
	254	652·2	7·4398	51·806	37·337	4149·8	3973·3	3·4572
24	255	709·5	6·5638	51·519	37·100	4421·8	4235·4	3·6697
	256	709·2	6·5326	51·346	36·993	4420·8	4235·0	3·6724
	257	708·9	6·4309	51·116	36·951	4419·9	4234·8	3·6840
	258	708·8	6·4270	51·577	36·975	4417·2	4231·4	3·7486
	259	708·8	6·5423	51·404	37·014	4417·1	4231·3	3·6791
	260	708·8	6·4975	51·333	36·953	4417·2	4231·7	3·7021
25	261	761·1	5·9060	51·566	37·015	4650·4	4454·8	3·9153
	262	761·4	5·8971	51·669	37·279	4651·5	4455·1	3·8756
	263	761·6	5·8781	51·550	37·014	4652·7	4457·1	3·9285
	264	761·8	5·8459	51·636	36·998	4654·9	4459·1	3·9750
	265	762·0	5·8279	51·583	36·953	4656·0	4460·4	3·9850
	266	762·1	5·8361	51·449	36·975	4656·7	4461·3	3·9369
	267	762·1	5·8742	51·098	36·835	4657·5	4463·2	3·8567
26	268	790·0	4·9084	45·363	32·695	4767·0	4589·8	4·0548
	269	790·2	4·8561	45·267	32·664	4768·1	4591·1	4·0768
	270	790·5	4·9163	45·252	32·637	4769·5	4592·6	4·0299
	271	790·8	4·8560	45·318	32·596	4768·6	4591·6	4·1140
	272	791·0	4·9588	45·241	32·452	4769·6	4593·1	4·0495
	273	791·4	4·8254	44·969	32·328	4772·1	4596·3	4·1138
27	274	842·2	4·9226	49·262	35·457	5025·0	4823·3	4·1477
	275	841·7	4·9145	49·220	35·430	5022·9	4821·5	4·1526
	276	841·7	4·9099	49·977	35·907	5021·0	4816·7	4·2350
	277	842·2	4·8966	49·482	35·679	5024·4	4821·7	4·1676
	278	842·6	4·8983	49·438	35·676	5026·3	4823·6	4·1525
	279	843·0	4·9039	49·521	35·665	5030·3	4827·4	4·1723
	280	843·0	4·8309	49·387	35·597	5030·6	4828·1	4·2158
	281	842·9	4·8106	49·320	35·491	5030·3	4828·3	4·2468
	282	842·8	4·9145	49·200	35·397	5030·2	4828·7	4·1502
28	283	899·1	4·6415	50·798	36·516	5249·4	5030·4	4·3394
	284	899·1	4·6189	50·864	36·520	5249·2	5030·1	4·3795
	285	899·2	4·5914	50·844	36·515	5249·7	5030·6	4·4008
	286	899·5	4·5916	50·969	36·572	5250·8	5031·1	4·4192
	287	899·5	4·5279	50·492	36·267	5254·2	5036·5	4·5173
	288	899·5	4·5956	50·654	36·255	5253·8	5035·7	4·4169
29	289	922·9	4·5112	52·490	37·459	5358·5	5128·6	4·5895
	290	923·3	4·5882	52·771	37·779	5359·6	5128·1	4·4963
	291	923·7	4·5405	52·690	37·911	5361·6	5129·9	4·4769
	292	923·5	4·5578	52·647	37·630	5360·9	5130·0	4·5343
	293	923·7	4·5537	52·619	37·536	5361·8	5131·2	4·5583
	294	924·1	4·5072	52·577	37·614	5358·5	5127·7	4·5706
	295	924·2	4·5298	52·550	37·653	5359·0	5128·3	4·5272
	296	924·3	4·5298	52·481	37·572	5359·6	5129·2	4·5467
30	297	941·1	4·4894	51·449	36·880	5364·2	5145·2	4·4899
	298	941·0	4·3508	51·380	36·879	5364·2	5145·1	4·6115
	299	941·0	4·3586	51·182	36·707	5364·7	5146·4	4·5962
	300	941·0	4·4442	51·182	36·720	5363·5	5145·3	4·5048
	301	941·2	4·3563	51·114	36·692	5364·4	5146·6	4·5829
	302	941·4	4·2701	51·017	36·663	5365·7	5147·8	4·6528
	303	941·5	4·3848	51·070	36·769	5366·1	5147·9	4·5134
	304	941·7	4·4483	51·278	36·806	5365·8	5147·2	4·5014

Table 7. Experimental data obtained using the series capillary viscometer

The nominal bore and length ratio of the capillaries was 1·7 mm and 35 mm:25 mm respectively.
The mean Reynolds number in the capillaries 7·44 Q/η.
The maximum Reynolds number obtained for the given set up 900.

Group	No.	t (°C)	$Q \times 10^2$ (g/s)	ΔP_1 (gf/cm^2)	ΔP_2 (gf/cm^2)	V_1 (cm^3/g)	V_2 (cm^3/g)	$\eta \times 10^4$ (poise)
31	305	301·7	2·4092	25·580	18·047	2596·0	2542·3	2·0185
	306	301·7	2·4104	25·609	18·036	2596·0	2542·2	2·0302
	307	301·6	2·4160	25·654	17·933	2595·4	2541·7	2·0738
	308	301·5	2·4295	25·802	17·933	2594·9	2541·0	2·1075
	309	301·4	2·4308	25·828	18·164	2596·3	2539·1	2·0307
	310	301·4	2·4332	25·908	18·177	2593·2	2538·9	2·0580
	311	301·3	2·4444	25·926	18·246	2592·7	2538·3	2·0315
32	312	392·5	2·4413	34·343	23·814	2969·6	2885·6	2·4057
	313	392·4	2·4414	34·276	23·827	2971·6	2889·0	2·3840
	314	392·3	2·4494	34·448	23·879	2970·9	2888·1	2·4070
	315	392·4	2·4814	34·914	24·039	2970·7	2886·9	2·4519
	316	392·5	2·4780	34·969	24·240	2971·1	2887·0	2·4121
	317	392·4	2·4838	34·849	24·226	2970·8	2886·9	2·5795
	318	392·5	2·4753	34·916	24·213	2971·2	2887·1	2·4121
33	319	490·4	2·3393	43·398	29·544	3433·3	3314·4	2·8342
	320	490·5	2·3372	43·468	29·613	3433·7	3314·5	2·8350
	321	490·4	2·3400	43·467	29·599	3433·2	3314·1	2·8355
	322	490·4	2·3471	43·448	29·631	3433·3	3314·1	2·8140
	323	490·4	2·3351	43·449	29·618	3433·3	3314·1	2·8521
	324	490·4	2·3358	43·411	29·540	3431·8	3312·8	2·8439
	325	490·4	2·3439	43·481	29·542	3431·7	3312·6	2·8502
34	326	600·0	2·2121	53·284	35·714	3906·6	3740·1	3·2996
	327	600·1	2·2130	53·270	35·726	3907·0	3740·5	3·2915
	328	600·0	2·2131	53·216	35·819	3907·1	3740·6	3·2564
	329	600·0	2·2116	53·225	35·736	3907·1	3740·7	3·2810
	330	600·0	2·2068	53·221	35·782	3907·1	3740·7	3·2760
	331	600·0	2·2010	53·020	35·675	3910·2	3744·3	3·2645
	332	600·1	2·1956	52·880	35·683	3910·5	3744·8	3·2391
35	333	698·4	1·8694	54·596	36·446	4321·4	4135·9	3·6534
	334	697·9	1·8706	54·599	36·448	4318·9	4133·8	3·6539
	335	697·8	1·8592	54·451	36·380	4318·8	4135·0	3·6566
	336	697·8	1·8624	54·465	36·328	4318·8	4134·1	3·6701
	337	697·8	1·8624	54·359	36·315	4321·0	4136·2	3·6456
	338	698·0	1·8643	54·503	36·220	4321·6	4136·7	3·7009
	339	698·1	1·8687	54·357	36·233	4322·3	4137·6	3·6532
36	340	802·6	1·4627	52·061	34·565	4838·4	4639·2	4·0531
	341	802·9	1·4641	52·017	34·776	4839·7	4639·9	5·9872
	342	803·1	1·4620	52·112	34·777	4840·5	4640·5	4·0031
	343	803·1	1·4641	52·057	34·523	4840·7	4641·4	4·0589
	344	803·9	1·4625	52·085	34·537	4843·3	4643·9	4·0645
	345	803·9	1·4639	52·107	34·561	4843·3	4643·7	4·0595
	346	803·9	1·4678	52·178	34·563	4843·1	4643·4	4·0487
37	347	855·0	1·3453	51·922	34·406	5041·9	4834·0	4·2389
	348	855·0	1·3491	51·864	34·363	5042·0	4834·4	4·2241
	349	854·9	1·3353	51·862	34·388	5041·4	4833·6	4·2594
	350	854·9	1·3426	51·673	34·147	5043·4	4838·3	4·2610
	351	855·0	1·3321	51·699	34·160	5042·4	4835·7	4·2954
	352	855·0	1·3468	51·688	34·281	5042·5	4835·5	4·2074
	353	855·0	1·3394	51·587	34·276	5042·7	4835·0	4·2034

Table 7—continued

Group	No.	t (°C)	$Q \times 10^2$ (g/s)	ΔP_1 (gf/cm^2)	ΔP_2 (gf/cm^2)	V_1 (cm^3/g)	V_2 (cm^3/g)	$\eta \times 10^4$ (poise)
38	354	906·5	1·3126	54·666	35·934	5267·7	5040·1	4·4451
	355	906·8	1·3102	54·644	36·043	5269·0	5041·2	4·4122
	356	907·0	1·3115	54·605	36·058	5270·0	5042·2	4·5915
	357	907·4	1·3096	54·520	35·828	5272·0	5044·7	4·4439
	358	907·7	1·3050	54·666	35·850	5273·0	5045·4	4·4927
	359	908·0	1·3123	54·601	36·024	5274·5	5046·6	4·5942
	360	908·3	1·3098	54·608	36·028	5275·8	5047·9	4·4027
39	361	951·6	1·2366	55·189	36·225	5482·3	5243·4	4·5895
	362	951·7	1·2376	55·398	36·235	5482·4	5243·1	4·6415
	363	951·8	1·2308	55·243	36·292	5483·0	5243·7	4·6044
	364	952·0	1·2399	55·213	36·303	5483·9	5244·7	4·5582
	365	952·1	1·2332	55·131	36·302	5485·7	5246·6	4·5593
	366	952·1	1·2267	55·184	36·301	5985·6	5246·4	4·5987
	367	952·1	1·2436	55·173	36·316	5485·6	5246·3	4·5284
40	368	1012·4	1·1293	55·475	36·380	5719·9	5469·1	4·8504
	369	1012·4	1·1323	55·502	36·402	5719·9	5468·9	4·8384
	370	1012·5	1·1362	55·476	36·469	5720·4	5469·3	4·7918
	371	1012·6	1·1314	55·568	36·496	5720·5	5469·1	4·8304
	372	1012·8	1·1270	55·542	36·482	5720·6	5470·2	4·8479
	373	1012·9	1·1310	55·399	36·374	5721·8	5473·1	4·8260
	374	1013·4	1·1283	55·343	36·456	5726·2	5475·3	4·7856
41	375	1060·2	1·0352	54·039	35·542	5914·1	5658·9	4·9596
	376	1060·0	1·0334	54·073	35·481	5913·2	5657·9	5·0010
	377	1060·1	1·0340	54·086	35·574	5913·6	5658·1	4·9692
	378	1060·2	1·0397	54·040	35·592	5914·1	5658·9	4·9214
	379	1060·2	1·0362	54·049	35·602	5913·3	5657·8	4·9375
	380	1060·2	1·0313	54·129	35·616	5913·1	5657·3	4·9816
	381	1059·9	1·0305	54·012	35·405	5912·1	5657·3	5·0238
42	382	819·7	1·4573	53·399	35·422	4921·2	4713·8	4·1020
	383	819·8	1·4592	53·480	35·431	4921·4	4713·8	4·1148
	384	819·6	1·4710	53·503	35·429	4920·5	4712·0	4·0875
	385	819·4	1·4520	53·535	35·459	4919·5	4711·8	4·1432
	386	819·2	1·4664	53·329	35·322	4919·1	4712·3	4·0894
	387	819·1	1·4455	53·178	35·346	4919·8	4713·3	4·1003
	388	819·1	1·4399	53·030	35·078	4920·2	4714·2	4·1556
43	389	977·6	1·1677	55·137	36·217	5641·8	5597·9	4·7151
	390	977·9	1·1630	54·986	36·223	5643·6	5400·1	4·6873
	391	978·2	1·1602	54·972	36·169	5644·9	5401·5	4·7108
	392	978·3	1·1676	54·813	36·050	5645·8	5403·2	4·6730
	393	978·5	1·1792	54·801	36·064	5646·8	5404·0	4·6183
	394	979·0	1·1681	54·859	36·085	5648·8	5405·8	4·6706
	395	979·1	1·1644	54·821	36·108	5649·4	5406·3	4·6659
44	396	1036·0	1·0964	55·743	36·506	5836·3	5578·9	4·9344
	397	1037·3	1·1069	55·809	36·506	5841·9	5584·1	4·9030
	398	1039·0	1·1016	55·781	36·438	5849·5	5591·5	4·9338
	399	1039·0	1·0987	55·810	36·440	5845·3	5587·2	4·9581
	400	1038·9	1·0937	55·957	36·639	5843·5	5585·5	4·9608
	401	1038·7	1·0999	55·906	36·641	5843·8	5584·9	5·0118

Table 8. *Experimental data obtained using the series capillary viscometer*

The nominal bore and length ratio of the capillaries was 1·5 mm and 37·5 mm:23 mm respectively.
The mean Reynolds number in the capillaries 8·33 Q/η.
The maximum Reynolds number obtained for the given set up 860.

Group	No.	t (°C)	$Q \times 10^2$ (g/s)	ΔP_1 (gf/cm^2)	ΔP_2 (gf/cm^2)	V_1 (cm^3/g)	V_2 (cm^3/g)	$\eta \times 10^4$ (poise)
45	402	294·2	2·0738	34·980	21·829	2597·4	2528·4	2·0044
	403	294·0	2·0662	34·991	21·907	2596·5	2527·4	2·0005
	404	293·8	1·6534	27·886	17·277	2604·7	2549·8	2·0474
	405	293·7	1·6440	27·890	17·280	2604·2	2549·3	2·0598
	406	293·4	1·2636	20·976	12·972	2609·9	2568·7	2·0380
	407	293·1	1·2580	20·783	12·834	2608·7	2567·9	2·0347
46	408	343·9	2·1406	43·169	26·945	2782·6	2690·2	2·2072
	409	343·9	2·1339	43·009	26·860	2782·8	2690·7	2·2035
	410	343·8	1·7208	33·865	21·068	2797·3	2724·9	2·1880
	411	343·8	1·7106	33·852	21·038	2798·1	2725·9	2·2042
	412	344·0	1·3271	25·784	15·800	2810·6	2755·8	2·2364
	413	344·1	1·3227	25·795	15·847	2811·1	2756·2	2·2344

Table 9. *Experimental data obtained using the series capillary viscometer*

The nominal bore and length ratio of the capillaries was 1·0 mm and 37·5 mm:23 mm respectively.
The mean Reynolds number in the capillaries 12·82 Q/η.
The maximum Reynolds number obtained for the given set up 890.

Group	No.	t (°C)	$Q \times 10^3$ (g/s)	ΔP_1 (gf/cm^2)	ΔP_2 (gf/cm^2)	V_1 (cm^3/g)	V_2 (cm^3/g)	$\eta \times 10^4$ (poise)
47	414	147·4	7·3026	34·714	20·080	1945·3	1894·0	1·3902
	415	147·8	7·3165	34·861	20·139	1945·1	1895·6	1·3950
	416	147·9	7·3488	34·868	20·276	1945·6	1895·9	1·3728
	417	148·6	6·0031	28·390	16·305	1950·3	1910·0	1·4066
	418	148·9	5·8954	28·078	16·170	1952·0	1912·1	1·4092
	419	149·4	4·4835	21·212	12·117	1958·1	1928·0	1·4267
48	420	242·0	7·5505	54·605	31·560	2346·9	2251·9	1·7065
	421	242·1	7·3846	54·570	31·403	2350·7	2255·7	1·7550
	422	242·2	7·4764	54·554	31·375	2347·9	2253·1	1·7369
	423	242·6	5·9281	42·833	24·482	2362·5	2288·2	1·7561
	424	243·1	5·9178	42·812	24·538	2364·9	2290·5	1·7482
	425	243·9	4·4836	31·333	17·895	2378·8	2324·4	1·7144
	426	244·2	4·2659	30·879	17·668	2380·7	2327·0	1·7699
49	427	437·0	3·5163	49·440	27·588	3154·5	3057·3	2·6410
	428	437·8	3·5567	49·644	27·643	3157·7	3040·0	2·6274
	429	438·2	3·6036	49·540	27·618	3159·7	3042·0	2·5814
	430	439·3	2·3165	32·593	18·480	3191·1	3113·1	2·6002
	431	439·9	2·3123	32·832	18·613	3195·4	3114·8	2·6219
	432	440·1	2·3216	33·427	18·963	3197·5	3117·2	2·6504
50	433	549·1	2·6629	50·676	28·325	3746·4	3607·5	3·0041
	434	548·7	2·6409	50·602	28·161	3744·7	3606·4	3·0481
	435	548·5	2·6154	50·342	28·018	3744·3	3606·7	3·0630
	436	548·5	2·6005	50·242	27·902	3747·2	3610·0	3·0835
	437	548·6	1·6156	31·365	17·798	3782·3	3695·2	3·0325
	438	548·5	1·6529	31·455	17·870	3781·0	3694·4	2·9685

Table 9—continued

Group	No.	t (°C)	$Q \times 10^3$ (g/s)	ΔP_1 (gf/cm^2)	ΔP_2 (gf/cm^2)	V_1 (cm^3/g)	V_2 (cm^3/g)	$\eta \times 10^4$ (poise)
51	439	660·8	1·8127	44·712	25·105	4198·9	4059·5	3·4738
	440	661·2	1·7895	44·690	25·001	4201·6	4061·5	3·5550
	441	661·7	1·7965	44·775	24·990	4202·8	4063·3	3·5411
	442	663·9	1·8125	44·511	24·937	4208·9	4069·5	3·4633
	443	664·7	1·8103	44·491	24·940	4212·5	4073·4	3·4601
	444	665·4	1·7823	44·487	24·872	4215·7	4076·5	3·5267
52	445	616·3	2·0491	45·693	25·509	4012·9	3877·1	3·3121
	446	617·2	2·0189	45·706	25·536	4017·0	3880·9	3·3549
	447	617·8	2·0232	45·692	25·575	4019·7	3883·6	3·3345
	448	618·1	1·3464	30·544	17·309	4053·5	3962·0	3·3175
	449	617·0	1·3402	30·538	17·306	4048·5	3957·1	3·3365
	450	616·0	1·3524	30·220	17·060	4044·5	3954·4	3·2971
53	451	532·7	2·4250	45·306	25·429	3720·2	3598·5	2·9715
	452	532·5	2·4503	45·519	25·482	3718·9	3596·7	2·9675
	453	532·4	2·4510	45·386	25·443	3718·6	3596·8	2·9520
	454	531·8	1·6378	30·686	17·253	3741·1	3658·7	3·0076
	455	531·8	1·6330	30·688	17·321	3747·1	3664·6	2·9934
	456	531·7	1·6040	30·636	17·269	3746·7	3664·4	3·0495
54	457	738·0	1·4899	43·389	24·244	4593·8	4446·6	3·7878
	458	738·1	1·4538	42·734	24·081	4595·6	4451·2	3·7734
	459	738·6	1·4755	43·037	24·135	4597·2	4452·0	3·7715
	460	739·1	1·4928	43·010	24·014	4592·6	4447·6	3·7559
	461	739·6	1·4658	42·930	24·060	4595·1	4450·1	3·7927
	462	739·8	1·4384	42·962	24·089	4595·9	4450·8	3·8640
55	463	111·7	7·1060	28·232	16·492	1712·4	1675·4	1·3046
	464	111·4	7·0639	27·855	16·391	1712·2	1676·0	1·2794
	465	111·2	7·0851	27·888	16·312	1710·4	1673·8	1·2916
	466	110·4	8·8213	34·642	20·277	1702·1	1656·7	1·2809
	467	110·3	8·8737	35·169	20·612	1701·2	1655·1	1·2893
	468	110·3	4·8039	19·019	11·206	1715·2	1690·2	1·2946
	469	110·3	5·0019	19·752	11·540	1714·5	1690·4	1·3122
56	470	188·0	7·9632	45·656	26·297	2058·6	1987·7	1·5690
	471	188·1	3·0367	45·645	26·269	2059·1	1988·2	1·5562
	472	188·6	6·9958	39·579	22·898	2066·6	2004·9	1·5432
	473	188·7	7·0526	39·634	22·846	2067·0	2005·3	1·5425
	474	189·1	5·6417	32·142	18·567	2074·8	2024·7	1·5680
	475	189·2	5·7210	32·135	18·570	2075·2	2025·1	1·5445
	476	189·3	4·2412	23·994	13·840	2080·1	2042·7	1·5737
	477	189·4	4·3201	23·976	13·818	2080·6	2043·2	1·5456
	478	189·4	4·2750	23·940	13·834	2080·6	2043·2	1·5526
57	479	316·9	5·4507	51·321	29·001	2607·9	2508·6	2·0900
	480	316·8	5·5274	51·335	29·022	2607·4	2508·1	2·0602
	481	316·7	4·6148	43·113	24·433	2618·4	2533·4	2·0758
	482	316·7	4·6081	43·151	24·443	2618·3	2533·2	2·0822
	483	316·7	3·8881	36·456	20·718	2627·8	2555·9	2·0843
	484	316·7	3·9145	36·520	20·663	2627·8	2555·8	2·0891
	485	316·8	2·8798	26·857	15·300	2641·6	2588·6	2·0795
	486	316·8	2·9646	27·531	15·642	2640·8	2586·4	2·0787

Table 10. *Experimental data obtained using the series capillary viscometer*

The nominal bore and length ratio of the capillaries was 2·0 mm and 37·5 mm:23 mm respectively.
The mean Reynolds number in the capillaries 6·50 Q/η.
The maximum Reynolds number obtained for the given set up 250.

Group	No.	t (°C)	$Q \times 10^2$ (g/s)	ΔP_1 (gf/cm^2)	ΔP_2 (gf/cm^2)	V_1 (cm^3/g)	V_2 (cm^3/g)	$\eta \times 10^4$ (poise)
58	487	869·8	1·6183	38·352	24·221	5081·9	4929·3	4·2897
	488	869·8	1·6141	38·417	24·269	5081·8	4928·9	4·3059
	489	869·9	1·6150	38·412	24·247	5082·3	4929·4	4·3081
	490	869·7	1·3969	33·135	21·025	5100·3	4968·2	4·2744
	491	869·5	1·4075	33·188	21·039	5099·3	4967·0	4·2566
	492	868·7	1·1551	27·402	17·288	5114·9	5006·0	4·3391
	493	868·3	1·1579	27·270	17·288	5113·4	5004·9	4·2744
	494	867·3	1·0416	24·468	15·442	5116·1	5018·9	4·3101
	495	867·2	1·0435	24·428	15·469	5115·8	5018·6	4·2713
59	496	962·4	1·5446	42·598	26·829	5474·1	5291·2	4·6245
	497	962·5	1·5545	42·617	26·824	5474·5	5291·6	4·6014
	498	962·4	1·5571	42·613	26·883	5474·1	5291·0	4·5752
	499	961·9	1·3553	37·046	23·434	5491·7	5332·4	4·5702
	500	962·0	1·3507	37·051	23·370	5492·1	5333·0	4·6089
	501	961·8	1·1704	31·966	20·135	5509·3	5372·0	4·6177
	502	961·8	1·1744	31·924	20·160	5587·0	5369·8	4·5777
	503	961·8	1·1742	31·872	20·108	5507·1	5370·2	4·5789
	504	962·2	0·9650	26·139	16·508	5528·6	5416·2	4·5797
	505	963·0	0·9569	26·147	16·553	5532·2	5419·5	4·5975
60	506	1035·8	1·3360	40·262	25·426	5775·5	5591·0	4·7809
	507	1033·8	1·3373	40·265	25·348	5775·5	5591·1	4·8028
	508	1033·7	1·1782	35·656	22·400	5792·5	5629·4	4·8625
	509	1033·6	1·1816	35·547	22·398	5792·4	5629·6	4·8097
	510	1033·5	1·0084	30·356	19·217	5813·3	5674·1	4·7921
	511	1033·7	1·0062	30·291	19·165	5814·4	5675·5	4·7968
	512	1033·9	0·8766	26·229	16·635	5830·2	5709·7	4·7623
	513	1033·9	0·8703	26·140	16·583	5830·4	5710·4	4·7779
	514	1034·0	0·8702	26·141	16·518	5830·9	5711·0	4·8110
61	515	832·6	1·5206	33·440	21·166	4919·3	4790·5	4·1236
	516	832·7	1·5078	33·419	21·161	4919·8	4791·0	4·1527
	517	835·5	1·2786	28·329	17·957	4941·9	4834·0	4·1650
	518	833·7	1·2828	28·326	17·935	4942·8	4833·4	4·1480
	519	834·0	1·2651	28·259	17·828	4944·2	4834·3	4·2195
	520	833·9	1·2796	28·271	17·854	4943·7	4834·8	4·1682
62	521	913·9	1·5153	38·441	24·319	5276·5	5117·2	4·4091
	522	913·8	1·5091	38·398	24·268	5276·2	5117·1	4·4302
	523	913·6	1·5122	38·407	24·266	5275·3	5116·2	4·4253
	524	913·5	1·6760	42·429	26·711	5264·3	5088·9	4·4226
	525	913·6	1·6771	42·663	26·872	5264·2	5087·7	4·4512
	526	913·9	1·3055	33·135	20·980	5299·1	5161·8	4·4189
	527	914·1	1·3123	33·200	20·931	5299·9	5162·5	4·4364
	528	914·1	1·0927	27·689	17·497	5322·8	5208·0	4·4408
	529	914·1	1·0866	27·483	17·408	5323·3	5209·4	4·4153

Table 10—*continued*

Group	No.	t (°C)	$Q \times 10^2$ (g/s)	ΔP_1 (gf/cm²)	ΔP_2 (gf/cm²)	V_1 (cm³/g)	V_2 (cm³/g)	$\eta \times 10^4$ (poise)
63	530	1003·8	1·6261	48·045	29·825	5699·0	5486·0	4·8476
	531	1003·7	1·6177	47·830	29·741	5699·1	5487·0	4·8388
	532	1003·5	1·6325	47·614	29·685	5698·8	5487·5	4·7531
	533	1002·7	1·3995	41·191	25·726	5720·0	5537·2	4·8074
	534	1002·6	1·3981	41·109	25·770	5719·8	5537·1	4·7734
	535	1002·4	1·1926	35·029	21·978	5741·1	5585·1	4·7831
	536	1002·7	1·1930	34·883	21·992	5742·8	5587·4	4·7224
	537	1003·6	1·0360	30·334	18·999	5762·7	5627·9	4·7948
	538	1003·6	1·0346	30·332	19·024	5762·7	5627·8	4·7897
64	539	1070·4	1·4878	47·708	29·681	5930·6	5712·2	5·0379
	540	1070·1	1·4929	47·517	29·687	5929·8	5711·9	4·9666
	541	1070·5	1·3078	41·644	26·135	5950·8	5754·1	4·9450
	542	1070·4	1·3082	41·548	26·036	5949·9	5755·0	4·9484
	543	1070·6	1·1111	35·268	22·159	5976·1	5809·5	4·9438
	544	1070·7	1·1093	35·187	22·128	5976·8	5810·5	4·9324
	545	1071·3	0·9563	30·288	19·061	5994·0	5850·7	4·9381
	546	1071·9	0·9589	30·341	19·167	5996·4	5852·6	4·8995
65	547	1048·6	1·5274	46·834	29·293	5769·6	5570·1	4·9286
	548	1048·4	1·5329	46·886	29·244	5768·6	5569·1	4·9403
	549	1048·1	1·3254	40·274	25·284	5795·1	5615·3	4·8621
	550	1048·0	1·3218	40·245	25·278	5794·7	5615·1	4·8118
	551	1047·9	1·3249	40·244	25·285	5794·3	5614·6	4·8547
	552	1047·3	1·1272	34·356	21·601	5814·6	5656·7	4·8817
	553	1047·1	1·1293	34·321	21·577	5812·6	5654·9	4·8700
	554	1046·4	0·9302	28·237	17·729	5832·4	5701·8	4·8974
	555	1046·4	0·9275	28·237	17·823	5832·4	5701·5	4·8689

A viscosity against temperature plot for the whole of the results obtained from both apparatus is given in Fig. 9. The curve which is shown on this graph was obtained from a fifth degree polynomial, which gave the best fit of several polynomials fitted to the data using the percentage least squares fit method. The coefficients and the overall standard deviation of the points from this equation are given below

$$\eta = A + BT + CT^2 + DT^3 + ET^4 + FT^5 \qquad T \text{ in } {}^\circ\text{K} \qquad (7)$$

where.

$A = -0{\cdot}65634 \times 10^{-5}$
$B = 0{\cdot}26700 \times 10^{-6}$
$C = 0{\cdot}25500 \times 10^{-9}$
$D = -0{\cdot}13303 \times 10^{-12}$
$E = -0{\cdot}22475 \times 10^{-16}$
$F = 0{\cdot}18488 \times 10^{-19}$

Standard deviation of the experimental points from this equation ±1·22 per cent

A polynomial which had been fitted to the mean value of each set of data obtained at each nominal temperature, with a given assembly, agreed very favourably with the above equation.

The deviation of the individual points from equation (7) is given in Fig. 10. More than 95 per cent of the points lie within a ±2 per cent band, thus giving an expected standard deviation of about ±1·3 per cent (2nd standard deviation), which is in agreement with the actual computed value of ±1·22 per cent.

A Sutherland equation of the form of

$$\eta = \frac{KT^{3/2}}{(C + T)} \quad \text{or} \quad T = K\left\{\frac{T^{3/2}}{\eta}\right\} - C \qquad (8)$$

was fitted to the experimental data in the temperature range 150–950°C. Below and above this temperature range the points tended to diverge from the equation. The values for the constants K and C were found to be 25·6, 10^{-5} poise/°K and 1150°K respectively, which is

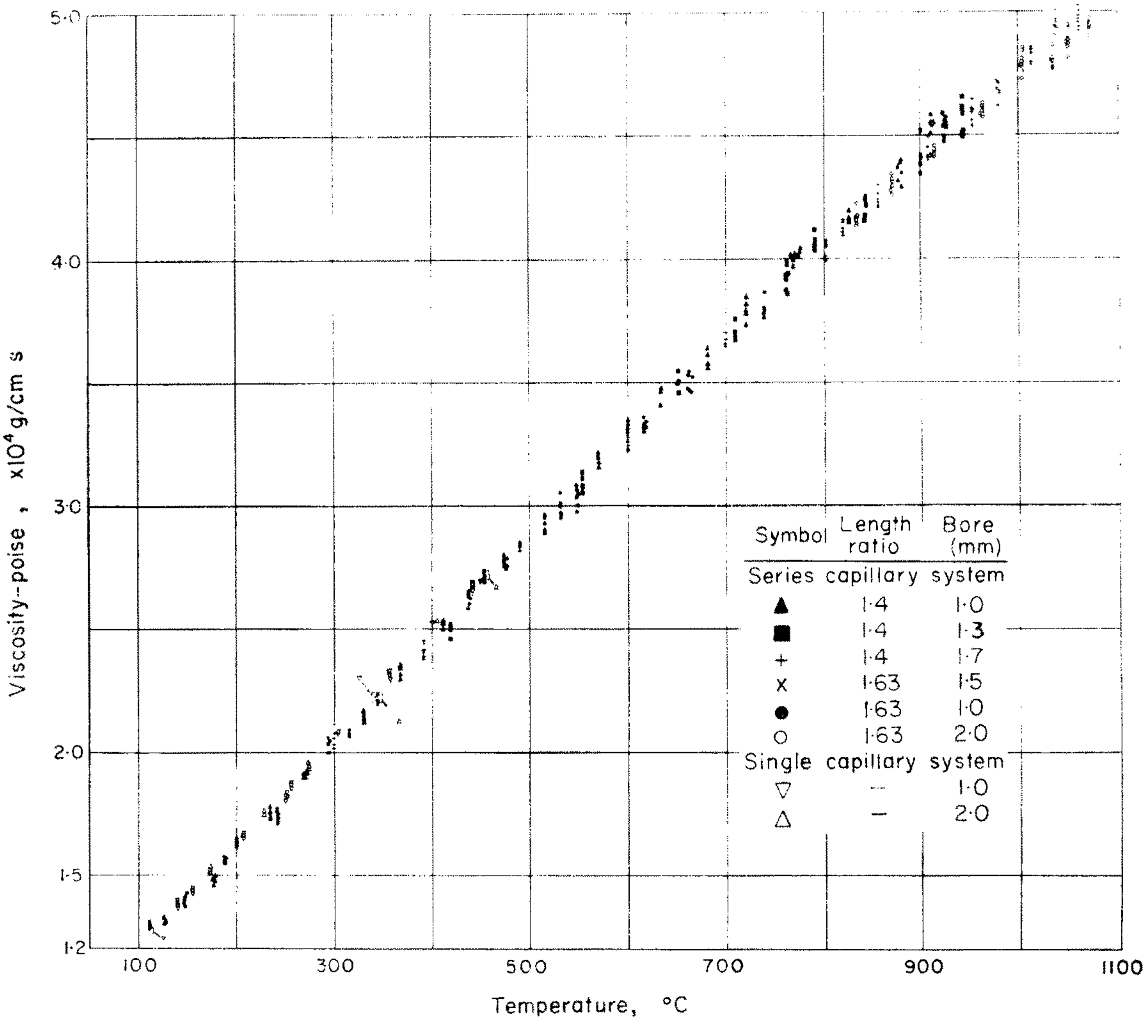

FIG. 9. Graph of viscosity against temperature.

in exact agreement with the values found by Shifrin. A more detailed analysis of the results, giving separate deviations plots for the experimental data obtained from each up, may be found in references 26 and 27. However, the following more concise details are given in Table 11, the maximum deviation of the points from the recommended values, the mean deviation of the points from the recommended values, the maximum Reynolds number used, and the temperature ranges used, for each of the capillary arrangements. Although there was very good agreement between the experimental results from each of the set ups, the results from first quartz arrangement did tend to infer that the atmospheric curve should have a greater slope than that which was finally used. However, the majority of the points agreed very favourably with the recommended values, and since a number of capillaries have a range of bores, lengths and length ratios were used, it was considered that there were no appreciable systematic or inherent errors in the viscosity values obtained using the present technique. That is, if the assumption that the method of using a capillary viscometer to determine the

Table 11

Arrangement	Group Nos.	Temperature range (°C)	Max *Re*	Max (+%)	Deviation (−%)	Standard deviation from the recommended values [equation (7)] (±%)
1	I to XII	112·8 to 449·6	890	1·8	1·1	0·5
2	XIII to XVIII	173·0 to 455·1	670	1·4	0·8	0·6
3	1 to 18	126·9 to 910·0	810	3·0	4·4	1·2
4	19 to 30	201·5 to 941·7	1130	3·0	2·0	1·2
5	31 to 44	301·3 to 1039·0	900	3·2	2·2	0·8
6	45 to 46	293·1 to 344·1	860	2·5	1·7	1·1
7	47 to 57	110·3 to 739·8	890	3·4	4·0	0·9
8	58 to 65	867·2 to 1071·9	250	1·8	2·2	0·7

Arrangements 1 and 2 were the single capillary glass apparatus.
Arrangements 3 to 8 were the series capillary quartz apparatus.

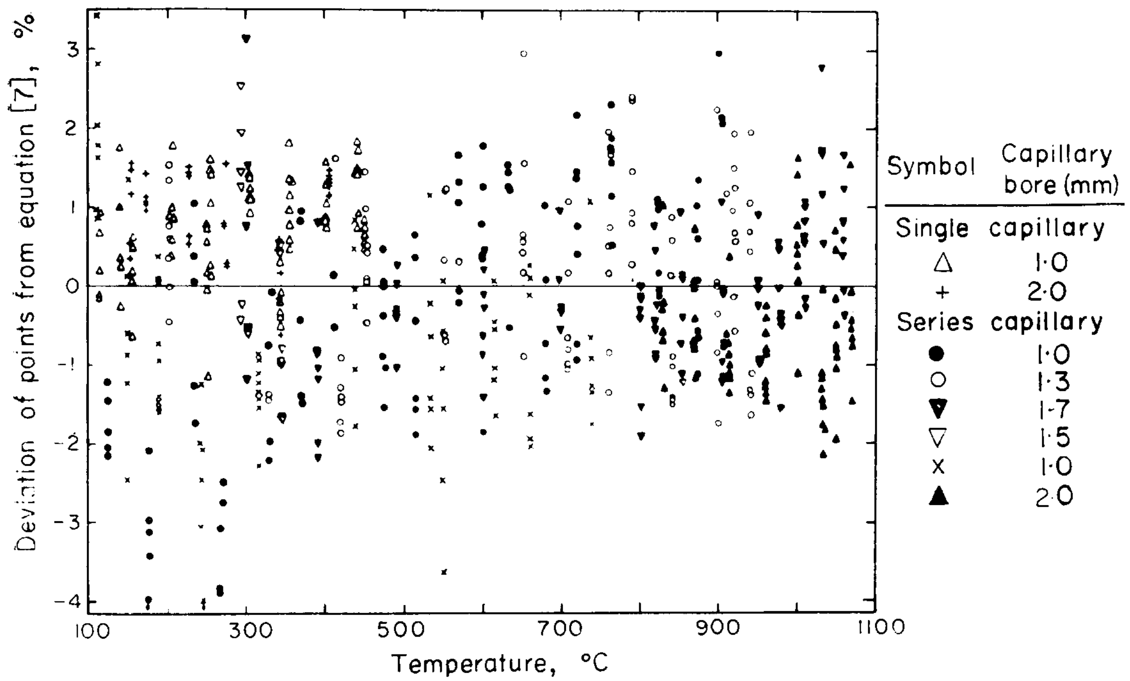

FIG. 10. Deviation of the experimental points from equation (7).

viscosity of a Newtonian fluid is valid. Some experimentors are of the opinion that there may be unforeseen factors which may limit the accuracy of certain apparatus, inferring that different apparatus may be capable of giving slightly different results at given densities and pressures. This argument can only be resolved by checking the agreement between the results obtained from completely different types of apparatus and therefore is not within the scope of this paper.

Table 12 gives the recommended values for the viscosity of steam at atmospheric pressure, generated at 10°C intervals between 100°C and 1100°C using equation (7).

A deviation plot comparing the values put

Table 12

t(°C)	0	10	20	30	40	50	60	70	80	90
100	1·214	1·254	1·294	1·334	1·375	1·415	1·456	1·497	1·538	1·579
200	1·621	1·662	1·704	1·745	1·787	1·829	1·871	1·913	1·955	1·997
300	2·039	2·081	2·123	2·166	2·208	2·250	2·292	2·334	2·377	2·419
400	2·461	2·503	2·545	2·587	2·629	2·671	2·713	2·754	2·796	2·837
500	2·879	2·920	2·962	3·003	3·044	3·085	3·126	3·166	3·207	3·247
600	3·287	3·328	3·368	3·407	3·447	3·476	3·526	3·565	3·604	3·643
700	3·681	3·720	3·758	3·796	3·834	3·872	3·909	3·947	3·984	4·021
800	4·057	4·094	4·130	4·166	4·202	4·238	4·273	4·309	4·344	4·379
900	4·413	4·448	4·482	4·516	4·550	4·584	4·617	4·651	4·684	4·717
1000	4·750	4·782	4·815	4·847	4·879	4·911	4·943	4·974	5·006	5·037
1100	5·068									

Units; viscosity × 10^4 poise, i.e. at 100°C viscosity is 1·214 10^{-4} g/cm s.

forward by Bonilla, Kestin, Shifrin and Krieger with the present work is given in Fig. 11. Bonilla and Shifrin agree quite well on the shape of the curve but have a constant difference of about 3·8 per cent,* however, Krieger's semi-empirical equation agrees more closely with Shifrin's data and the present work, especially in the temperature range 200–650°C. The agreement between the shape of Krieger's curve and the curve fitted to Shifrin's experimental data is remarkable, considering that Krieger based his equation on a rather limited amount of low temperature data. Kestin's data, which the author feels is one of the more reliable sets of low pressure data, agrees very favourably with the present work. However, Kestin's data only covers a limited temperature range and consequently the form

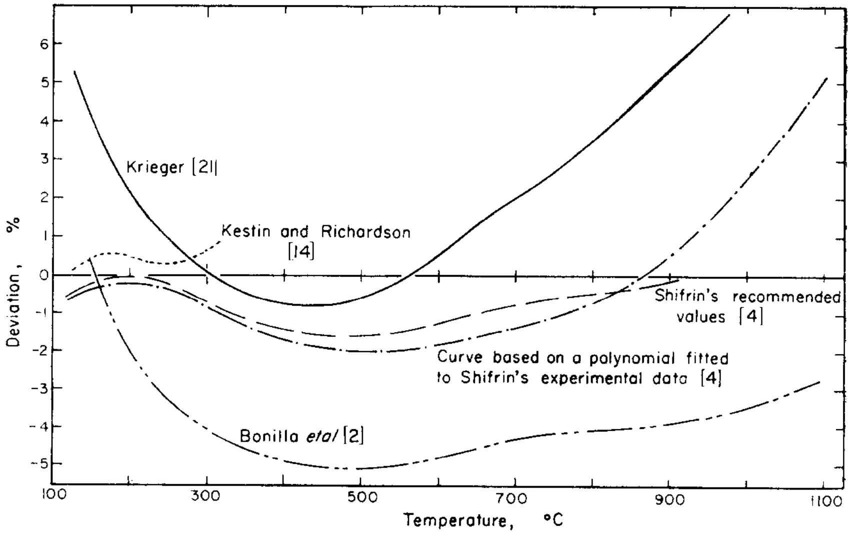

FIG. 11. Deviations of Shifrin's, Bonilla's, Krieger's and Kestin's recommended values for the 1 atm curve from equation (7).

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* The author does not feel that he is in a position to comment on the reason for the difference between Bonilla's work and the work of the majority of other investigators, apart from pointing out that there appears to be an inherent error, probably due to some error in the equation for spiral capillaries.

of the curve cannot be accurately predicted if only his work is considered.

It appears that either the present methods of extrapolating the high pressure data are not really valid, (since Timrot's, Timrot's and Khlopkina's and Hawkins' data diverge by an unrealistic amount when extrapolated to atmospheric pressure) or the high pressure data is not sufficiently accurate to justify extrapolation to low pressures. The latter reason is more likely to be the cause of the deviation of the extrapolated high-pressure data for use at low pressures.

The author does not agree with Shifrin's conclusion that his curve could quite reliably be extrapolated to 1500°C without additional high temperature experimental data, since the present work shows a definite increase in the rate of change of the slope of the atmospheric curve at the higher temperatures, which if extrapolated to 1500°C would be considerably different to the values obtained by extrapolating Shifrin's curve to 1500°C. In actual fact a third degree polynomial was fitted to Shifrin's experimental data (which was the best fit out of several polynomials) and showed a deviation from the present work of about 5 per cent at 1100°C, which is not exactly indicated by his given equation. Several polynomials were fitted to the experimental data obtained from each individual capillary assembly. It was noted that on examination of this computation data that in a number of cases (especially when based on the lower pressure determinations of the more sparse data) when extrapolated showed considerable deviation at the extreme temperatures, although over the measured temperature ranges the polynomials fitted very well.

There was very good agreement between the measurements taken with different sets of capillaries, the temperature ranges for each capillary arrangement being such that they overlapped for all the assemblies. This procedure was carried out in order to remove any suspicion of inherent errors that might exist if only one capillary assembly had been used. The main reason for using a number of capillary assemblies, and therefore several different length and diameter ratios, was to make the viscometer more versatile with regard to temperature.

A graph of mean Reynolds numbers against temperature, for the mean conditions at each nominal temperature is given in Fig. 12. It can be seen that the Reynolds numbers used were all well below the critical value for laminar flow conditions, the maximum was below 1250. Estimations of the entrance development length based on the Reynolds numbers were made, and indicated that for some of the capillaries, when being used at their lowest temperatures (lowest reasonable temperatures depended on the capillary length and diameter and the minimum, allowable pressure drop to give a reasonable mass flow rate) was up to and more than 50 per cent of the capillary length. However, there appears to be no appreciable difference between the viscosity measurements made under these conditions and measurements made when the development length was small.

An attempt was made to obtain the value of the end correction constant m for square cut ended tubes, using the two capillary apparatus. Two methods were originally considered (i) to determine the value of the viscosity of the steam at given conditions and then use that data in the individual flow equations for the two capillaries and hence calculate the value of m. or (ii) add the two simultaneous flow equations and eliminate η and obtain an equation for m. When the actual experimental data was used in either of the above methods to find m, it was found that the value obtained varied by as much as 50 per cent in some cases, at a given isotherm. An estimation of the precision was made (based on the observed fact that the precision of the mass flow collection was not better than $\pm 0{\cdot}5$ per cent in the majority of cases) and predicted that this uncertainty in m could be even larger than the actual experimental scatter obtained. It was difficult to make a rigorous estimation of the precision of the two methods for finding m, since the accuracy and precision of m depended on the overall value of the end correction $(mQ)/(8\pi l)$, in the flow equation. It was obvious that for given values of m and l, as Q was decreased, the ratio $(mQ/8\pi l)/\eta_P$ where η_P, the Poiseuille viscosity $= \pi d^4 g \Delta P/128 Q l V_s$ also decreased and consequently any experimental scatter in the values of Q or η (the major variables in the equations), would be much amplified when finding m.

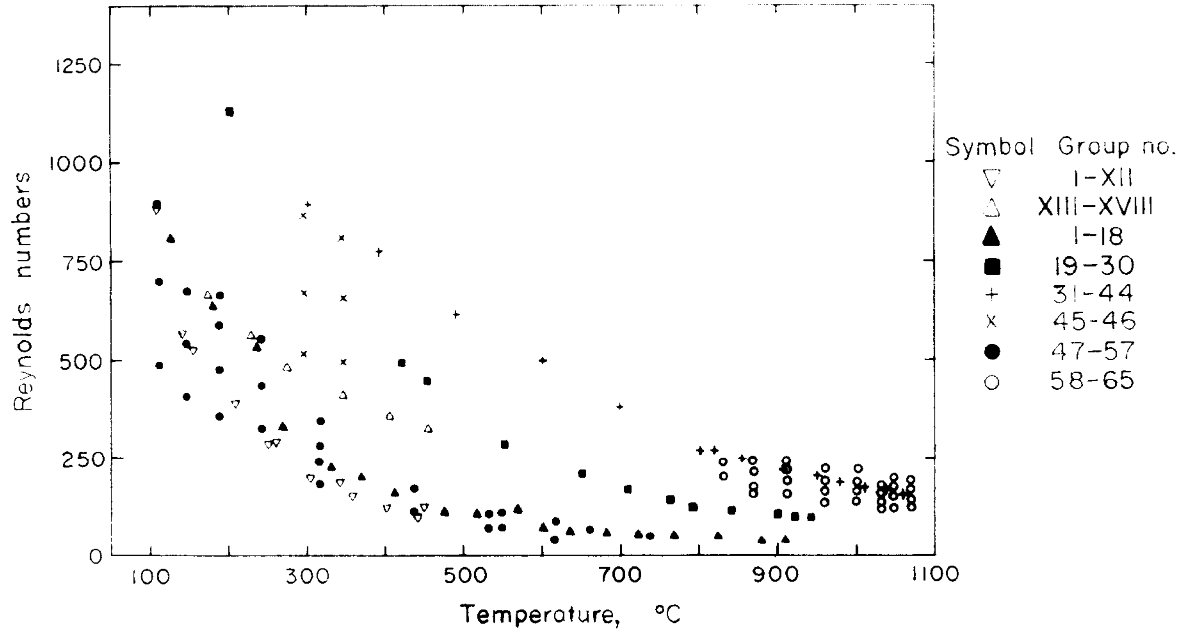

FIG. 12. Mean Reynolds numbers for each mass flow rate.

A graphical solution for finding *m* and *n* was attempted using the equation $\eta = \eta_P - mQ/8\pi l$ where η_P is the Poiseuille viscosity, by varying the mass flow rate at a given temperature. This was actually attempted for the last three capillary sizes. After the points from several of these sets of results had been plotted it was apparent that η could be ascertained to a reasonable accuracy but unfortunately with the experimental scatter it was impossible to determine even a rough value for *m*, since almost any number of straight lines having the same slopes could be fitted to the experimental data and still give reasonable intercepts on the η axis.

It was noted that Flynn *et al.* Ross [31] who used the semi-graphical method of extrapolating to zero flow conditions, deduced that the method could be quite successfully employed to determine η and *m*. However, on closer scrutiny of their theses it was apparent that they had some difficulty, since in several of their runs the value of *m* varied quite considerably (even negative values were reported). Unlike the present work they did not make a large number of runs at a given temperature and therefore it is rather difficult to assess whether they would have had more scatter in their computed value of *m*, as the present work did.

It was deduced that with the experimental scatter obtained, unless a much larger number of determinations were made, at each nominal temperature, no recommendation for the value of *m* could be made. However, it was noticed that even with the relatively few determinations made at a given temperature, a value for η could be extrapolated with reasonable accuracy. It was felt that the graphical or semi-graphical methods for obtaining η and *m* could not be used with the present apparatus, unless either the experimental scatter could be reduced and/or a much larger number of individual determinations could be made at a given temperature.

CONCLUSIONS

(i) The viscosity of steam at a pressure of one bar can be expressed by equations of the form of

$$\eta = A + BT + CT^2 + DT^3 + ET^4 + FT^5$$

over the temperature range 100–1100°C,

and

$$\eta = \frac{KT^{3/2}}{(C+T)}$$

over the temperature range 150–950°C.

(ii) The results confirm Shifrin's assertion that the method of using two capillaries in series can be used with accuracy to measure the viscosity of Newtonian fluids at atmospheric pressure.

(iii) The accuracy of the recommended values for the viscosity is thought to be better than ±2 per cent over the temperature range 110–1100°C.

(iv) The method of using two capillaries in series is not suitable for determining the end correction coefficient m for tubes with any reasonable accuracy, unless high experimental precision is obtainable.

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Résumé—Cet article donne les résultats expérimentaux de la mesure de la viscosité de la vapeur d'eau à la pression atmosphérique dans la gamme de température 110–1071°C. Ce travail a été entrepris à cause de la mauvaise concordance entre les résultats antérieurs dans la gamme 100–600°C, des observations relativement rares au-dessus de 600°C, et du besoin d'obtenir des valeurs fiables à la pression atmosphérique pour a corrélation des mesures à haute pression. On croit que les résultats rapportés ici remplissent d'une façon adéquate ces conditions.

Deux appareils ont été imaginés, et étudiés, tous les deux étant des viscosimètres du type capillaire à transpiration permettant des déterminations absolues. La conception de l'appareil était telle que l'on puisse vérifier les diamètres intérieurs des capillaires avant et après usage et que l'on puisse introduire des capillaires de différentes longueurs et diamètres intérieurs.

Le premier appareil, qui était un viscosimètre à capillaire de verre unique, a été étudié comme prototype pour le second appareil. Deux capillaires différents ayant approximativement la même longueur, étaient employés dans la gamme de température 110–460°C.

Le second appareil qui était fabriqué en quartz, utilisait six couples différents de capillaires en série. Trois d'entre eux avaient un rapport différent des longueurs de capillaires. L'appareil était employé dans toute la gamme de températures 110–1071°C.

Plus de 500 observations différentes sont rapportées et l'on pense que la précision des valeurs recommandées est meilleure que 2 pour cent. On a ajusté aux résultats du travail actuel un polynôme du cinquième degré pour la température et une équation du type de Sutherland.

Zusammenfassung—In diese Arbeit sind die Versuchsergebnisse der Viskositätsmessung von Dampf bei Atmosphärendruck für den Temperaturbereich von 110 bei 1071°C angegeben. Diese Arbeit wurde einmal wegen mangelnder Übereinstimmung unter den Ergebnissen früherer Arbeiten im Bereich von 100 bis 600°C, zum anderen wegen der relativ geringen Anzahl von Beobachtungen über 600°C hinaus und wegen der Notwendigkeit, zuverlässige Werte bei Atmosphärendruck für Beziehungen zu Messungen bei hohen Drücken zu erhalten, angeregt.

Es wird angenommen, dass die hier vorgelegten Ergebnisse diesen Forderungen entsprechen.

Es wurden zwei Apparaturen entworfen und entwickelt, die beide vom Typ des kapillarviskosimeters (transpiration) waren und Absolutmessungen ermöglichten. Der Entwurf der Apparatur sah vor, dass die Bohrung der Kapillaren vor und nach Gebrauch überprüft werden konnte, und dass Kapillaren verschiedener Längen und Weiten eingeführt werden konnten. Die erste Vorrichtung, die aus einem einzigen Kapillarviskosimeter aus Glas bestand, wurde als Prototyp für die zweite Versuchseinrichtung entwickelt. Zwei verschiedene Kapillaren annähernd gleicher Länge wurden für den Temperaturbereich zwischen 110°C und 460°C verwendet.

Die zweite Versuchsvorrichtung aus Quarz benützte zwei Kapillaren in Reihe. Drei davon in der einen Gruppe hatten ein unterschiedliches Längenverhältnis der Kapillaren gegenüber den anderen drei. Die Apparatur wurde für den Temperaturbereich von 110 bis 1071°C verwendet. Es werden 500 getrennt durchgeführte Messungen angegeben und die Genauigkeit der empfohlenen Werte wird für besser als 2 Prozent gehalten. Den Ergebnissen dieser Arbeit wurde ein Polynom fünften Grades für die Temperatur und eine Gleichung vom Typ Sutherland angepasst.

Аннотация—В данной статье приводятся экспериментальные результаты измерения вязкости пара при атмосферном давлении в диапазоне температур от 110 до 1071°C. Такие эксперименты были поставлены вследствие недостатка согласованности между результатами ранних работ, проводимых в диапазоне 100–600°C, наличия сравнительно небольшого числа наблюдений при температуре выше 600°C и желания получить надежные атмосферные значения для корреляции измерений при высоких давлениях. Следует надеяться, что сообщаемые здесь результаты отвечают этим требованиям.

Сконструированы и разработаны два аппарата типа испарительнокапиллярных вискозиметров, позволяющих производить абсолютные измерения. Конструкция аппарата позволяла проверять внутренний диаметр капиллярной трубки перед и после проведения эксперимента и вводить капилляры различной длины и внутреннего диаметра.

Первый аппарат, стеклянный вискозиметр с одной капиллярной трубкой, был разработан как прототип второго аппарата. Два различных капилляра, имеющих приблизительно ту же длину, использовались в температурном диапазоне от 110 до 460°C.

На втором аппарате, изготовленном из кварца, применялись последовательно по два капилляра. Три пары капилляров имели различные отношения длин капилляров в установке к другим трем. Аппарат работал в диапазоне температур 110–1071°C.

Выполнено свыше 500 наблюдений. Предполагается, что точность предложенных значений имеет погрешность менее 2%. Результаты настоящей работы могут быть описаны полиномом пятой степени для температуры и уравнением типа Сазерлэнда.