



<https://theses.gla.ac.uk/>

Theses Digitisation:

<https://www.gla.ac.uk/myglasgow/research/enlighten/theses/digitisation/>

This is a digitised version of the original print thesis.

Copyright and moral rights for this work are retained by the author

A copy can be downloaded for personal non-commercial research or study,
without prior permission or charge

This work cannot be reproduced or quoted extensively from without first
obtaining permission in writing from the author

The content must not be changed in any way or sold commercially in any
format or medium without the formal permission of the author

When referring to this work, full bibliographic details including the author,
title, awarding institution and date of the thesis must be given

Enlighten: Theses

<https://theses.gla.ac.uk/>
research-enlighten@glasgow.ac.uk

1st copy

THE EXPERIMENTAL DETERMINATION OF THE VISCOSITY
OF STEAM AT HIGH PRESSURES

By

Einar Kjelland-Fosterud, B.Sc.

Submitted for the Degree of Ph.D.,
University of Glasgow.

ProQuest Number: 10656380

All rights reserved

INFORMATION TO ALL USERS

The quality of this reproduction is dependent upon the quality of the copy submitted.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if material had to be removed, a note will indicate the deletion.



ProQuest 10656380

Published by ProQuest LLC (2017). Copyright of the Dissertation is held by the Author.

All rights reserved.

This work is protected against unauthorized copying under Title 17, United States Code
Microform Edition © ProQuest LLC.

ProQuest LLC.
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106 – 1346

CONTENTS

	<u>Page</u>
Preface	1
Introduction	2
List of Symbols	4
Chapter I. Historical Review	6
Chapter II. Selection of Viscometer	11
Chapter III. Detail Design of Viscometer	29
Chapter IV. Sources of Errors, Corrections, Calibrations and Flow Formulae	38
Chapter V. Procedure	66
Chapter VI. Estimation of Overall Accuracy	76
Chapter VII. Account of the Stages of Development of the Apparatus	81
Acknowledgements	86
Bibliography	87
Appendix I.	89
Appendix II.	100
Figures 1 - 13	

PREFACE

So substantial a part of the research task involved in this project has been the study of the subject of viscometry, as such, that the writer has thought it necessary to devote Chapters 1 and 2 of this thesis to it.

Einar Kjelland-Fosterud.

The Experimental Determination of the Viscosity
of Steam at High Pressures.

By

Einar Kjelland-Fosterud

INTRODUCTION

This thesis is the record of the work involved in the measurement of the viscosity of steam over a range of pressures from 200 at. to 1000 at., and over a range of temperatures from 370°C. to 680°C.

The experimental work of earlier researchers is discussed and the various types of viscometers which may be used for measurements on steam at high pressures are examined, particularly the rotating cylinder viscometer and the main types of capillary viscometers.

For the capillary viscometer used the considerations on which the design is based are given, as well as a complete description of the equipment used. The viscometer is based on the principle introduced by Rankine,⁽¹⁾ but a fundamentally new design has had to be developed to obtain results for steam at high temperatures. Some of the auxiliary equipment, especially the furnace used, also incorporates new and original features. A complete examination of the known sources of error and of the necessary corrections and calibrations is given. The procedure

adopted for the measurements on steam and for the calibrations and the precautions which have been observed are fully discussed.

Detailed records of all observations are given together with the calculation procedure for a specimen set of readings.

The final values obtained for the viscosities are listed and compared to those of other workers in the same range of pressure and temperature. It is believed that the results compare favourably with those obtained by other experimenters and that the accuracy of the values listed is better than 2%.

LIST OF SYMBOLS

<u>Symbol</u>	<u>Meaning</u>	<u>Units</u>
η	Dynamic viscosity	g/cm.sec.
ν	Kinematic viscosity	cm ² /sec.
v	Specific volume	cm ³ /g
ρ	Density	g/cm ³
V	Volume (also voltage)	cm ³
w	Mass flow rate	g/sec.
p	Pressure	1 at = $\frac{Kg}{cm^2}$
Δp	Pressure difference	dyn/cm ²
t°	Degrees Centrigade	
T	Degrees absolute	$t^{\circ} + 273$
A	Cross sectional area Also Ampere	cm ²
g		981 cm/sec ²
d	Capillary diameter	cm.
l	Capillary length	cm.
C	Capillary constant $\frac{d^4}{128\ell}$	cm ³
D	Droptube diameter	cm.
L	Droptube timed length	cm.
G	Droptube constant $\frac{1}{(\frac{L}{4} D^2)^2 L}$	cm ⁻⁵
K	Viscometer constant = $C \times G$	cm ⁻²
W	Mercury pellet weight	grams
a	Surface tension drag on pellet	grams
t	Time	seconds

<u>Symbol</u>	<u>Meaning</u>	<u>Units</u>
Δt	Timing error	seconds
U	Velocity	cm/sec.
Δ	Linear coefficient of thermal expansion	cm/cm. $^{\circ}$ C.
Re	Reynolds number $\frac{\rho U d}{\tau}$	-
H	Hagenbach end correction (expressed in text)	
\uparrow	Shear stress	dyn/cm 2
λ	Mean free path	cm.
F	Factor used in calculating results (expressed in text)	
B, E, J, M, N, P, R, etc.	Constants expressed in text.	
m, n	Constants in equation of state for gases.	

CHAPTER I

HISTORICAL REVIEW

Experimental work on the measurement of the viscosity of steam at pressures above atmospheric was first published by Speyerer⁽²⁾ in 1925. The upper limit of Speyerer's pressure range was 10 at.

More recent work has been carried out by Sigwart⁽³⁾, Hawkins, Potter and Solberg⁽⁴⁾⁽⁵⁾, Shugaiew⁽⁶⁾, Jackson⁽⁷⁾⁽⁸⁾ and Timroth⁽⁹⁾.

It is proposed first to examine the types of viscometers used by the above workers and the range of pressures and temperatures covered.

Speyerer's apparatus, which was of the capillary type, is shown diagrammatically in figure 1. Steam was produced in a gas-fired boiler, passed through the gas-fired primary superheater and the electrically heated secondary superheater to the capillary, which was 240 cm. long and of 0.19 cm. bore diameter. The pressure and the flow rate were regulated by means of a throttle valve, the flow rate being measured by condensing the steam and weighing. The pressure drop was measured over the central 200 cm. of the capillary by an alcohol in glass manometer. The tappings to this manometer were taken through 0.02 cm. wide slits in the capillary. By the use of 20 cm. long approach and exit lengths the necessity for an end correction was avoided.

Sigwart⁽³⁾ used an apparatus similar in principle to

Speyerer's, but modified in two respects.

- (a) The pressure drop was measured across the whole length of the capillary, and an end correction was applied.

This enabled Sigwart to use capillaries only 36 cm. long. Two capillaries were used, one of 0.0375 cm. bore diameter, the other of 0.0547 cm. bore.

- (b) A ring balance was used to measure the pressure drop.

This enabled Sigwart to measure the small pressure drop used, 8 g/cm², to an accuracy of 1% or better.

Sigwart measured the viscosity of steam up to approximately 400°C. and up to the critical pressure.

In his experiments, Sigwart found that he could not keep the ring balance from rotating. When the ring balance is moving, water flows through the connection tubes to the capillary. The flow of steam through the capillary is therefore different from the flow rate calculated by measuring the condensate, and there will also be an error in the pressure drop measured. This made it necessary for Sigwart to do two sets of experiments, in which the movements of the ring balance were different, so that the error could be eliminated.

At Purdue University, Hawkins, Solberg and Potter⁽⁴⁾ measured the viscosity of steam at pressures up to 3500 lb/in², using a nickel capillary of 0.093 in. bore. To avoid the need for any end correction a length of 118 ft. was used and the capillary was coiled to a 2 ft. diameter helix, enclosed in a thermostat. Prior to this⁽⁵⁾, the same investigators used a Lawaczeck viscometer⁽¹⁰⁾. For the

capillary viscometers the pressure drop was measured by mercury-in-steel manometers, in which the mercury levels were detected by taking x-ray photographs of the limbs.

Jackson⁽⁷⁾⁽⁸⁾ used the same method for measuring the pressure drop, but he used an annulus instead of a capillary. The annulus was 0.3 in. diameter, 0.005 in. wide, and the pressure drop was measured over a section at the centre, 4 in. long. The steam flowed in an axial direction through the annulus, which extended long enough on each side of the 4 in. central portion to avoid the necessity for end corrections. This viscometer, in common with the capillary viscometers described, depends on a throttle valve for regulating the flow. It is therefore difficult to keep the flow rate constant bearing in mind the small flow rates involved, and thus both the flow rate and the pressure drop may vary during a test. Also when the steam is supplied from a reservoir, the volume of the reservoir needs to be very large to allow sufficient time to obtain steady conditions, especially at the higher pressures. Further, regulation of the temperature of this reservoir to give a constant flow rate must be progressively more difficult as the pressure is then increased.

To overcome these difficulties Timroth⁽⁹⁾ used a development of Sigwart's apparatus. In Timroth's apparatus, the fluid flows in a closed circuit. The viscometer is shown in figure 2. When a load is applied to one side of the ring balance, water will flow into the annulus surrounding the capillary. It evaporates and is heated to the test temperature. The steam then flows through the

capillary, is condensed, and flows into the other side of the ring balance. The flow rate is thus proportional to the angular displacement of the ring balance, and the pressure drop proportional to the load on one side of the ring balance. The complete apparatus is suspended with the capillary horizontal on knife edges, in such a way that it is in equilibrium with no load on the balance. Timroth applied the end corrections proposed by Hagenbach⁽²²⁾ and investigated the field up to 600°C. and 350 at. More recently he has performed experiments up to 500 at.

Shugaiew⁽⁶⁾ used a Rankine viscometer for pressures up to 93 at. and temperatures up to 400°C. In the Rankine viscometer, figure 3, the differential pressure is obtained by a liquid metal pellet flowing in a vertical tube. This tube is connected to the ends of a narrow bore capillary tube, so that a closed circuit is formed. The differential pressure, which is proportional to the weight of the pellet, subject to a correction for the surface tension drag on the pellet, causes the fluid contained in the viscometer to be displaced round the circuit. The flow rate is thus proportional to the rate of fall of the pellet, provided the fluid is incompressible. If the fluid is compressible, a small correction must be applied. The whole apparatus may be enclosed on a thermostat. Shugaiew used a mercury pellet at the lower temperatures, and molten tin at the higher.

Schiller⁽¹¹⁾ used a nozzle to calculate the viscosity

of steam. The steam flowed through the nozzle at different rates and the coefficient of discharge was calculated. Assuming that the coefficient of discharge of a nozzle varies only with the Reynolds number, the nozzle could be calibrated by a fluid of known viscosity, so that the relation between the Reynolds number and the coefficient of discharge was known for the nozzle used. The Reynolds number could then be found for steam, and an estimate of the viscosity of the steam could be obtained. This is not a method to which great accuracy could be attributed.

CHAPTER II

SELECTION OF VISCOMETER

With the exception of Schiller's apparatus and the Lawaczeck viscometer used by Hawkins, Solberg and Potter, all the viscometers used for the determination of the viscosity of steam have been of the capillary type. A large variety of viscometers have been used for other fluids, and it seems possible that one of the types other than the capillary type could be developed for measurements on steam. Apart from the capillary type there are two types of viscometer which have been used successfully for precision measurements on the viscosity of fluids, namely the rotating cylinder viscometer and the oscillating disc viscometer.

The rotating cylinder viscometer is illustrated in figure 4. It consists of two concentric cylinders, one of which rotates. In the usual layout, which is illustrated, the outer cylinder rotates, while the inner cylinder is suspended on a torsion wire, so that the torque imparted to it can be measured by observing the angular displacement of the cylinder. This torque is proportional to the speed of rotation of the outer cylinder and the viscosity of the fluid between the cylinders.

The relation connecting the torque with the viscosity of the fluid is obtained from Newton's law

$$\tau_x = \eta \frac{du}{dy} \dots\dots\dots 2.1$$

Equation 2.1 may be integrated for the case of infinitely long

concentric circular cylinders, and an exact solution can be obtained for this case. To avoid the need for end corrections due to the finite length of the cylinders, guard cylinders are employed to make the flow pattern over the suspended cylinder substantially similar to the case for infinite cylinders. Using a relaxation method, it can be shown that the necessary length of guard cylinder to make the velocity gradient at the surface of the suspended cylinder less than 0.1% different from the case with infinite cylinders is approximately only 10 times the width of the annulus.

An added advantage of this viscometer is that the flow between the cylinders is laminar up to extremely high Reynolds numbers, as has been shown by Taylor⁽¹²⁾ provided the rotating cylinder is the outer one. This type of viscometer has been used by a number of workers⁽¹³⁾⁽¹⁴⁾⁽¹⁵⁾. It has mainly been used for determinations of the viscosity of air at atmospheric pressure and room temperature in connection with the oil-drop method of measuring the electronic charge due to Millikan⁽¹⁶⁾. In this method, an error in the viscosity of air will give an error in the value of the unit charge found. The electronic charge has also been found by the fundamentally different x-ray method, and the close agreement between the values found indicate the degree of accuracy of both methods, and hence the accuracy obtainable by the rotating cylinder viscometer.

The oscillating disc viscometer is illustrated in figure 5. This type has been used extensively, mainly for gases

at room temperature and for liquids at very low temperatures.

The most important work in which the oscillating disc viscometer was used is probably Maxwell's⁽¹⁷⁾. To test the validity of the kinetic theory of gases, Maxwell undertook a series of experiments to find whether the viscosity of air varies with pressure. It consists of a flat circular disc suspended horizontally on a torsion wire. The disc performs slow oscillations, damped by the viscous forces from the fluid surrounding the disc, and by the hysteresis in the torsion wire. The damping can be measured, and the viscosity of the fluid can thus be determined. The most complete analysis to date of the oscillating disc viscometer appears to be that done by Kestin^{(18)(19)&(20)}.

Over the range of pressures and temperatures which it is desirable to cover in an investigation on the viscosity of steam, the range of viscosity and density of the steam is extremely large so that the range of Reynolds number experienced is inevitably large. To obtain sufficient accuracy, it is therefore desirable that the type of viscometer selected can be used over as large a range of Reynolds number as possible, and also that the relation connecting the viscosity with the measured quantity is known to a sufficient degree of accuracy over the range of Reynolds number experienced. At the time when the choice of viscometer for the author's experimental work was made, the theory for the oscillating disc viscometer was not thought sufficiently complete to justify an attempt to develop it for use with steam.

The theory for the rotating cylinder viscometer is complete, and since the range of Reynolds number which can be used is very wide, it was thought that this would be a suitable type to use for steam, if a design could be developed which would be adequate for the severe conditions experienced.

It was thought that the difficulties which could be expected would be due mainly to the following:-

- (1) The torsion wire, which needs to be highly stressed, if the apparatus is to be sufficiently sensitive with the optical method usually employed for measuring the torque. There is the possibility that the elasticity of the torsion wire would alter unpredictably due to the high temperature and pressure.
- (2) The suspended cylinder, which should be as light as possible. Due to the thin sections necessary distortion of the cylinder at the higher temperatures is a possible source of error.
- (3) The bearing for the rotating cylinder. A ball bearing may be run unlubricated for sufficiently long periods if the speed and loading are low, even at quite high temperatures. It was therefore thought that provided the bearing was a ball or roller bearing made from suitable materials, an adequate life would be obtained at temperatures up to 600°C. or perhaps even higher.

- (4) The system for measuring the deflection. This is usually of the optical type, and with the usual layout it would be necessary to keep the mirror and the window through the pressure vessel in contact with the hot steam.

A design such as that illustrated in figure 6 avoids most of these difficulties. In principle it differs from the conventional layout only in having the suspended cylinder (1) supported by an upper suspension wire (4) with a torsion wire (6) in the cold part of the apparatus. The upper end of the torsion wire moves with the suspended cylinder, while its lower end is actuated by the shaft (7) which extends through a gland to the atmosphere. The shaft (7) can be rotated, and the angle of rotation can be accurately measured by a micrometer or a microscope. The shaft (9) which connects the suspended cylinder (1) with the torsion wire (6) also carries the mirror for the optical system (5), and there is a window for this optical system in the cold pressure vessel (10). The tube (11) connects the cold pressure vessel with the hot pressure vessel (12) containing the rotating and suspended cylinders. The guard tube (13) surrounds the shaft (9) to ensure that no torque is imparted to the suspended system from the drive tube (10) to the rotating cylinder.

In operation, the speed of the rotating cylinder is absorbed by twisting shaft (7) so that the suspended cylinder does not rotate, as shown by the optical system. The upper suspension

wire will then not be twisted, and the torque is thus proportional to the rotation of shaft (7).

The advantages of this arrangement are:

- (1) The torque is measured by the twist of a torsion wire which carries only a small tensile load, and which is virtually at room temperature.
- (2) The accuracy of the torque measurements is unaffected by any distortion in the window due to pressure, so that a stiffer suspension wire can be used than is possible for the same precision in the conventional layout.
- (3) Since the upper suspension wire is not twisted, a flat ribbon may be used. Since a flat section has a smaller torsional stiffness than a circular wire of the same cross-section, provided the ratio of thickness to width of the ribbon is small, a heavier suspended cylinder can be used. With the thicker sections that this admits, distortions at the higher temperatures would be easier to control.

The leading dimensions would be :

Suspended cylinder length 5 cm. diameter 5 cm.

Rotating cylinder internal diameter 5.5 cm.

Guard cylinders each 3 cm. long.

Materials: 18/8 type stainless for all parts except

the suspension wire, which should be 80%Ni 20%Cr

type alloy, flat strip 0.0025 cm. x 0.010 cm.,

20 cm. long.

The bearing should be a double ball or roller bearing made from an 18/8 type stainless alloy.

When the design was developed to this point it was apparent that although the apparatus should, when fully developed, prove capable of good precision and accuracy, the complicated design made it probable that the development time would be long. A design for a capillary viscometer was therefore prepared, so that the merits of the two types might in due course be compared.

Design of a Capillary Viscometer.

It will be apparent that the capillary viscometers which have been used for steam are of two different types; the open circuit type which was used by Speyerer, and later by Sigwart, Hawkins, Solberg and Potter, and the closed circuit type such as the Rankine viscometer used by Shugaiew, and the viscometer used by Timroth.

The principle of the open circuit viscometer will appear from figure 1, which illustrates the type as used by Speyerer. In the closed circuit type the fluid is displaced round a closed circuit by the imposition of a differential pressure on the ends of the capillary. The differential pressure is fixed, and the flow rate is measured indirectly.

Capillary viscometers, as well as other types, may also be subdivided into primary and secondary viscometers. In the primary capillary viscometer the capillary dimensions are measured directly, as are the observations from which the pressure drop and

the flow rate are calculated.

The secondary viscometer is an apparatus in which the dimensions are inferred from observations which are obtained when the viscometer is tested with a fluid whose viscosity is known. The accuracy of a secondary viscometer can never be better than the accuracy of the assumed value of the viscosity of the calibrating fluid, while the accuracy of the primary type is limited by the accuracy of the measurements of the critical dimensions. The dimensions of a primary viscometer, especially the dimensions of the capillary, must be such that they can be measured to the required accuracy. Since the diameter enters the Poiseuille's equation to the fourth power, it must be known to a very high degree of accuracy. With a secondary type of capillary viscometer the calibrating fluid should preferably be air or nitrogen, since the viscosities of these gases are known to a very high degree of accuracy. Proof of this is found in Millikan's determination of the electronic charge by the oil drop method which involves Stoke's law. In this determination an error in the assumed value of the viscosity of air will cause a similar error in the electronic charge, and since the accepted value for the viscosity of air will yield a value for the electronic charge which is in extremely good agreement with the values obtained from the fundamentally different x-ray method, it appears that the viscosity of air is known to a similar degree of accuracy.

The maximum rate of flow through the capillary is

determined by the Reynolds number, since the flow needs to be laminar. To quote Keenan and Keyes⁽²¹⁾, "The flow regime in the capillary must of course be strictly "streamline", which implies clearly that the rate of flow must be small; strictly speaking infinitely small". This means that the Reynolds number should be as small as possible. It is not known at what Reynolds number the flow regime deviates so far from the strictly streamline condition that the resulting error is noticeable, but it seems that this Reynolds number may well be less than 2000, where the transition from laminar to turbulent flow is usually considered to occur. If the Reynolds number is small enough, the open circuit type of viscometer should yield results of satisfactory accuracy if the following criteria are satisfied.

- (a) Systematic errors are not present.
- (b) All measurements are taken with the necessary precision.
- (c) The proportions of the apparatus are chosen such that
fluctuations in pressure, temperature and flow rate
cause the smallest possible errors.
- (d) The fluctuations referred to in (c) are kept to a minimum.

The criteria are self-evident and possible sources of errors may be anticipated and avoided by a suitable design. However, consider now the criteria (a) (b) (c) and (d) in detail.

(a) Systematic errors.

The chief source of error in a capillary viscometer is the error in the capillary constant $C = \frac{\pi d^4}{128 \ell}$. In a

primary instrument this error may arise because (i) the capillary is not cylindrical, (ii) the bore is not circular, (iii) the ends are not square, (iv) surface irregularities in the bore cause eddies below the critical Reynolds number and (v) the correction for end effects is not accurate.

In a secondary instrument the errors (i) (ii) and (iii) do not arise, because the true value of the capillary constant is found when the capillary is tested with a fluid of known viscosity, but an error arises due to (vi) the viscosity of the calibrating fluid being inaccurate, and the scatter in the calibration experiments may cause a further error.

(i) The cross-sectional area of a metal capillary may be measured by inserting a short pellet of mercury of known volume and using x-rays to photograph the pellet in different positions. If the average cross-section is obtained and used in calculations the viscosity found will be too large and this will be especially marked if the cross-section varies widely. However, capillaries with palpably varying cross-sections would be considered unsuitable and only those with slight variations in cross-section would be acceptable.

(ii) This can be discovered only by cutting the capillary into short lengths and examining the bore under a

microscope after all experiments have been completed. Resort to such action prevents further use of the capillary.

(iii) (iv) and (v) These may be avoided if the Reynolds number is small or they may be detected if the Reynolds number is varied. At normal Reynolds numbers an end correction due to Hagenbach⁽²²⁾ must be applied, but this is empirical.

(b) Errors in measurements.

These can probably be best assessed by referring to the Poiseuille equation

$$Q = \frac{\pi d^4}{128 \ell} \frac{\Delta p}{w} \dots\dots\dots 2.2$$

The chief sources of error lie in the measurement of Δp , w and d . If Δp and w are large and constant no difficulty arises. However, in a primary viscometer, where the capillary diameter would probably have to be fairly large in order to enable it to be measured to sufficient accuracy, the pressure drop will have to be very small, otherwise the Reynolds number would be too large over part of the pressure and temperature ranges. Variations in Δp and w will have two effects:

- (i) The ratio $\frac{\Delta p}{w}$ is required in equation 2.2. The true average of this ratio over a test period will in general be different from the result obtained

by using the averages of Δp and w .

- (ii) A manometer has water or steam stored in it and part of this will pass through the capillary when the manometer moves due to an alteration in Δp . Hence the flow rate through the capillary will be different from that measured. This effect may be minimised by arranging to have the mass of fluid stored in the manometer small compared to the mass flow rate through the capillary.

For the highest precision the flow rate should be large and the mass stored in the manometer and viscometer should be as small as possible.

When measuring very small pressure differences, to avoid buoyancy errors, the manometer should be in the steam space. Such a manometer will require relatively large operative areas if small pressure differences are to be measured with any precision. This implies that the volume of the manometer will be relatively large. It is clear that a conflict arises here with (ii) above.

(c) and (d) Errors due to fluctuations in pressure and temperature.

Variations in pressure and temperature each bring about density variations which cause steam to be 'stored' in the

apparatus, with the result that the flow rate is not proportional to the rate at which condensate is collected. This error is minimised by the use of large flow rates, as compared with the mass of steam in the viscometer. The error due to pressure and temperature variations will be greatest where the density is great and where it varies rapidly with pressure and temperature, i.e. at high pressures near the saturation line.

The only way to combine the requirements of reasonably large pressure drops, low Reynolds numbers and a large mass flow is by the use of an apparatus incorporating a number of capillaries in parallel. The apparatus would need to be supplied from a steam generator capable of producing the necessary amount of steam at a steady rate and at constant pressure.

By skilful and patient procedures results have been obtained with apparatus which do not satisfy these criteria, but the results, especially at the higher pressures, still appear to contain serious errors.

The closed circuit viscometer will now be examined in the light of these criteria:

(a) Systematic errors.

The same precautions must be observed as with the open circuit type.

(b) Errors in measurements.

In this type the pressure drop causing the flow is

constant and predetermined. It is therefore in general not necessary to measure the pressure drop during the observations. No error in the ratio $\frac{\Delta p}{w}$ can result when Δp is constant. There is a minimum practicable pressure drop which can be used both in Rankine's viscometer and in that used by Timroth; in the case of the Rankine type due to the correction for the surface tension drag on the mercury pellet, and in the case of Timroth's viscometer due to the correction necessitated by the lack of perfect equilibrium in his apparatus. Both these corrections ought to be small compared to the pressure drop.

To limit the Reynolds number when using pressure drops of the necessary magnitude, the capillary diameter must be small and the capillaries must be calibrated.

(c) and (d) Errors due to fluctuations in pressure and temperature.

Since this type can be operated at constant volume, errors can only arise by simultaneous variations in the density of the fluid in different parts of the viscometer such that the average density remains constant. By selection of suitable layout and dimensions this error can be substantially eliminated.

It seems probable that, provided the fluctuations in temperature and pressure are of the same order in the two types, the consequent errors in the open circuit type can only be reduced to the same level as those expected in the closed circuit type if the flow is considerable, and since

this would require a small steam generator with all its necessary equipment, it would appear more economical to use a viscometer of the closed circuit type.

The alternatives on which the design could be based are:

- (a) The Rankine type and
- (b) The viscometer used by Timroth.

Other types of closed circuit viscometers exist, but these appear to be less suitable for development than the above mentioned types.

The original Rankine apparatus is unsuited for use at elevated temperatures, due to the danger of oxidation and evaporation of the mercury.

The apparatus used by Timroth has the drawback that the whole apparatus consisting of pressure vessel, ring balance, pressure gauge, furnace with insulation and thermocouples is supported on knife edges and rotate bodily during a test. The complete apparatus is first balanced so that it is in near equilibrium at all angles of rotation, and an out of balance weight, which is proportional to the pressure drop through the capillary, is added. Since this weight can be only a small fraction of the total weight of the apparatus, it is apparent that great skill in operating the apparatus is required to obtain sufficient accuracy, and severe limitations are imposed on the design of the apparatus.

In the present work it was felt desirable to use an apparatus which did not suffer from these limitations, and attention was again

turned to the Rankine viscometer. It was found that this type of viscometer could be modified so that it could be used at high pressures and temperatures by heating the capillary only, connecting this to the vertical drop tube by tubes in which condensation and evaporation would occur. The connecting tubes would have to be horizontal to avoid buoyancy errors.

The design in having the connecting tubes to the capillary concentric and horizontal uses a feature which is also used by Timroth. The apparatus is shown in figure 7.

The capillary (1) of nominal bore 0.2 mm. and 300 mm. long, is connected to the glass drop-tube (6) by the horizontal connection tube (2), and the mercury trap (4). The mercury pellet may be stored in the reservoirs (5) and (7) at either end of the drop-tube. When the viscometer is rotated on the journal bearings (13) the pellet starts falling, displacing water, which is evaporated in the connecting tube, and passed through the capillary. The return flow is through the annulus formed between the pressure vessel and the connecting tube.

During the falls the mercury pellet successively closes several sets of platinum contact wires, figure 8, (2) and (4). One wire from each set is earthed, the other is connected to an insulated lead, figure 2, (4), which is connected to an electronic relay. When the mercury pellet closes the first set of contacts, the relay starts a stop watch, and when the pellet closes the next pair, the stop watch is stopped. Drop-tubes with four, six or eight pairs of

contact wires have been used, which give two, three or four timings in each direction. After all the timings in one direction have been obtained, the whole viscometer is rotated on journal bearings, figure 7, (13) and the pellet thus flows in the reverse direction. To obtain even flow at the subcritical pressures it was found necessary to insert a bubble former in the connection tube. This is a spiral of oxide-coating Nickel/Chromium resistance wire. To stop convection currents in the annulus between the connection tube (2) and the pressure tube (3) another spiral of resistance wire is used over the region where there is a temperature gradient.

Since more than one timing is obtained during the fall of the pellet, a comparison of the flow rates will tell whether the flow rate is uniform. The differential pressure can be diminished by securing the drop tube at several angles between 0° and 90° from the horizontal.

Thus the differential pressure across the capillary ends is given by the length of the pellet, corrected for surface tension drag, buoyancy, and pressure drop in the connecting tubes to the capillary, while the flow rate is given by the volume displaced by the pellet during the timed interval measured.

This viscometer is easily adaptable for use at elevated temperatures and extremely high pressures, since the pressure vessel is small.

The simple flow system gave promise that the development time necessary would be short, that its accuracy would be good if a suitable calibration method were used both for the capillary and the

drop tube and that, since both the flow rates and the pressure drop could be small without impairing accuracy, the maximum Reynolds number could be limited to a value low enough to prevent errors due to incipient turbulence. In the belief that this viscometer would be suitable for measurements of the viscosity of steam over a greater range of pressures than that covered in earlier investigations, with a satisfactory accuracy, this type was chosen for development rather than the rotating cylinder viscometer described previously.

? Time to steady
? Δp correction.

CHAPTER III

DETAIL DESIGN OF VISCOMETER

Capillary.

It has been shown that the capillary diameter should be small to achieve a small Reynolds number, otherwise the pressure drop must be limited to a very low value. Since there is a lower limit to the pressure drop which can be used with the chosen viscometer, the best capillary diameter is the smallest which can be handled conveniently. The chosen diameter is 0.02 cm. nominally. For the same pressure drop, the Reynolds number will be inversely proportional to the length of the capillary, but since it is difficult to keep the temperature uniform over a long capillary, the length chosen is 30 cm. The capillary is made of a 10% Rhodium 90% Platinum Alloy, by Johnson, Matthey Ltd. A stainless capillary of approximately the same dimensions has also been used, and also a stainless capillary of 0.012 cm. bore approximately, but of the same length as the others.

The pressure drop is limited by the surface tension drag on the pellet, due to the different shapes of the front and rear member of the moving pellet. This drag was found by preliminary experiments to be approximately 3 g/cm^2 , and was found to vary with the purity of the mercury and the cleanliness of the drop tube. It was therefore thought best to assume that the minimum pressure drop necessary to give satisfactory precision would be 40 g/cm^2 . With the nominal capillary dimensions the maximum Reynolds number

would be approximately 600 for this pressure drop. The corresponding maximum Hagenbach end correction is then less than 2%, and the maximum flow rate less than 10^{-2} g/sec.

? Com tubes
bends.

Drop tube.

From a series of preliminary experiments on several glass tubes of different diameters, it was found that

- (a) the surface tension drag decreases with increasing diameter,
- (b) the maximum flow rate possible without leakage of water between the pellet and the wall of the drop-tube is largest for tubes of between 0.2 and 0.25 cm. bore.

? D A

The drop-tube diameter chosen is therefore within this range. Details of the drop tube shown in figure 8. The contact wires are 0.02 cm. diameter, made of platinum. It was found that when the contact wires were placed normal to the surface of the bore, with the tip of the wire not extending past the centreline of the bore, no detectable disturbance to the flow rate occurred due to their presence. The total length of the drop tube is 75 cm. This length has been found more than sufficient to give a uniform flow rate over the timed lengths.

The drop tube is made from Pyrex glass, fitted with a reservoir for the mercury pellet at either end. The inner end is connected to a stainless steel mercury trap which is silver soldered to the tube which is connected to the capillary.

The contact wires are fused through the glass in the

normal way, by blowing a small hole in the tube with a pointed oxygen-gas flame, putting a glass bead on the wire, and fusing in the bead. After fusing in the wires, the bore of the glass tube was checked by measuring the length of a short string of mercury. The cross-section was adjusted by careful blowing until the cross-sectional area was uniform within 2% in the region of the contact wires.

Since no glass blower would work to this accuracy, all the drop tubes used were blown in the laboratory.

?
who?

The connecting wires to the relay were soft-soldered to the contact wires, and the joints sealed by a drop of molten polythene. The joints were then covered with a length of surgical rubber tubing for protection and insulation. One wire from each pair is earthed, the other is connected to a lead through the pressure vessel. This lead is insulated by a thin sleeve, turned from Perspex rod, which also acts as the packing in the self-sealing joint for the insulated lead.

Timing.

The circuit is shown in figure 9.

The pellet, on closing the contacts in the drop-tube connects the grid of the triode valve to earth. A current then passes through the d-c solenoid, which switches on the supply for the a-c solenoid and this in turn starts a stopwatch. When the pellet closes the next set of contacts, the process is repeated, and the stopwatch stops. Since the same events occur when stopping

as when starting, any delay in the circuit will be the same, and the errors will cancel. The delay is not more than 0.05 seconds. A bias potential of 6v is connected across the relay, through a 4000- Ω resistance, and a milliampère meter is inserted in the lead to the contacts, so that the current can be measured.

?
Tan 10
drop

When the circuit is arranged as described, there is a stray current to the drop tube of 0.02 mA or less, due to impurities in the water and incomplete insulation. When the mercury touches the contacts, the current rises to 1.6 mA. The relay trips when the current is 0.4 mA. approximately. The stray current provides a useful check on the purity of the water. The stopwatch beats and records to 1/40 seconds, the seconds hand rotates one revolution per 10 seconds. It carries an N.P.L. Certificate that it is accurate to 1/40 seconds over 10 seconds.

Connecting tubes.

The bore of the connecting tube between the capillary and the drop tube should be small, to ensure that small changes in the density of the steam in it do not cause significant errors in the measured flow rate. Changes in density in this tube may be caused by a drift in temperature, especially in that part of it where there is a large temperature gradient, after the flow has been started or reversed, or after the pressure in the apparatus has been altered. Since the diameter should also not be so small that the pressure drop in it becomes significant, a stainless tube of 1.2 mm. bore was first used. At the higher temperatures the corrosion

resistance of this was not sufficient, and it was exchanged for a tube of Nimonic 75 of $\frac{1}{8}$ " bore, $\frac{1}{4}$ " outside diameter. The bore of this was filled with Brightray C resistance wire to reduce the steam volume in it.

*br.
increase sp.*

Mechanical Design of Viscometer.

The construction is shown on figure 7.

The pressure vessel consists of two Nimonic 80A tubes, $5/16$ " i.d. and $9/16$ " o.d. and 90 cm. long each, connected by a central body made of 18/8 type stainless steel. This body houses the mercury trap, to which is connected the glass drop tube and the connection tube to the capillary, and the oil/water separating membrane. All metal parts in contact with water or steam are made of Nimonic or 18/8 type stainless steel.

All pressure joints are of the self-sealing lens ring type. Where a mechanical joint is not practicable, silver solder is used for cold permanent connections, and pure gold is used to solder the connections exposed to high temperatures.

The separator body is of mild steel, 1" i.d., 3" o.d. The membrane which separates the castor oil in the pressure balance system from the water in the viscometer is a rubber fingerstall held in position between a lip on the central body and a groove in the lens ring. Prolonged tests have shown that this membrane is impervious to both water and the castor oil used in the pressure balance.

To take up the 180° rotation of the viscometer the connection to the pressure balance incorporates a packed joint. All the stressed parts were designed to have an elastic stress equal to or less than that in the Nimonic tubes, as calculated from Lamé's equation, but no attempt was made to obtain consistent safety factors or load factors for the various parts. The materials and the sections were rather chosen from those available with a reasonable delivery time at the time the design was started, and the design was chosen to accommodate them, so that the minimum amount of machining was necessary.

At 15000 lb/in.² pressure, the elastic stress in the Nimonic tubes will be 11.8 t/in.² At this stress, Nimonic 80A has the following creep rates:

At 750°C, 0.1% creep in 300 hours, rupture in 1000 hours, at 0.5% creep.

700°C. 0.1% creep in 1000 hours, rupture at between 5000 and 10000 hours.

650°C. 0.1% creep in 10000 hours.

At 20°C. the 0.1% proof stress is 252 t/in.²

The sections should therefore be sufficient to give an adequate creep life.

The elastic stress in the mild steel separator body will be approximately 8.4 t/in.² This should not be excessive, since fatigue will not be a problem with the small number of times that the maximum pressure is used.

Furnace.

The furnace is of novel design. Normally annular end heaters are used to provide a zone of uniform temperature near the middle of the furnace. In this furnace disc shaped end heaters, figure 7, (18) are used, and these extend the constant temperature zone to 3" from either end of the furnace. The main heater, figure 7, (17) is of normal annular construction and to balance the heat loss from the exposed part of the pressure vessel an auxiliary heater (19) is wound in to the Nimonic tube. The power input is obtained from a 115 V, 2 kW, constant voltage transformer to avoid temperature variations due to fluctuations in the mains voltage. The wiring diagram for the heaters is shown in figure 10. The main heater control is step-wise, by series and parallel resistances, such that the power output from the constant voltage transformer is always more than 0.5 kW. Below this output the efficiency of the regulation deteriorates. The inputs to the three auxiliary heaters are regulated by series resistances, the steps being covered by slide wire resistances.

Pressure Measurement.

The pressure is measured and regulated by a dead-weight pressure balance unit, shown in figure 11, which was available from a previous piece of research apparatus. This has been used with only small modifications, mainly to adapt it for the present use.

The piston (1) is forced up by the internal pressure in the viscometer, and the force is balanced by the overhung weights (2).

To eliminate static friction the piston and weight carrier is rotated slowly by an electric motor. The drive is such that no significant force is transmitted in the vertical direction. The position of the piston is transmitted to the pointer system (3). On this pointer are mounted two mercury switches, (4) which actuate the motor (7) and the pumps (8) through a system of relays, and increase or decrease the total volume of the apparatus so that the pressure is maintained. The pressure is brought up by the hand pump (14). To give an indication of the pressure the test gauge (11) is fitted, and the valves (12) enable the various parts of the apparatus to be isolated.

The absolute accuracy of the pressure balance is greater than that necessary for the viscosity measurements, but the balance is so sensitive that small deviations from equilibrium pressure in the viscometer are detected. The pressure balance thus ensures a high degree of precision, and accelerates operation of the viscometer. To use this sensitivity the connecting tube to the viscometer must be short, and a packed joint is therefore necessary in this tube to allow the viscometer to rotate.

Temperature Measurement.

The temperatures are measured by five Platinum - 13% Rhodium Platinum thermocouples, figure 7, (16 a - e), distributed over the outside of the pressure tube (3). The thermocouples are distributed so that couple 16a measures the temperature adjacent to the outer end of the capillary, 16b that adjacent to the centre

and 16c that adjacent to the inner end of the capillary. The couple 16d provides a check that the steam flowing into the capillary is at the same temperature as the capillary, and the couple 16e is used to find the correct heat input to the tube heater (19). The thermocouple ends are fitted with double-radiation shields, and the thermocouples are brought out along the pressure tube inside separate thin-walled stainless steel sheaths to the disc (20), where they are connected to compensating leads. The potentials are measured on a Pye Precision potentiometer, to 1 microvolt which corresponds approximately to 0.10° , at the test temperatures.

CHAPTER IV.

SOURCES OF ERRORS, CORRECTIONS AND NECESSARY CALIBRATIONS. DERIVATION OF THE FLOW RELATION USED.

The following sources of errors must be investigated and, if necessary, corrected for:

1. Temperature measurements:

The temperature measured is that of the pressure tube inside the furnace. It is assumed that this temperature is equal to that of the capillary, and, it should be shown that no significant error will result from this assumption.

2. Flow rate errors:

(a) The rate of volume displacement by the pellet may not be proportional to the mass flow rate through the capillary because of changes in the density of the fluid in the connecting tube to the capillary.

(b) Leakage of water between the pellet and the drop tube wall may occur, causing the measured flow rate to be larger than the true value.

3. Pressure drop errors:

The differential pressure across the capillary will be different from that given by the pellet weight divided by the cross-sectional area of the drop tube because of (a) surface tension drag on the pellet, (b) pressure loss in the connecting tubes between the pellet and the capillary.

4. Errors in the calibration constants.
5. The capillary constant will vary with temperature, due to thermal expansion of the capillary material. In addition the effect of the finite length of the capillary varies with Reynolds number.

1. Temperature errors.

The five thermocouples are fitted with a double radiation shield to ensure that the potential observed corresponds to the temperature of the pressure tube. As will appear from figure 7, thermocouple 16a, 16b and 16c are situated near the outer end of the capillary, the middle and the inner end respectively. It is clear that if there is no appreciable difference between the temperatures recorded by these couples there can be no appreciable difference between these temperatures and those of the capillary.

The alternatives to this arrangement are:-

- (i) Using bare thermocouples fixed to the capillary and properly insulated, with connections through the pressure vessel in the cold part of the viscometer.
- (ii) Using a thermocouple pocket, such that the hot junction of the couple is situated near the outer end of the capillary. Because of the small flow rate the response of a couple in this position to a change in the temperature of the steam flowing through the capillary would be poor, and no advantage would be derived as compared with a properly shielded couple fixed to the

outside of the pressure tube.

The alternative (i) may seem attractive, and is possible at the expense of considerable complication, but there is a serious danger of errors due to possible contamination of the thermocouples by the steam. It is therefore thought that the use of surface-mounted thermocouples is the best of the possible alternatives, for this type of viscometer.

2. Flow rate errors.

(a) Errors due to changes in density.

If the temperature of any part of the viscometer varies during a test, the density of the fluid in this part will alter, causing an error in the observed flow rate. No error in the flow rate can result from this source if the density of the steam in the connecting tube between the pellet and the capillary remains constant. The average density of the fluid in the viscometer may be kept constant by keeping the volume available constant; this can be achieved by stopping the motor rotating the pressure balance piston, in which case static friction between the piston and the cylinder will prevent the piston from moving. But since the density of the steam in different parts of the viscometer may still change in opposite directions, so that the average density remains constant, an error may still result.

If both the pressure and the volume of the fluid in the viscometer are constant during a test, the apparatus must be in temperature equilibrium and no error can result.

Two methods of working the viscometer are possible:

- (i) keeping the volume constant, and
- (ii) keeping the pressure constant.

The relations giving the flow rate errors will now be worked out for both alternatives: -

The steam space in the viscometer may be divided into two parts:-

- (a) The part near the capillary, which is surrounded by the heavily lagged furnace and in which any temperature drift will be extremely slow, of the order of 0.5°C. per hour or less, and
- (b) the part near the tube heater, part of which is exposed to the atmosphere, and in which there is a large temperature gradient. The temperature at any point in this region may fluctuate quite rapidly due to variations in heat loss caused by stopping and starting the flow, or caused by draughts.

For the purpose of estimating the error which may result from this, it is assumed that the following relations hold:

$$pv^n = C_1 \quad \text{for } T = \text{constant} \dots\dots\dots 4.1$$

$$\text{and } v = C_2 T^m \quad \text{for } p = \text{constant} \dots\dots\dots 4.2$$

in which n and m are constant whose values will in general be different in the two parts considered. In the part where there is a temperature gradient the temperature, pressure and values of the indices m and n used are assumed to be representative rather than relating to a particular cross-section, and, neglecting the effect of the flow on the temperatures, the pressure, specific volume and temperature should

be practically the same in the connecting tube and in the annulus at any given cross-section.

Thus, near the tube-heater the following equation is assumed to hold, for small variations in pressure and temperature:

$$\frac{\delta V_1}{V_1} = m \frac{\delta T}{T} - n_1 \frac{\delta p}{p} \dots\dots\dots 4.3$$

where n_1 is the magnitude of the index n at the conditions p and T ., and near the capillary, where any variation in the temperature may be neglected, the equation

$$\frac{\delta V}{V} = - n_2 \frac{\delta p}{p} \quad (\text{from equation 4.1}) \dots\dots\dots 4.4$$

is assumed to hold, where n_2 is the magnitude of the index n at p and the capillary temperature.

If it is further assumed that the length over which there is a temperature gradient is L and that the cross-sectional areas in this region are A_1 for the connecting tube and A_2 for the annulus, and that the volumes of the steam spaces in the region where the temperature is uniform is V_1 for the connecting tube and V_2 for the annulus, the nett volume change due to changes in temperature and pressure will be

$$\delta V_c = L A_1 \left(m \frac{\delta T}{T} - n_1 \frac{\delta p}{p} \right) - V_1 n_2 \frac{\delta p}{p} \dots\dots\dots 4.5$$

in the connecting tube, and

$$\delta V_a = L A_2 \left(m \frac{\delta T}{T} - n_1 \frac{\delta p}{p} \right) - V_2 n_2 \frac{\delta p}{p} \dots\dots\dots 4.6$$

in the annulus.

The total volume change is then

$$\delta V = \delta V_c + \delta V_a = L (A_1 + A_2) = m \frac{\delta T}{T} - \frac{\delta p}{p} [n_1 L (A_1 + A_2) + n_2 (V_1 + V_2)] \dots\dots\dots 4.7$$

If the total volume of the viscometer is kept constant, $\delta V = 0$, and

$$L (A_1 + A_2) m \frac{\delta T}{T} = \frac{\delta p}{p} [n_1 L (A_1 + A_2) + n_2 (V_1 + V_2)]$$

so that

$$\frac{\delta p}{p} = m \frac{\delta T}{T} \frac{1}{n_1 + n_2 \frac{V_1 + V_2}{L (A_1 + A_2)}} \dots\dots\dots 4.8$$

The volume change in the connecting tube is then obtained by substituting this value of $\frac{\delta p}{p}$ in equation 4.5. Hence

$$\delta V_c = L A_1 m \frac{\delta T}{T} - \frac{(n_1 L A_1 + n_2 V_2) m \frac{\delta T}{T}}{n_1 + n_2 \frac{V_1 + V_2}{L (A_1 + A_2)}}$$

or simplified

$$\delta V_c = m \frac{\delta T}{T} \frac{L n_2 (A_1 V_2 - A_2 V_1)}{L n_1 (A_1 + A_2) + n_2 (V_1 + V_2)} \dots\dots\dots 4.9$$

Therefore the viscometer is immune from flow rate errors due to variations in temperature provided

$$\frac{A_1}{A_2} = \frac{V_1}{V_2}$$

Since the value of L, the length of the region where there is a temperature gradient, is of course indeterminate, the steam space in the connecting tube should be of the same length as the annulus, and the ratio of the cross-sectional areas should be constant

over the hot part of the viscometer if it is desired to take full advantage of this property.

In the design of the viscometer an attempt was made to utilise this property by assuming a value for the length, and by filling in the bore of the connecting tube with the appropriate thickness of Brightray C wire.

If the pressure is kept constant, the error is

$$\delta V_c = L A_1 m \frac{\delta T}{T} \text{ from equation 4.5.}$$

In this case the error may be kept small by decreasing the cross-sectional area of the connecting tube and any error will be detected by the pressure balance, whose piston would move to accommodate the change in volume. The change in volume in the annulus will be given by

$$\delta V_a = L A_2 m \frac{\delta T}{T}$$

Hence, of the total volume change, which must be proportional to the movement of the pressure balance piston, the proportion $\frac{A_1}{A_1 + A_2}$ will be the change in the connecting tube.

In the viscometer $A_1 = 0.002 \text{ in}^2$ and $A_2 = 0.038 \text{ in}^2$ approximately, so that this proportion is $\frac{2}{40}$ or 5%. Since the volume displaced by the pressure balance piston in moving through its full stroke is $15 \times 10^{-3} \text{ cm}^3$ and since the total volume of water displaced during a timed interval is $150 \times 10^{-3} \text{ cm}^3$, it follows that if the piston were to move through its full stroke during a timed fall the error in the observed flow rate would be

$$5\% \times \frac{15}{150} = 0.5\%$$

A technique is adopted which over the pressure range investigated limits the effect to a fraction of this value. Away from the saturation line and the critical region no difficulty has been experienced in keeping the pressure balance piston steady, apart from the slight drop due to the leakage past the piston, and the transient movement due to the small change in the total volume of the viscometer which takes place when the viscometer is rotated on its journal bearings. This is caused by the thrust bearing in the packed joint, which is a screw.

Near the saturation line and in the critical region the compressibility of steam is great, and it is difficult to attain proper equilibrium. It is suspected that the pressure drop in the connecting tube to the pressure balance is too great, due to the great viscosity of the oil used, to allow the pressure balance to respond sufficiently quickly at the lower pressures.

At pressures greater than 300 at., therefore, the constant pressure method is used, and the pointer showing the position of the pressure balance piston is watched while the times of fall are measured. The timing is rejected if the pointer moves through more than 1/4 of its travel. At the lower pressures and near the critical point the constant volume method has to be used. Naturally, this method has been tried at the higher pressures too, and the results obtained have been compared. By a suitable choice of the diameter of the Brightray wire partially filling the bore of the connecting

tube the precision of this method has been improved till the results obtained by both methods are equally good, and it is therefore hoped that the error in the flow rate due to temperature fluctuations will be negligible, although this can only be confirmed when the constant pressure method is used.

After the flow has started, the temperatures of the viscometer appears to reach equilibrium quite quickly. When equilibrium is reached, the pressure balance ceases pumping, and the balance piston remains steady.

A small and uniform rate of change in furnace temperature will not cause any error, since the error in the flow rate for the fall in the direction will be in the opposite sense, and almost equal, to the error for the fall in the reverse direction.

2b. Leakage of water between the mercury pellet and the wall of the glass drop-tube.

This would cause an error in the flow rate measured. To determine whether there is any leakage, the following experiment was done before the apparatus was built.

A series of glass tubes having bore diameters between 1.5 mm. and 3.5 mm. were cleaned by passing through them a hot solution of 50% methyl alcohol in water and saturated with sodium hydroxide. They were then washed with 10% hydrochloric acid, then cleaned with distilled water, and dried by passing dry filtered air through them. A tube was mounted at an angle and a glass capillary was fitted to the lower end of the tube. The outlet of

the glass capillary could be closed with a clip. With the clip closed, a volume of dried, redistilled mercury was injected into the top end of the tube. A volume of distilled water was then injected in such a way that no air bubbles were formed, and finally a volume of clean mercury which had been stored under distilled water was injected, so that a volume of water was trapped between two mercury pellets. The pellets were then run down the tube and their position adjusted by means of carefully opening the clip so that the rear pellet coincided with a mark on the tube, and the distance between the mercury pellets was measured by a travelling microscope.

The clip was then opened, and the pellets moved down the tube until the rear pellet was opposite a second mark nearer the capillary end of the tube. The distance between the pellets was again measured. Since the diameter of the glass tube at the two marks on the tube had previously been measured by measuring the length of a known volume of mercury, the volume of water between the pellets could be found before and after the fall. The difference divided by the total volume displaced during the fall is the fractional leakage. The flow rate was measured with a stopwatch timing over a 50 cm. length near the middle of the fall.

The experiment was repeated with different flow rates. The results, which are given in Appendix II, show that there is a critical flow rate, which depends on the diameter of the tube, but which is independent of the length of the pellet. Above this

critical flow rate, which was approximately $30 \times 10^{-3} \text{ cm}^3/\text{sec}$, for tubes of between 0.2 cm. and 0.25 cm. bore, the leakage increased from less than 0.1% to several per cent., and the movement of the pellets became irregular.

It was noticed that when the leakage was measurable, the front meniscus did not show a continuous line of contact between the mercury and the glass. It was usually bent back at one point, and directly behind this point small drops of water could be seen between the mercury and the glass. This effect could be observed even when the leakage rate measured was less than the experimental error in this experiment, i.e. if no drops of water could be detected between the pellet and the wall of the drop-tube, it could be assumed that the leakage rate was certainly less than 0.1%. Since this test is quicker and more sensitive than measuring the leakage, all drop-tubes used in the calibrations and for the experiments on steam have been checked for leakage in this way.

The flow rates used are always less than half of the smallest flow rate at which leakage could be detected, and it can therefore be assumed that the error due to leakage past the mercury pellet is negligible, provided the critical flow rate does not decrease markedly with increasing pressures. This seems a reasonable assumption, since the leakage can be assumed to depend on the viscosity of the water, and the interfacial tensions between mercury, water and glass. These do not change appreciably with pressure. Also, if leakage occurred during an actual experiment

the apparent surface tension drag found by the normal procedure would be unusually large, since the flow rate with the drop-tube inclined would be too small to cause leakage.

3. Pressure Drop Errors.

(a) Surface tension drag.

Rankine, ⁽¹⁾ found that there is a drag on the pellet, due to the different shapes of the front and rear menisci. He found that the drag is independent of the rate of movement of the pellet, and of its length, but that it increases with decreasing diameter of the drop tube. It also varies with the state of cleanliness of the drop tube and of the mercury, and with the fluid in contact with the mercury.

The correction can be found by two methods:-

- (i) By splitting the pellet, in which case the drag is doubled and,
- (ii) by inclining the drop tube, in which case the drag remains the same, while the pressure exerted by the pellet is diminished.

In either case the correction is found by comparing two consecutive results. The method (i) is more accurate for the purpose of finding the surface tension drag than method (ii), but since the flow rates with method (i) are nearly equal, this method gives no check that the Hagenbach correction is accurate, nor does it give any indication whether any leakage between the pellet and the drop tube occurs.

The method (ii) is less accurate because the value found for the correction is sensitive to the assumed value of the angle of inclination of the drop tube, so that another source of error is introduced, but since tests show that the drag correction as found by either method agree well, method (ii) has been used.

(b) Pressure loss in connecting tubes.

The viscometer was designed to keep this as small as possible. It could be made entirely negligible by using larger cross-sections. There is an upper limit to the drop-tube diameter, which was found in the experiments on leakage past the mercury pellet, and it has already been shown that errors due to a change in temperature are proportional to the cross-sectional area of the connecting tube between the drop tube and the capillary. With the dimensions chosen the pressure loss will not be negligible, so that it should be measured and corrected for.

Timroth⁽⁹⁾, who used an apparatus having a similar flow circuit to this viscometer, measured the pressure loss directly, by repeating his experiments without the capillary, and using a much smaller differential pressure. He obtained a linear relationship between flow rate and pressure loss for all the steam conditions used.

In the present viscometer this direct method is not possible, because there is a minimum pressure drop necessary to ensure stable flow, since if the pellet weight is only a little larger than necessary to overcome the surface tension drag, the flow will not start, and if started, the flow rate would not be

constant.

Two alternatives are then possible:

- (i) The pressure loss may be increased by a known amount, by inserting a throttling capillary in the circuit at a point where the temperature is low and accurately known, and measuring the sum of the pressure drops using the normal procedure. Assuming a value for the viscosity of the water at the throttling capillary, the pressure drop through it could be calculated, and the loss could be found as a difference.

Since, however, the pressure loss has been found to be always less than 1.3% of the pressure drop through the capillary, when the viscometer is used for steam, it is clear that the precision attainable in the above determination of the pressure loss would be inadequate to determine the pressure loss itself.

- (ii) Assuming that the flow is laminar throughout the viscometer, the pressure loss Δp_e is given by the relation

$$\Delta p_e = w \phi E \nu \dots\dots\dots 4.9$$

where $\frac{1}{E}$ is analogous to a capillary constant, and Δp_e denotes the pressure loss.

The temperature, and hence the viscosity, will be uniform for the part of the viscometer inside the furnace, and for the part

at room temperature.

The equation 4.9 then simplifies to

$$\Delta p_e = [F \nu_S + L \nu_R + \oint E \nu] w_1 \dots\dots\dots 4.10$$

where the first term refers to the part of the viscometer inside the furnace, the second to the part at room temperature and the third term to the part where the temperature falls from that of the furnace to room temperature. This part is approximately 20 cm. long, and since the kinematic viscosity there will be small, this term may be neglected when applying the correction for pressure loss.

The following experiment was carried out:

The viscometer was assembled without the capillary and with the mercury reservoir at the top of the drop tube removed. Water was caused to flow in through the drop tube, through the connecting tube to the capillary fitting, and back through the annulus. It was then collected in a measuring cylinder. A water manometer showed the pressures of the inflowing and outflowing water at points very close to the viscometer and the pressure drop through the viscometer could be measured with a measuring microscope to 0.01 cm. head of water. To ensure that the pressure drop was constant, the water supply was taken from a constant head tank, and another constant head device was used at the outlet to the measuring cylinder.

The temperature of the furnace was measured by the thermocouples attached to the viscometer and the temperature of the water was measured by a mercury-in-glass thermometer where the water left the viscometer. The flow was timed for every 2 cm³ to a total

of 20 cm^3 for each test. No variation in the flow or the pressure difference could be detected. Two tests were done, one with the furnace at room temperature, and one with the furnace heater to give a uniform temperature of 70°C .

The results obtained were:-

With the furnace at 14°C ., water exit temperature 18°C ., the flow rates and corresponding pressure drops found were:-
 $5.1 \times 10^{-3} \text{ cm}^3/\text{sec}$., 0.56 g/cm^2 ; $18.3 \times 10^{-3} \text{ cm}^2/\text{sec}$., 2.01 g/cm^2 ;
and $15.0 \times 10^{-3} \text{ cm}^2/\text{sec}$., 1.66 g/cm^2 .

With the furnace at 70°C ., water exit temperature 19°C ., the flow rates and corresponding pressure drops were:-
 $28.7 \times 10^{-3} \text{ cm}^2/\text{sec}$., 1.97 g/cm^2 and $24.0 \times 10^{-3} \text{ cm}^2/\text{sec}$, 1.62 g/cm^2 .

The results show that the flow was laminar throughout the parts of the apparatus where pressure losses occur.

Inserting these values, with the viscosity values corresponding to the furnace and room temperatures, in equation 4.10 one obtains:-

$$2.01 \times 981 = 18.3 \times 10^{-3} \left[F \times 11.71 \times 10^{-3} + L \times 10.56 \times 10^{-3} + \phi E \right] \quad \dots\dots\dots 4.11$$

$$1.97 \times 981 = 28.7 \times 10^{-3} \left[F \times 4.061 \times 10^{-3} + L \times 10.30 \times 10^{-3} + \phi E \right] \quad \dots\dots\dots 4.12$$

The term F refers to a length of 65 cm. and E to a length of 20 cm. of the horizontal pressure tube. The cross-section of flow in this tube is the same for both sections. One can therefore assume that

$$E = \frac{20}{65} F.$$

If it is also assumed that the average temperature in the section E is the mean of the room temperature and the furnace temperature, one obtains:

$$F = 4.1 \times 10^6, \quad L = 4.3 \times 10^6 \quad \text{and} \quad E = 1.26 \times 10^6.$$

Neglecting the term E, the pressure drop across the capillary is:-

$$\Delta p = \frac{8(W-a)}{\pi D^2} \left(1 - \frac{\rho_w}{\rho_m}\right) - w \left[4.1 \times 10^6 v_S + 4.3 \times 10^6 v_R \right] \dots 4.13$$

Inserting this in Poiseuille's equation

$$v_S = C \frac{\Delta p}{w}$$

one obtains:

$$v_S = \frac{8C(W-a)}{\pi D^2 w} \left(1 - \frac{\rho_w}{\rho_m}\right) - 4.1 C \times 10^6 v_S - 4.3 C \times 10^6 v_R \quad \dots 4.14$$

To see the magnitude of the correction for pressure loss, the value $C = 2.78 \times 10^{-10}$, which refers to the platinum capillary, is substituted in the equation 4.14. The correction becomes

$$v_S = v' \left[1 - 11.2 \times 10^{-4} - 12 \times 10^{-4} \frac{v_R}{v_S} \right]$$

The maximum value of the ratio $\frac{v_R}{v_S} = 10$, so that the maximum value of this correction is 1.3%. Since the correction is so small it is believed that the various approximations used in the estimation of this correction are justified. It is believed that the error in the correction is less than $\pm 20\%$, causing an error

in viscosity of less than $\pm 0.25\%$.

4. Calibration of the capillaries and drop tubes, and consequent errors.

Calibration procedure:

The drop tube and the capillary were calibrated together in the apparatus shown in figure 12. The capillary was mounted in a holder similar to the end-fitting for the connecting tube in the viscometer, and the joint checked for leakage. The holder was then connected to the end of the drop tube with a rubber tube, a mercury pellet was inserted in the reservoir at the end of the drop tube, and the apparatus assembled. The apparatus was then evacuated and filled with air which was purified and dried by bubbling it slowly first through a concentrated solution of sodium hydroxide and then through concentrated sulphuric acid. The apparatus was evacuated and filled several times.

The apparatus was rotated through 180° and the times of fall measured in the same way as used for the tests on steam. The surface tension drag was found by splitting the pellet. The temperature was measured by a standard thermometer to 0.1°C ., which was situated with its bulb touching the middle of the capillary holder, and which could be read through the glass condenser walls. The tests were only done near room temperature. To ensure constant temperature, uniform over the length of the condenser, the condenser jacket was connected to an electric pump which circulated water through it from a large tank.

The capillary constant was measured in the same apparatus, by the same method, but using a drop tube having only two sets of constants and a larger bore. The bore was measured at 5 stations along the timed length using a mercury pellet, and the lengths between the contacts were measured with a measuring microscope to 0.01 cm. The results of these calibration experiments are given in Appendix II.

Since, in general, the cross-sectional area of the drop tubes may vary over their length, the value of Δp will also vary, and the specific volume of the gas which is contained in the drop tube between the pellet and the capillary will alter so that the observed flow rate will be in error. The error will be greater the greater the pressure drop, and the greater the volume of the compressible gas which is contained between the pellet and the capillary tube. An estimate of this error can therefore be found by calculating the rate of fall of the pellet over a short length of the drop tube having varying cross-sectional area, and comparing this with the rate of fall which would be observed had this short length been situated near the capillary, so that the volume of gas contained would be negligible. The flow relation will first be calculated for the case when the volume of gas between the pellet and the capillary need be considered.

If the volume of gas in the drop tube between the pellet and the length of capillary fall is V_0 the volume after the pellet has fallen through a length x is

$$V_0 - \int_0^x f(x) dx$$

where $f(x)$ is the cross-sectional area of the drop tube at x , if further the effective weight of the pellet is W , corrected for surface tension drag, the atmospheric pressure is p and the specific volume of the gas at this pressure is v , the mass of gas in the drop tube is

$$w = \frac{V_0 - \int_0^x f(x) dx}{v \left(1 - \frac{W}{p f(x)}\right)} \dots\dots\dots 4.15 \quad \text{small } w$$

The rate of change of this is

$$\frac{dw}{dt} = \frac{dw}{dx} \frac{dx}{dt} = \frac{1}{v} \frac{dx}{dt} \left[\frac{-f(x)}{1 - \frac{W}{p f(x)}} + \frac{W}{p} \frac{-f'(x)}{\left[f(x)\right]^2} \right]$$

$$\frac{v_0 - \int_0^x f(x) dx}{\left[1 - \frac{W}{p f(x)}\right]^2} \dots\dots\dots 4.16$$

This must equal the mass flow into the drop tube through the capillary

$$= - \frac{C W g}{\gamma v f(x) \left[1 - \frac{W}{2p f(x)}\right]} \dots\dots\dots 4.17$$

which can be derived from Poiseuille's equation.

Hence

$$\frac{dx}{dt} \frac{f(x) + \frac{W}{p} \left[V_0 - \int_0^x f(x) dx \right] \frac{f'(x)}{\left[f(x)\right]^2} - \frac{W}{p}}{\left[1 - \frac{W}{p f(x)}\right]^2} = \frac{C W g}{\gamma f(x) \left[1 - \frac{W}{2p f(x)}\right]}$$

or

$$\int_{x_1}^{x_2} \frac{f(x) - \frac{W}{2p}}{\left[1 - \frac{W}{p f(x)}\right]^2} \left[f(x) - \frac{W}{p} + \frac{W}{p} \frac{f'(x)}{\left[f(x) \right]^2} \left(V_0 - \int_0^x f(x) dx \right) \right] dx$$

$$= \frac{C W g t}{\quad} \dots\dots\dots 4.18$$

If the same part of the drop tube were situated nearer the capillary, the volume $V_0 - \int_0^x f(x) dx$ would be smaller, and the error in the observed flow would consequently be less. If it were zero the error in the flow rate would also be zero, and the error in the flow rate due to the compressibility of the gas which is stored between the pellet and the capillary, i.e. in the volume $V_0 - \int_0^x f(x) dx$, is therefore the flow given by the left hand side of equation 4.18 minus that which would result if the factor $V_0 - \int_0^x f(x) dx$ in this equation were zero.

Thus the error in t, Δt , equals

$$\Delta t = \frac{\tau}{C W g} \int_{x_1}^{x_2} \frac{W f'(x) \left[V_0 - \int_0^x f(x) dx \right] \left[f(x) - \frac{W}{2p} \right]}{p \left[f(x) - \frac{W}{p} \right]^2} dx \dots\dots 4.19$$

where $x_2 - x_1$ equals the length of the part of the drop tube considered.

The drop tube may be assumed to be made up of sections, each having a cross-sectional area $A = B + Ex$, where B and E may be different for each section.

At the start of the section considered $A_1 = B + E x_1$ and at its end $A_2 = B + E x_2$. Hence the error in the time of fall over

this section is

$$\Delta t = \frac{\gamma}{C p g} B \int_{A_1}^{A_2} \frac{[\sqrt{V_0 - \frac{1}{2} A^2 + \frac{1}{2} A_1^2}] [\sqrt{A - \frac{W}{2p}}]}{[\sqrt{A - \frac{W}{p}}]^2} dx$$

$$= \frac{\gamma}{C p g} B \int_{A_1}^{A_2} \left[\sqrt{V_0 + \frac{1}{2} A_1^2} - \frac{3}{2} \left(\frac{W}{p} \right)^2 \left(\log(A - \frac{W}{p}) - \frac{W}{2p(A - \frac{W}{p})} \right) \right. \\ \left. - \frac{1}{4} (A^2 + \frac{3W}{p} A) \right] \dots\dots 4.20$$

The time of fall over the same length of the drop tube, neglecting the effect of the compressibility of the stored volume of gas, is

$$t = \frac{\gamma}{C W g} \int_{x_1}^{x_2} \frac{(f(x) - \frac{W}{2p})(f(x) - \frac{W}{p})}{[\sqrt{f(x) - \frac{W}{p}}]^2} dx \dots\dots\dots 4.21$$

Since $\frac{W}{p f(x)} = \frac{\Delta p}{p}$, and since Δp is only approximately 0.02 at., while $p = 1$, the argument will still be valid if it is assumed that

$$t = \frac{\gamma}{C W g} \int_{x_1}^{x_2} B^2 dx = \frac{\gamma}{C W g} B^2 (x_2 - x_1) \dots\dots\dots 4.22$$

or

$$t = \frac{\gamma}{C W g} \frac{B^2}{E} (A_2 - A_1) \dots\dots\dots 4.22a$$

Integrating equation 4.19 one obtains

$$\Delta t = \frac{\eta}{C W g} E \left\{ \left[\sqrt{V_0} + \frac{1}{2} A_1^2 - \frac{3}{2} \left(\frac{W}{p} \right)^2 \right] \left[\log \frac{A_2 - \frac{W}{p}}{A_1 - \frac{W}{p}} + \frac{W}{2p} \frac{A_2 - A_1}{(A_2 - \frac{W}{p})(A_1 - \frac{W}{p})} \right. \right. \\ \left. \left. - \frac{1}{4} \left[A_2^2 - A_1^2 + \frac{3W}{p} (A_2 - A_1) \right] \right\} \dots 4.19a$$

If it is assumed the cross-sectional area of the drop tube increases by as much as 10% over the length considered, and that $W = 1.2$ grams and $p = 1000$ grams/cm², the expression for Δt becomes:

$$\Delta t = \frac{\eta}{C g} \left\{ \left[\sqrt{V_0} + \frac{1}{2} A_1^2 - \frac{3}{2} \times 1.44 \times 10^{-6} \right] \left[\log \left(1 + \frac{0.1 A_1}{A_1 - 1.2 \times 10^{-3}} \right) \right. \right. \\ \left. \left. + 0.6 \times 10^{-3} \frac{0.1 A_1}{1.1 A_1 - 1.2 \times 10^{-3}} (A_1 - 1.2 \times 10^{-3}) \right] \right. \\ \left. - \frac{1}{4} \left(0.21 A_1^2 + 0.36 \times 10^{-3} A_1 \right) \right\} \dots \dots \dots 4.19b$$

The drop tubes used for the observations on steam, and in finding the combined calibration constant for the viscometer, have a cross-sectional area of approximately 0.03 cm³. Substituting this value, equation 4.19b becomes approximately,

$$\Delta t = \frac{\eta E}{C g} \left\{ \left[\sqrt{V_0} + 0.45 \times 10^{-3} - 2.16 \times 10^{-6} \right] \left[0.1 + 0.6 \times 10^{-3} \times 0.1 \right] \right. \\ \left. - \frac{1}{4} \left(0.18 \times 10^{-3} + 0.36 \times 10^{-3} \times 0.03 \right) \right\} \\ = \frac{\eta E}{C g} \left\{ \left[\sqrt{V_0} + 0.45 \times 10^{-3} \right] \times 0.1 - 0.045 \times 10^{-3} \right\} \\ = \frac{\eta E}{C g} \left\{ 0.1 V_0 \right\} \dots \dots \dots 4.19c$$

On the same assumption, equation 4.22a becomes

$$t = \frac{\eta}{C W g} \frac{B^2}{E} \times 3 \times 10^{-3}$$

so that the fractional timing error $\frac{\Delta t}{t}$ becomes

$$\frac{\Delta t}{t} = 1.2 \times 10^{-3} \frac{E^2}{L^2} \frac{0.1 V_0 \times 10^3}{3} = 0.04 V_0 \left(\frac{E}{B}\right)^2$$

In the drop tube used for steam the length from the outer set of contacts to the capillary is approximately 55 cm. so that

$$V_0 = 55 \times 0.03 = 1.65 \text{ cc.}$$

Hence

$$\frac{\Delta t}{t} = 0.066 \left(\frac{E}{B}\right)^2$$

If the length of this section is ΔL , then $E = \frac{0.1 B}{\Delta L}$

and the resulting fractional timing error over the whole of the timed length is

$$\frac{\Delta t}{t} = 0.066 \frac{0.01}{(\Delta L)^2} \frac{\Delta L}{L} = \frac{0.066}{L \times \Delta L} \times 10^{-2}$$

If $L = 5$ and $\Delta L = 1$, the timing error will be 0.013%.

Since the drop tubes are carefully blown, so that the variation in cross-sectional area is always less than 10%, the error in the calibration constants will be negligible.

5. Errors in the assumed capillary constant.

(a) Thermal expansion of the capillary.

The capillary constant $C = \frac{\pi d^4}{128 l}$ has the dimension cm^3 . The value of C at a temperature t° will therefore be

$C = C_0 (1 + 3 \Delta t^\circ)$, where C_0 is the value of C and 0°C ., and Δ is the coefficient of thermal expansion for the capillary material.

(b) End correction.

The conventional end correction due to Hagenbach⁽²²⁾ is applied in the form given by Timroth⁽⁹⁾.

(c) In case there should be doubt whether the Poiseuille equation holds for a capillary tube at the Reynolds numbers used, due to incipient turbulence caused by the capillary not being cylindrical and circular in section, or caused by irregularities in the bore, an attempt was made to calibrate the capillaries over the range of Reynolds number. For this attempt the same calibration apparatus was used, with a special drop tube in which mercury pellets of up to 50 cm. length could be used. The fluid used was hot distilled water.

The results were of poor accuracy, due to dust from the atmosphere which tended to block the capillary partially, and which may have been introduced into the apparatus during assembly, due to the dusty atmosphere in the room where this requirement was attempted. Later conditions improved, and the experimental technique also, and no troubles of this kind were experienced during the calibration runs with air or during the measurements on steam. The calibration experiment to find the variation of the capillary constant with Reynolds number have not been repeated, since the results showed that this variation is negligible at all the Reynolds numbers used.

If an error were present, the viscosities found would be too large, and since the surface tension drag is found by comparing, in effect, the viscosities found at two Reynolds numbers, which differ by a factor of 1.5, the correction for surface tension drag would be less at the higher Reynolds numbers than at the lower. Since no such

effects were found, it was concluded that the error, if any, is too small to be detectable in the apparatus used.

Flow relation.

Poiseuille's equation, with the Hagenbach correction added, is

$$\nu = \frac{\pi d^4}{128 \ell} \frac{\Delta p}{w} - \frac{1.12 w}{8\pi \ell \rho_s} \dots\dots\dots 4.23$$

The capillary constant $\frac{\pi d^4}{128 \ell}$ is found by calibration and is denoted by C.

Since this must be corrected for thermal expansion the value which should be used is $C = C_0 (1 + 3 \Delta t^0)$. Since the flow rate

is

$$w = \rho_w \frac{\frac{\pi}{4} D^2 L}{t}$$

and the pressure drop, from equation 4.13, is

$$\Delta p = g \frac{W (1 - \frac{a}{W})}{\frac{\pi}{4} D^2} (1 - \frac{\rho_w}{\rho_m}) - w (4.1 \times 10^6 \nu_s + 4.3 \times 10^6 \nu_w)$$

The ratio $\frac{\Delta p}{w}$ then becomes

$$\frac{\Delta p}{w} = g t \frac{W (1 - \frac{a}{W})}{(\frac{\pi}{4} D^2)^2 L} (\frac{1}{\rho_w} - \frac{1}{\rho_m}) - (4.1 \times 10^6 \nu_s + 4.3 \times 10^6 \nu_w)$$

Substituting this and the capillary constant $C_0 (1 + 3 \Delta t^0) = \frac{\pi d^4}{128 \ell}$

in equation 4.23 one obtains

$$\nu = C_0 (1 + 3 \Delta t^0) g t \frac{W (1 - \frac{a}{W})}{(\frac{\pi}{4} D^2)^2 L} (\frac{1}{\rho_w} - \frac{1}{\rho_m}) - C_0 (4.1 \times 10^6 \nu_s + 4.3 \times 10^6 \nu_w) - \frac{1.12 w}{8\pi \ell \rho_s} \dots\dots 4.24$$

Since the capillary constant $C_0 \doteq 2.78 \times 10^{-10}$ and the temperature of the cold part of the apparatus is always near 20°C . so that $\nu_w \doteq 0.01$, the second term in equation 4.24 is

$$(1.14 \times 10^{-3} \nu_s + 1.2 \times 10^{-5})$$

The factor $\frac{1}{(\frac{\pi}{4} D^2) L}$ is denoted by G . The value of G is

different for each timed length, and is found either by direct measurement or by calibration of the capillary in conjunction with the capillary.

Substituting equation 4.24 becomes

$$\begin{aligned} \nu = G C_0 t W (1 - \frac{a}{W}) g (1 + 3 \Delta t^0) (\frac{1}{\rho_w} - \frac{1}{\rho_m}) (1 - 1.14 \times 10^{-3}) \\ - 1.2 \times 10^{-5} - 1.12 \frac{W}{8\pi e \rho_s} \dots 4.24a \end{aligned}$$

The factor

$$F = g (1 + 3 \Delta t^0) (\frac{1}{\rho_w} - \frac{1}{\rho_m}) (1 - 1.14 \times 10^{-3})$$

is constant for all observations at one temperature and pressure, and can be worked out in advance.

Since the Hagenbach correction is always less than 4% no significant error is caused if the flow rate used for its evaluation is that observed over only one timed length, rather than the average of several. For this timed length, therefore,

$$W = \rho \frac{\frac{\pi}{4} D^2 L}{t}$$

and the Hagenbach correction thus contains the constant factor

$$\frac{1.12}{8\pi\ell} \frac{\pi}{4} D^2 L$$

which is denoted by h. The contact used is the last one of each run, i.e., the last timing obtained during an out and return fall of the pellet.

The final flow relation is then

$$V = G C t F \left(1 - \frac{a}{w}\right) - 1.2 \times 10^{-5} - h \frac{\rho_w}{\rho_s} t_1, \dots\dots 4.25$$

where C = the calibrated capillary constant

G = the calibrated drop tube constant

t = the observed time of fall

F = the factor $g (1 + 3\Delta t^0) \left(\frac{1}{\rho_w} - \frac{1}{\rho_m}\right) (1 - 1.14 \times 10^{-3})$

h = the factor $\frac{1.12}{8\pi\ell} \frac{\pi}{4} D^2 L$ for contact 1'

and t_1 = the time of fall over contact 1'

In evaluating the results the following values are assumed:

$$g = 981 \text{ cm/sec}^2$$

$$\Delta = 9 \times 10^{-6} \text{ } ^\circ\text{C}^{-1} \text{ for the platinum capillary}$$

ρ_s is obtained from Vukalowich' steam tables⁽²³⁾ for pressures up to 300 at., and temperatures up to 700°C. At temperatures above 700°C. graphically extrapolated values are used. Above 300 at. pressures Kennedy's⁽²⁴⁾ p V-T data are used. It should be noted that ρ_s only enters into the Hagenbach correction, which is small.

ρ_w and ρ_m are evaluated from the compressibilities of water and mercury given in Chemical Engineer's Handbook⁽²⁵⁾.

CHAPTER V

PROCEDURE

Furnace regulation

The main heater input was adjusted to give a temperature near that desired, and the inputs to the auxiliary heaters were set at values thought to give uniform temperature. After equilibrium was attained, usually after about 16 hours, the temperature distribution in the furnace was measured with a probe thermocouple. Usually the setting of the auxiliary heater was incorrect, so that the temperature variation over the length of the furnace was rather large. The auxiliary heater inputs were then adjusted to give an error in the opposite direction, and by noting the change in inputs and the corresponding change in temperature a satisfactory final setting could be reached.

The settings were considered satisfactory if the temperature over the working length of the furnace, i.e. within 6 in. from each end, was uniform within 2°C. The variation of temperature over the capillary was then 1°C. or less. Observations were then made at this temperature and at pressures in the range 100 at. to 1000 at.

Assembly.

Before the first assembly the Nimonic tubes were pickled according to the directions given by the makers, and cleaned by a jet of steam and boiling water. All other parts were machined all over and needed no pickling, only degreasing and a wash in boiling water

to remove traces of flux from the soldered joints. The inner tube with the capillary and the mercury trap was inserted in the horizontal Nimonic tube through the central body. The separating membrane and the mild steel body were degreased and dried, and screwed in place. The glass drop tube was threaded into the cold Nimonic tube, and a weighed amount of mercury dropped into the lower mercury reservoir. The drop tube was pressed into the rubber sleeve in the mercury trap and the cold pressure tube was screwed tight. The cap containing the perspex insulating sleeve for the contact lead was screwed on, and a glass fitting secured over its end with a rubber sleeve. The glass fitting was made with two openings. One was connected through a stop-cock to the filter pump, the other incorporated a glass filter disc and was connected to a flask containing boiling, distilled water, also through a stop-cock.

The viscometer was evacuated and filled with water. The water used was deaerated by prolonged boiling. This was repeated several times to ensure that no air remained in the viscometer. The filter pump was then connected to the oil-side of the membrane, and more water drawn in until the membrane was fully extended. The connecting tube to the pressure balance was then screwed on, the glass fitting was taken off, and the hand oil pump given a few strokes to run out the water near the top of the drop-tube which had been in contact with the air for the short time since the glass fitting was removed. This opening was then closed while the water was flowing slowly out, by screwing tight the lead from the contact wires.

Operation.

The pressure was brought up with the hand pump and the automatic pressure regulation switched on. The input to the tube heater was increased to a value thought to give uniform temperature distribution. This was necessary because the heat loss from the furnace through the viscometer increased when the pressure was increased above atmospheric. The apparatus was then left for at least 30 minutes so that temperature equilibrium could be reached. The flow was started by rotating the viscometer on its journal bearings through 180° . The times were recorded and the viscometer was rotated back again when it was estimated that the pellet was near the outer end of the drop tube, so as to give the longest possible approach time before the observations were again made for the flow in the reverse direction.

The thermocouple, figure 7 (16e) was kept permanently connected to the galvanometer and its reading was watched to see whether there were any temperature fluctuations which might cause errors in the flow rate, and the movement of the piston on the pressure balance was also watched.

The first runs were usually inaccurate, since the heat loss from the viscometer is greater when there is circulation in it. There is a change in the equilibrium temperatures in the part of the viscometer near the tube heater where there is a large temperature gradient.

Runs were also done with the drop tube at a fixed angle from the vertical, to find the correction for the surface tension drag

on the pellet. Readings were taken until a sufficient number were obtained to show that they were consistent. The drop tube was then fixed in the horizontal position and the pressure altered. The same procedure was used at all pressures. The temperature at each thermocouple was measured at each pressure.

During one complete run four or more timings were obtained. The average obtained from a series of runs are used in calculating the drag correction and the viscosity at each steam condition.

It was found that the drag correction increased with the time, presumably as a consequence of the electric current through the mercury pellet and the water. To cut down the increase in this correction, the current to the drop tube contacts was only switched on when a signal was due, and switched off as soon as the signal was obtained. Since a large error could be caused if the mercury formed two pellets instead of one, the time taken for the pellet to traverse one of the contacts was measured after each time the mercury had been stored in the reservoirs at each end of the drop tube. This showed approximately the weight of the flowing pellet, and whether more than one pellet was flowing.

The milliampère meter in the timing circuit shows the contact current, and indicates whether contact is made cleanly. If there are impurities in the water or a deposit on the contact wires, the current will rise gradually before contact is made, and the time recorded might be inaccurate. If the meter shows a sudden jump in the current, the timing will be accurate. After prolonged running

the stray current, i.e. the current through the water in the viscometer due to faulty insulation and impurities in the water, will rise. When the current increases to 0.08 mA the viscometer is dismantled, the drop tube is cleaned and the apparatus refilled with clean mercury and water. The stray current should then be less than 0.03 mA. This corresponds to a resistance of approximately $150,000 \Omega$, falling to approximately $60,000 \Omega$ due to impurities in the water, before the water is again changed. The apparatus is dismantled and refilled sufficiently often to ensure that the results are repeated over at least half the range of pressures. A complete record of the results obtained are given in Appendix I. As will be seen from Appendix I the experiments were started at a pressure where the flow rate was large, so that it could quickly be established whether the viscometer was working properly. The pressure was then increased in steps to 1000 at., and then decreased in steps to the minimum pressure used.

When the water and mercury were changed, the mercury used was dried and weighed, to check whether any mercury remained in the viscometer. The water was watched to see if any gas bubbles formed. This would indicate whether any corrosion of the viscometer, which would liberate hydrogen, had occurred during the tests.

When the apparatus was first used, large amounts of gas were formed, until a stable oxide layer was formed. No gas was found after the tests for which results are given in the table. All the runs obtained after the apparatus was fully developed are

included in this table except the runs which were rejected for the following reasons:

- (a) Lack of temperature equilibrium, shown by the balance piston moving, or by the galvanometer showing a temperature variation. Since the galvanometer deflection is of the order of 5 cm./ $^{\circ}$ C. this is a sensitive test for temperature variation.
- (b) The calculations for the surface tension correction show that the drag is increasing. The apparatus was dismantled, the drop-tube cleaned, and the apparatus refilled with fresh water and mercury.
- (c) Tests obtained at the same steam conditions with two different pellets disagree by more than 0.5%. Some tests were then repeated with a third pellet and the series which proved inconsistent with these was rejected. The lack of agreement was always due to an error in the weight of the moving pellet, or to the pellet not falling all in one piece.
- (d) The stray current increases to more than three times its initial value, which is never above 0.03 mA. The apparatus is then dismantled, the drop tube is cleaned and the apparatus is refilled.
- (e) One of the timings was missed during a run.

Sample calculations

Stainless capillary, of length 30 cm.

Mercury pellet weight, 2.595 grams.

Calibration of capillary and drop tube together gave the following values of the constants K in equation 4.25.

$$K_1 = 290.2 \times 10^{-7} : K_2 = 301.85 \times 10^{-7} : K_2' = 310.86 \times 10^{-7} : \\ K_1' = 288.4 \times 10^{-7} .$$

Runs 56 and 58 were obtained with the drop tube inclined to 52° from the horizontal, in order to find the correction for surface tension drag. They are not included in the averaged values.

Values of Kt:

$$K_1 t_1 = 5513.8 \times 10^{-7} : K_2 t_2 = 5518.0 \times 10^{-7} : \\ K_2' t_2' = 5510 \times 10^{-7} : K_1' t_1' = 5438 \times 10^{-7}$$

$$\text{Average Kt:} = 5494 \times 10^{-7}$$

Determination of the surface tension drag. From the equations 4.25 and 4.25a it is seen that the drag correction is

$$\frac{a}{W} = \frac{t_2 \sin\theta - t_1}{t_2 - t_1} + \frac{H_1 - H_2}{K W F (t_2 - t_1)}$$

where H_1 is the Hagenbach correction for the drop tube vertical and H_2 the correction for the drop tube inclined at the angle θ from the horizontal.

TABLE OF RESULTS.

Run No.	Contact No.				Thermocouple No.					Cold junction temp.
	1	2	2'	1'	1	2	3	4	5	
53	19.000	18.375	17.775	18.925						
54	19.000	18.325	17.900	18.750						
55	19.000	18.300	17.775	18.775	3.597	3.608	3.593	3.585	3.530	20°C
56	23.800 ^x	22.900 ^x	22.925 ^x	24.350 ^x						
57	19.000	18.300	17.500	18.900						
58	23.900 ^x	22.900 ^x	22.875 ^x	--						
58a	--	22.900 ^x	22.200 ^x	24.400 ^x						
59	19.000	18.350	17.650	18.825						

Average:

19.000 18.330 17.725 18.835 Temp. 430.5°C.

Runs 56 and 58 were obtained with the droptube inclined at to 52° from the horizontal in order to find the correction for surface tension drag. They are not included in the averaged values.

Values of Kt: $Kt_1 = 5513.8 \times 10^{-7}$, $Kt_2 = 5518.0 \times 10^{-7}$,
 $Kt_2' = 5510 \times 10^{-7}$, $Kt_2'' = 5438 \times 10^{-7}$.

Average values: $Kt = 5495 \times 10^{-7}$.

Determination of the surface tension drag:

From equations 4.25 and 4.25a it is seen that the correction is

$$\frac{a}{W} = \frac{t_2 \sin \theta - t_1}{t_2 - t_1} + \frac{H_1 - H_2}{KWF(t_2 - t_1)}$$

where H_1 refers to t_1 and H_2 to t_2 .

Since

$$H = \frac{44.7 \times 10^{-3}}{\rho_s} \frac{\pi}{4} \frac{D^2 L}{t}$$

and since for the drop tube used, $l = 30\text{cm}$. $\frac{\pi}{4} D^2 L = 0.258 \text{ cm}^2$
average for all four timed lengths.

Hence

$$H = \frac{0.385 \times 10^{-3}}{\rho_s t}$$

where t is the average fall time and

$$\frac{a}{W} = \frac{t_2 \sin \theta - t_1}{t_2 - t_1} + \frac{0.385}{K W F \rho_s L t_2 (K_1 t_1)}$$

Substituting the values

$$t_1 = 18.47$$

$$t_2 = 23.415$$

$$\sin \theta = \sin 52 = 0.788$$

$$W = 2.595 \text{ grams}$$

$$F = 981 (1 + 3 t^\circ) (1 - 11.2 \times 10^{-4}) (1 - 0.072 - 0.004 \frac{p}{100})$$

For $\Delta = 18 \times 10^{-6}$ (stainless capillary), at $t^\circ = 430$ and $p = 600 \text{ at}$.

$$F = 1 - 0.076$$

Hence

$$\frac{a}{W} = 0.034$$

Substituting this value in equation 4.25 the value for
viscosity works out at

$$\begin{aligned} \nu &= 5.494 \times 10^{-7} \times 2.595 (1 - 0.034)(1 - 0.076) - 12 \times 10^{-6} - 0.051 \times 10^{-3} \\ &= (1.271 - 0.051) \times 10^{-3} \\ &= \underline{1.22 \times 10^{-3}} \end{aligned}$$

The drop tube used for these runs, 53 - 59 was unfortunately broken before the constants K could be checked after the runs. There is therefore an uncertainty of 0.4% in the final result, due to the value of K_1 , adopted.

It cannot be seen directly from this set of readings that no leakage occurred or that there is no error due to the Reynolds number being too high. This can only be seen by comparing the value of the drag correction 'a' for this set with the values obtained at conditions where the Reynolds number is different. For the results for which the sample calculation is given the Reynolds number was at the maximum value used, namely 830, and the flow rate was also near the maximum.

It will be apparent, if a check calculation is carried out using the observations given in Appendix I, that the correction 'a' does not fluctuate widely, a result which should be expected if there are no serious errors in the Hagenbach end correction or errors due to leakage or turbulence.

CHAPTER VI

ESTIMATION OF OVERALL ACCURACY

Errors may be subdivided into three groups:

1. Systematic errors causing all results to be inaccurate by the same percentage amount.
2. Systematic errors affecting equally all results obtained at any one steam condition.
3. Random error, which is different for each observation.

1. These systematic errors are caused by

- (i) the uncertainty in the viscosity of the calibration fluid, which has been assumed to be $\pm 0.25\%$ for air. The values used are those listed in the International Critical Tables, as quoted by the Chemical Engineer's Handbook⁽²⁵⁾.
- (ii) Error due to the inaccuracy of the standard thermometer used in the calibration experiments. This error should not exceed $\pm 0.2^{\circ}\text{C.}$, since the calibration tests are all done at room temperature. As the viscosity of air varies 0.25% per degree, at 20°C. , this error should not exceed 0.05% .
- (iii) Error in weighing the mercury pellet. The balance used is a high-precision instrument, graduated to 0.1 mg. and accurate to 0.5 mg. , which produces a maximum error of 0.02% .
- (iv) Errors in the measurements on the calibration drop tube. As the capillary constants obtained from two calibration tubes differ by less than $\pm 0.25\%$, the maximum error from

this course should not exceed $\pm 0.5\%$. The capillary constants chosen are those obtained with the second drop tube, which is of more uniform bore and more carefully measured than the first.

The maximum variation in the observations used is $\pm 0.1\%$.

The sum of these errors is $\pm 0.9\%$.

2. Other systematic errors.

(i) Inaccuracy in the correction for pressure loss in the connecting tubes. As the maximum value of this correction is 1.3% , it has been assumed that the maximum error from this source is $\pm 0.25\%$. Since the magnitude of the correction is small at the steam conditions where the flow rates are small, this error should be smaller than the assumed $\pm 0.25\%$ for most of the observations.

(ii) Errors due to

(a) Inaccuracy in the assumed coefficient of thermal expansion of the capillary. The correction factor is $(1 + 3\Delta t^\circ)$. The maximum value of this correction is 2.16% at 800°C . for the platinum capillary, and 2.7% at 540°C . for the stainless capillaries.

If the error in the coefficient were 5% , the error in the values found for viscosity would be $\pm 0.14\%$.

(b) Inaccuracy in the Hagenbach correction.

(c) Errors due to turbulence

(d) Errors due to leakage.

As stated before, the errors (b) (c) and (d) may be detected by their effect on the correction for surface tension drag.

As an example, the effect on the drag correction of any of these errors if large enough to cause an error in the flow rate of 1% will be worked out for the same reading as used in the sample calculation:

$$\frac{a}{w} = \frac{t_2 \sin\theta - t_1}{t_2 - t_1} + \frac{H_1 - H_2}{\rho_s}$$

where t_1 = observed fall time with the drop tube vertical

t_2 = observed fall time with the drop tube inclined to the angle θ from the horizontal.

H_1 = Hagenbach correction corresponding to t_1

H_2 = Hagenbach correction corresponding to t_2 .

For this reading $\sin\theta \doteq 0.6$, $H_1 = 0.051$, $H_2 = 0.036$

Hence

$$\begin{aligned} d\left(\frac{a}{w}\right) &= \frac{-dt_1(t_2 - t_1) + dt_1(t_2 \cdot 0.6 - t_1)}{(t_2 - t_1)^2} \\ &= -dt_1 \frac{0.4 t_2}{(t_2 - t_1)^2} \end{aligned}$$

Since $\frac{a}{w}$ = small, $0.6 t_2 \doteq t_1$

Thus

$$d\left(\frac{a}{w}\right) \doteq - \frac{dt_1}{0.4 t_2} = -1.5 \frac{dt_1}{t_1}$$

If $\frac{dt_1}{t_1} = -1\%$, $d\left(\frac{a}{w}\right) = +0.015$

For this set $\frac{a}{w} = 0.034$, so that 1% error in the flow rate would cause the value of $\frac{a}{w}$ found to be 0.05. The values obtained for the correction $\frac{a}{w}$ are all compared to the values previously obtained. If any difference is detected, a second run is recorded, and the correction worked out again.

The results show that the drag correction is independent of pressure and flow rate, thus confirming that the errors (b) (c) and (d) are smaller than can be detected in the observations.

Scatter.

From the list of results in Appendix I it can be seen that the individual recorded fall times yield flow rates which vary up to $\pm 1.2\%$. The sum of the fall times observed for each run, however, vary only up to $\pm 0.3\%$, and the root mean square deviation for the observations at one steam condition is never more than $\pm 0.25\%$. The large fluctuations ($\pm 1\%$) in the flow rates as seen when the individual timings are compared are thought to be due to fluctuations in temperature and pressure which are too rapid to enable the pressure balance to respond. These fluctuations could probably be minimised by further development of the apparatus, but since the variations appear to be completely random, it was thought that sufficient accuracy was obtained by the use of a number of observations. If, as is apparent from the observations, these fluctuations are purely random, the errors from this source should be less than $\pm 0.5\%$.

Overall Accuracy.

The sum of the individual errors considered is $\pm 2\%$.

It is therefore hoped that the results obtained are correct to better than $\pm 2\%$.

This belief is supported by the smooth curves which result when the results are plotted graphically, as may be seen from figure 13, which show the values of kinematic viscosity observed to a base of temperature.

CHAPTER VII

ACCOUNT OF THE STAGES OF DEVELOPMENT OF THE APPARATUS

Since the first trial run was attempted in February 1957 the apparatus has been continuously developed in order to obtain a greater known accuracy in the results.

At that time the apparatus was situated in a room in which the temperature fluctuated 30°F . daily. It was anticipated that considerable development work might be necessary and with this in mind the design of the main parts was chosen to give some latitude in the construction of the minor parts. Initially a drop tube of only 12 in. length was used, with only one set of contacts, giving one timing in each direction of fall of the mercury pellet. The platinum capillary was gold soldered to a wide bore connecting tube, and the viscometer was connected to the pressure balance through a tube, 20 ft. long, which accommodated the 180° rotation of the viscometer.

Shortly after the first successful run the capillary was found to be blocked, and on examination it was found by Mr. Mackie of the Engineering Department at Glasgow University to be contaminated with mercury and silver solder, which had entered the connecting tube because the mercury trap was inadequate. The danger of this occurring had not been foreseen, since mercury alone does not amalgamate with platinum, and since it was believed that

sufficient care had been taken to exclude silver solder from the parts which might be in contact with mercury. The mercury trap was then improved, and the filling procedure altered so as to avoid large transient flow rates in the viscometer which might cause mercury to pass through the mercury trap into the connecting tube.

Tests were then resumed with a stainless capillary, which was silver soldered to the connecting tube. It was soon apparent that considerable flow errors occurred due to fluctuations in the heat loss from the exposed part of the horizontal pressure tube, and this was remedied by mounting dummy thermocouple sheaths over this part, so that these, in conjunction with the original five sheaths, were evenly distributed over the tube. A cross-section of the exposed part of the pressure tube would now be radially symmetrical, and the heat loss would thus be independent of the angle of inclination of the drop tube. It was also apparent that it would be desirable to have a check that the flow rates were uniform, and to provide this the drop tube was lengthened to 36 in., which provided room for more sets of contacts, so that the flow rates could be measured more than once during the fall in each direction. With the apparatus in this form the preliminary results given in Appendix I were obtained at temperatures of 370°C . and 540°C . approximately. These results were compared with the values given in the Vukalovich steam tables⁽²³⁾ and it was found that by assuming a suitable capillary constant all the preliminary results differed from the steam table values by

less than 0.5%.

The apparatus was then dismantled in order to calibrate the capillary, but the capillary unfortunately broke, and only part of it was calibrated. A capillary constant was obtained, which, when multiplied with the ratio of the calibrated length divided by the original length of the capillary somewhat fortuitously gave a constant which yielded results only 1% higher than the Russian values.

This appeared encouraging, and further modifications were therefore carried out, in order to realise the possibilities of the instrument.

To avoid having to heat the capillaries during assembly and thus altering the capillary constant due to a build-up of the oxide layer in the bore the capillaries were fastened to the connecting tube by a mechanical joint, and at the same time the bore diameter of the connecting tube was reduced to 0.049 in. to decrease the magnitude of errors in the flow rate due to fluctuations in temperature. It was further found that the response of the pressure balance to pressure fluctuations was poor due to the considerable length of narrow bore tubing filled with castor oil which connected the balance to the viscometer. This tube was therefore discarded and a packed joint substituted. The glass blowing technique was improved and a number of drop tubes were made, in which the bores were more uniform than in the drop tubes previously used.

The new platinum capillary, as well as the stainless capillaries,

were calibrated with air, and the apparatus moved to another room where the temperature was more uniform and the working conditions better. To ensure that the pressure would remain constant, and to speed up operation of the apparatus the pressure balance operation was made automatic. With the apparatus in this form the results at 430°C. approximately were obtained, and results at 540°C. were attempted, when it was found that rapid oxidation of the connecting tube and the stainless steel capillary was taking place. This was thought to be caused by overheating, due to a short circuit in the furnace series resistance which occurred at that time.

At the end of May 1958, therefore, a new connecting tube of Nimonic 75 was substituted for the stainless tube, and the platinum capillary was brought into use. Since the connecting tube available was 1/8 in. i.d. and 1/4 in. o.d., the bore was partly filled with three Brightray C resistance wires to decrease the steam volume. The length of the filler wires was chosen such that the ratios of the cross sectional areas and the volumes were constant for the steam space in the connecting tube and in the annulus, in line with the conclusion obtained on page 44. To avoid causing too large a pressure drop in the connecting tubes the cross-sectional area of this had to be larger than that of the previous stainless tube, but it was found that the precision of the results was impaired, whether the apparatus was worked at constant pressure or constant volume.

The second series of results at approximately 540°C . were obtained with the apparatus in this form. The bore of the connecting tube was then filled with a Brightway C wire of 0.120 in. diameter, which was ground flat on one side to provide the channel for the steam flow. The cross-sectional area of the steam space in the connecting tube is now little more than that of the stainless steel tube used previously, while the resistance correction is the same. The later results are all obtained with the apparatus in this form.

The auxiliary equipment apart from the pressure balance has needed no development.

The author himself designed the apparatus used in this work including the furnace with all its control equipment, the timing mechanism and the automatic pressure regulating mechanism on the pressure balance.

ACKNOWLEDGEMENTS.

The author wishes to record his thanks and to make acknowledgement to the following:-

The University of Glasgow and in particular Professor James Small who has made it possible by the extending of facilities, help and encouragement for this work to be done.

The Central Electricity Authority for the financial support which it brought to the work in its later stages.

Norges Teknisk-Naturvitenskapelige Forskningsvåd, (Royal Norwegian Council for Scientific and Industrial Research) for grants which gave support to the author in the earlier years.

Dr. C. D. Weir who, as supervisor, during the greater part of the period of the research gave advice and offered valuable suggestions.

Dr. E. A. Bruges for his interest and guidance in the preparation of this thesis.

Mr. W. W. Mackie for advice on metallurgical and corrosion problems.

Mr. M. Needleman for advice on chemical matters and Mr. J. Baird, the Foreman Mechanic and his staff for the continuous care and skill they have shown in the construction of the apparatus.

BIBLIOGRAPHY.

1. RANKINE Proc. Roy. Soc. London. A84, 1911, p.181
Faraday Soc. 17, 1922, p.119
2. SPEYERER Forschungs arb. a.d. Geb. d. Ing. W. 273, 1929.
3. SIGWART Forschungs arb. a.d. Geb. d. Ing. W. 7B, 1936,
p.125
Forschungs arb. a.d. Geb. d. Ing. W. 9, 1938, p.312
Forschungs arb. a.d. Geb. d. Ing. W. 10, 1939
4. HAWKINS, POTTER Trans. A.S.M.E., 58, 1936, p.258
& SOLBERG Trans. A.S.M.E., 62, 1940, p.677
Trans. A.S.M.E., 65, 1943, p.401
5. HAWKINS, POTTER Trans. A.S.M.E., 57, 1935, p.395
& SOLBERG
6. SHUGAIEV Journal of Exp. & Theor. Phys. USSR 3, 1933, p.247
7. JACKSON Ph.D. Thesis, Purdue University.
8. JACKSON & THOMAS Contribution ASME., Annual Meeting 1957
9. TIMROTH Journal of Physics. USSR II, No. 6, 1940
10. LAWACZECK Zeitschrift d. Verein d. Ing., 63, 1919, p.677
11. SCHILLER Forschungs arb. a.d. Geb. d. Ing. W. 5, 1934, p.71
12. TAYLOR Phil. Trans. Roy. Soc., 223, 1923. p.289
13. KELLSTROM Phil. Mag. 23, 1937, p.313
14. YEN Phil. Mag. 6S No. 38, 1919, p.582
15. GILCHRIST Phys. Rev. 1, 1913, p.125
16. MILLIKAN Phil. Mag. 34, 1917, p.1
Phil. Mag. 35, 1930, p.1231
17. MAXWELL Phil. Mag. 156, 1866, p.249
18. KESTIN & Trans. A.S.M.E., 76, 1954, p.987
PILARZYEK

19. KESTIN & PERSEN Proc. 9th Int. Congress of Applied Mechanics, Brussels, 1957
20. KESTIN & MOSZYNSKI Trans. A. S.M.E., Paper 57-A-237
21. KEENAN & KEYES Proc. 2nd Gas. Dyn. Symposium of the American Rocket Soc., Evanston, 711, U.S.A., 1957
22. HAGENBACH Pogg. Annalen 109, 1860, p.385
23. VUKALOVICH Thermodynamische Eigenschaften des Wassers und des Wasserdampfes: VEB Verlag, Berlin, 1954.
24. KENNEDY Amer. J. Sci. 248, 1950, p.540
25. Chemical Engineer's Handbook, McGraw-Hill Publishing Co. Ltd. 1950 (3rd Ed.)

APPENDIX I.

PRELIMINARY RESULTS.

Run No.	Contact No.							Thermocouples		Cj
	2	3	4	3'	2'	1'	Sum times	1	3	
38	14.825	15.850	15.600	14.675	15.425	14.525	90.900	3.078	3.065	16.5
39	15.300	16.000	14.400	15.825	15.325	14.550	91.400	3.079	3.064	16.5
40 ^x	24.900	27.800	25.225	27.675	26.050	25.725	157.375	3.080	3.072	16.8
41	15.550	16.200	14.625	16.475	15.925	15.225	94.000	3.080	3.072	16.8
42	15.925	16.725	15.000	16.850	16.625	15.575	96.700	3.102	3.102	17.0
43 ^x	26.600	28.125	27.275	28.850	26.925	26.425	164.200	3.089	3.088	17.5
44	15.900	16.800	15.150	16.525	16.375	15.375	96.125	3.086	3.086	18.0
45	16.150	17.175	15.525	16.675	16.775	15.975	98.275	3.084	3.084	18.4
46 ^x	27.175	29.025	27.250	30.100	28.000	26.825	168.375	3.078	3.079	18.6
50	43.850	47.100	42.550	48.600	45.175	43.550	270.825	4.799	4.753	18.0
51 ^x	74.625	78.825	74.300	91.200	78.250	78.650	475.850	4.782	4.778	18.5
52	44.600	46.825	41.325	47.725	46.825	44.100	271.400	4.786	4.785	20.0
53	20.775	21.850	18.850	22.925	21.850	21.050	127.300	4.783	4.783	20.9
54	20.725	21.900	18.975	21.950	21.025	19.700	124.275	4.779	4.789	21.0
55 ^x	32.875	35.450	31.850	36.650	34.225	32.550	203.600	4.772	4.789	21.6
56	26.025	27.700	24.900	28.200	27.075	25.600	159.500	4.774	4.784	22.1
57 ^x	43.125	46.700	41.425	47.475	44.775	43.100	266.600	4.774	4.803	23.0
58	26.275	28.050	24.900	27.850	27.050	25.650	159.775	4.772	4.802	23.1
59	67.075	73.300	64.300	71.700	67.750	63.000	407.125	4.771	4.801	23.6

x During these tests the drop tube was inclined to 37° from the horizontal, to find the surface tension drag correction.

Runs No.	Pressure	Temperature.	Pellet weight	Reynolds No.	η	η_r
38-40	300 at	377°C	1.3509g	830	1.2×10^{-3}	1.2×10^{-3}
41	300 at	378°C	1.3509g	830	1.227×10^{-3}	1.2×10^{-3}
42	500 at	380°C	1.3509g	750	1.27×10^{-3}	
44	500 at	380°C	1.3509g	750	1.23×10^{-3}	
45	700 at	380°C	1.3509g	600	1.24×10^{-3}	
50	300 at	538°C	1.3244	535	3.50×10^{-3}	3.52×10^{-3}
52	300 at	539.6°C	1.3244	525	3.51×10^{-3}	3.52×10^{-3}
53	Rejected. Pellet ran in two parts over contacts 4' - 1'					
54	700 at	540°C	1.3244	760	1.59×10^{-3}	
56-58	500 at	541°C	1.3244	810	2.01×10^{-3}	
59	200 at	542°C	1.3244	240	5.42×10^{-3}	5.42×10^{-3}

Method of calculating viscosities:

These preliminary observations were taken before any calibrations were carried out. The capillary constant is therefore not known. For the purpose of comparing these observations with the values given in Vukalovich's Steam Tables the following formula was used:

$$\eta = B W \sum t \left(1 - \frac{a}{W}\right) (1 + 3\Delta t^\circ) \left(\frac{1}{\rho_w} - \frac{1}{\rho_m}\right) - H$$

where B is a proportionality constant, and Δ is the coefficient of thermal expansion for the capillary material, in this case 18% Cr 8% Ni type stainless steel. A value was assumed for the constant B which when used with the above observations yielded the viscosity results listed in the above table.

The drop tube used was measured in the following way:

A mercury pellet of weight 2.3206 grams was inserted into the drop tube, and was moved inside the drop tube so that it covered the four timed lengths in turn, and its lengths were measured with a vernier travelling microscope which could be read to 0.1 mm. The individual timed lengths were also measured. The results were as follows:

Contact No.	Pellet length	Timed length
1	5.28 cm.	4.59 cm.
2	5.16 cm.	4.34 cm.
3	5.04 cm.	4.26 cm.
4	5.40 cm.	4.38 cm.
4'	5.40 cm.	4.35 cm.
3'	5.04 cm.	4.20 cm.
2'	5.16 cm.	4.39 cm.
1'	5.28 cm.	4.60 cm.

The volume of the pellet was 0.1713 cm^3

The volume of the menisci was 0.0016 cm^3

Volume of cylindrical part of the pellet = 0.1697 cm^3

For the timed length number 2 the cross-sectional area was then assumed to be

$$\frac{\pi}{4} D^2 = \frac{0.1697}{5.15} = 0.03827 \text{ cm}^2$$

Hence

$$\frac{1}{\left(\frac{\pi}{4} D^2\right)^2} = 926 \quad \text{and} \quad G_2 = \frac{926}{4.34} = 214$$

Similarly $G_3 = 208$, $G_4 = 232$, $G_{4'} = 233$, $G_{3'} = 210$,
 $G_{2'} = 212$ and $G_{1'} = 211$.

Since the drop tube cross-section varied considerably, and since the averages of the cross-sectional areas are used instead of the averages of the inverse of the squares of the cross-sectional areas are used these values may be inaccurate. The values found for the factor G are therefore only used to check whether there is a detectable trend in the variations in the observed flow rates. If the values found for the factors G are multiplied by the corresponding recorded fall times, it will be found that no steady trend can be discerned, and hence that there is no systematic error in the flow rates, nor any systematic error due to systematic variations in the flow rates in the viscosities found.

Second Series of Results.

Stainless capillary.

From the calibration tests listed in Appendix II it was found that the factors K for the capillary and drop tube used in this series were:

$$K_1 = 293.13 \times 10^{-10}, \quad K_2 = 300.83 \times 10^{-10}, \quad K_{2'} = 310.56 \times 10^{-10}$$

$$K_{1'} = 281.1 \times 10^{-10}.$$

The results are worked out as shown on page 74.

Run No	Contact No.				Sum times
	1	2	2'	1'	
43	20.700	19.825	19.300	20.450	80.280
44 ^x	25.925	24.500	24.925	26.625	101.976
45	20.725	19.825	19.300	20.550	80.360
46	50.000	48.850	47.650	50.350	196.840
47	51.425	48.650	47.500	50.400	197.976
48	50.875	48.300	46.000	49.275	194.440
49 ^x	64.500	60.825	61.600	64.800	251.524
50	51.900	48.775	47.625	49.675	197.976
51	51.400	49.025	47.050	49.200	196.680
Runs 53 - 59 recorded on p.73					
61	19.700	18.775	18.425	19.350	76.252
62	19.350	18.825	18.225	19.450	75.852
63	19.450	18.750	18.175	19.275	75.652
64 ^x	24.725	23.400	23.175	25.250	96.560
65	19.400	18.700	18.225	19.200	75.524
66 ^x	24.600	23.400	23.275	25.200	96.480
67	19.375	18.700	18.400	19.200	75.608
68	19.200	18.250	18.075	18.900	74.424
69	19.050	18.150	17.900	18.900	74.000
70 ^x	24.025	22.575	22.975	24.400	93.976
71	19.025	18.225	18.100	18.900	74.252
72	29.125	27.750	25.925	27.575	110.376
73	28.900	28.100	26.350	27.425	110.776
74	29.050	27.425	26.200	27.600	110.276
75	29.150	27.500	26.175	27.575	110.352
76	28.850	27.625	26.250	-	-
77	28.875	27.750	26.000	27.800	110.424
78	28.875	27.500	26.075	27.600	110.052

Pressure 400 at. Cold junction
15.5°C. Thermocouples:
1: 3.587, 2: 3.580, 3: 3.575,
4: 3.568, 5: 3.508.

Pressure 200 at. Cold junction
18°C. Thermocouples: 1: 3.589,
2: 3.599, 3: 3.576, 4: 3.565,
5: 3.503.

Run No. 48 rejected because of
pressure balance fluctuations

Pressure 1000 at. Cold junction
17.5°C.
Thermocouples: 1: 3.614,
2: 3.624, 3: 3.630, 4: 3.642,
5: 3.624.

Pressure 600 at. Cold junction
18°C. Thermocouples: 1: 3.624,
2: 3.641, 3: 3.645, 4: 3.651,
5: 3.597

Pressure at 300 at. Cold junction
19°C. Thermocouples: 1: 3.591,
2: 3.570, 3: 3.580, 4: 3.500
5: 3.542.

^xDrop tube inclined to 52° from
horizontal.

For runs 43 - 78 pellet weight = 2.5947 grams.

Results:

Runs No.	Temperature	Pressure	Kinematic Viscosity	Reynolds No.
43-45	427°C	400 at	$\nu = 1.352 \times 10^{-3}$	810
46-51	428.5°C	200 at	$\nu = 3.346 \times 10^{-3}$	720
53-59	430.5°C	600 at	$\nu = 1.22 \times 10^{-3}$	830
61-67	430.5°C	1000 at	$\nu = 1.237 \times 10^{-3}$	650
68-71	432°C	600 at	$\nu = 1.225 \times 10^{-3}$	830
72-78	428°C	300 at	$\nu = 1.827 \times 10^{-3}$	1200

After these runs were recorded a short occurred in the furnace series resistance, so that the temperature of the furnace increased to approximately 780°C. In the subsequent 63 runs it was observed that the viscosity values found increased steadily, and on the recalibrating the capillary it was found that the capillary constant had increased. These runs are therefore rejected.

Third Series of Results.

This series was obtained with the apparatus in its final form, with the platinum capillary mounted on a Nimonic 75 connecting tube. After the tests were taken it was found that the gold-soldered joint between the capillary and the Stellite end piece was tight only at room temperature.

Since, however, it appears that the values derived for the kinematic viscosity from these tests are between 10% and 20% lower than the true values, it is thought that the variation of viscosity with

pressure which they show is reasonably correct. They are included because of the lack of other data at these steam conditions.

Run No.	Contact No.					
	2	3	4	3'	2'	1'
1	30.575	23.600	30.300	23.900	29.600	23.150
2	29.750	23.500	30.125	23.550	29.600	23.050
3	29.800	24.200	29.900	24.100	29.500	22.900
4	29.925	23.850	29.650	24.225	29.750	23.050
5	29.425	23.550	29.800	24.100	29.225	22.950
6 ^x	48.875	41.000	51.700	42.625	48.100	37.525
7	29.400	23.200	29.600	24.625	29.275	23.050
8 ^x	49.775	39.875	52.000	-	47.500	37.600
9	29.600	23.350	29.775	24.075	29.500	23.450
10	32.800	25.875	33.200	26.850	33.150	25.575
11	32.950	26.200	33.275	27.975	33.225	26.200
12	33.050	26.100	33.600	26.675	33.150	26.100
13	32.975	25.675	33.575	27.150	33.200	26.200
14 ^x	54.150	45.000	61.700	-	55.000	44.575
15	31.725	25.800	33.375	26.050	33.250	26.150
16	33.500	26.100	33.425	26.025	33.400	26.150
17	43.725	33.450	-	35.650	43.750	34.275
18	43.025	33.825	43.825	35.500	43.050	33.900
19 ^x	70.100	54.500	-	-	-	-
20 ^x	70.800	57.400	78.100	58.150	69.950	55.700
21	42.300	33.175	43.050	34.175	42.875	33.725
22	42.325	33.500	42.650	34.200	42.650	33.250
23	42.850	33.925	43.425	34.475	43.075	34.200
24	42.800	33.825	43.300	34.425	43.000	34.050

Pressure 1000 at.
Cold junction 15°C.

Thermocouples:
1: 4.903, 2: 4.886
3: 4.906, 4: 4.960
5: 4.920.

Run No. 1 rejected,
because of
fluctuations in
pressure.
Temperature 547°C.

Pressure 700 at.
Cold junction 15.5°C.

Thermocouples:
1: 4.898, 2: 4.886
3: 4.898, 4: 4.898
5: 4.811.

Run No. 10 rejected,
because of pressure
fluctuations.
Temperature 547°C.

Pressure 500 at.
Cold junction 18.6°C.

Thermocouples:
1: 4.851, 2: 4.843,
3: 4.873, 4: 4.911
5: 4.875.

Temperature 546°C.

Run No.	Contact No.					
25	52.000	41.575	55.250	42.550	53.200	41.925
26	52.650	41.275	54.000	42.075	53.400	41.950
27 ^x	85.950	73.900	96.600	71.025	88.100	68.275
28	52.350	40.600	53.075	-	54.850	43.275
29	54.525	-	53.300	43.275	54.400	-
30	54.650	42.525	55.000	43.650	54.500	43.300
31	54.125	42.525	54.675	43.325	54.300	43.200
32 ^x	88.025	71.625	92.525	73.000	88.200	70.075
33	54.275	42.550	55.000	43.400	54.850	43.150
34	72.400	55.000	71.300	55.425	71.000	55.400
35 ^x	120.650	90.000	125.000	93.950	113.300	89.600
36	69.500	54.725	70.900	56.500	70.450	55.050
37	69.225	54.850	69.400	55.125	71.600	56.625

Pressure 400 at.
Cold junction 18°C.

Thermocouples:

1: 4.850, 2: 4.842,
3: 4.854, 4: 4.883,
5: 4.814.

Temperature 545°C.

Pressure 300 at.
Cold junction 19°C.

Thermocouples:

1: 4.847, 2: 4.837,
3: 4.846, 4: 4.840,
5: 4.709.

Temperature 544°C.

^x Drop tube inclined to 37° from the horizontal.
Pellet weight for runs 1 - 37 = 1.2958 grams.

38	34.875	27.550	35.825	27.850	34.950	27.250
39	35.325	27.150	35.725	-	35.150	27.425
40 ^x	58.900	44.925	59.300	47.500	59.975	45.500
41	34.925	27.450	35.200	27.825	35.000	27.225
42	35.075	27.350	35.550	27.500	35.000	27.450
43	35.075	27.450	35.400	27.525	35.100	27.450

Pressure 700 at.
Cold junction 20°C.

Thermocouples:

1: 6.427, 2: 6.415,
3: 6.434, 4: 6.469,
5: 6.457.

Temperature 684°C.

Run No.	Contact No.						
44	27.425	21.200	27.600	22.200	27.950	21.400	Pressure 1000 at. Cold junction 19.5°C. Thermocouples: 1: 6.402, 2: 6.383, 3: 6.390, 4: 6.419, 5: 6.395. Temperature <u>680°C.</u>
45	27.925	21.200	27.425	21.450	27.925	21.675	
46	27.350	21.200	27.475	22.100	27.900	21.850	
47	27.350	21.200	27.450	21.450	27.875	21.875	
48 ^x	46.200	34.850	46.400	37.150	45.850	36.450	
49	27.450	21.225	27.350	22.175	27.650	21.825	
50	27.450	21.225	27.400	21.900	27.450	21.800	
51	39.575	30.500	39.175	30.900	39.750	31.150	
52	39.375	30.150	39.500	31.275	39.725	31.200	
53	39.475	30.225	39.550	30.975	39.600	30.925	
54 ^x	65.725	50.750	67.750	-	65.700	51.750	Pressure 600 at. Cold junction 20.5°C. Thermocouples: 1: 6.408, 2: 6.389, 3: 6.399, 4: 6.413, 5: 6.373 Temperature <u>681°C.</u>
55	39.700	30.725	39.725	31.075	40.050	31.300	
57	46.200	35.475	46.475	36.625	46.550	36.550	
58	46.175	35.850	46.100	36.750	46.450	36.450	
59	46.175	36.000	46.125	36.400	46.800	36.375	
61	45.800	35.825	46.200	36.775	47.050	36.350	
62 ^x	77.100	59.475	78.275	63.050	80.200	62.150	
63	-	35.725	46.500	36.325	46.950	36.475	
64	56.850	43.800	56.950	44.750	57.450	44.800	
65	56.350	44.000	57.450	45.150	57.975	45.125	
66	56.950	44.225	57.625	45.000	59.000	44.525	

^x Drop tube inclined to 37° from horizontal.

Pellet weight runs 44 - 66 = 1.8543 grams.

The values of the factors K for the platinum capillary and the drop tube used in the runs No. 1 - 66 of this series were:

$$K_1 = 0.457 \times 10^{-7}, \quad K_2 = 0.386 \times 10^{-7}, \quad K_3 = 0.488 \times 10^{-7},$$

$$K_4 = 0.380 \times 10^{-7}, \quad K_{4'} = 0.399 \times 10^{-7}, \quad K_{3'} = 0.4853 \times 10^{-7},$$

$$K_{2'} = 0.3858 \times 10^{-7}, \quad K_{1'} = 0.4854 \times 10^{-7}$$

The observations on which these calibration values are based are recorded in Appendix II.

Results:

Run	Pressure (at)	Temperature °C.	Kinematic Viscosity
1 - 9	1000	547	1.236×10^{-3}
10 - 16	700	547	1.382×10^{-3}
17 - 24	500	546	1.793×10^{-3}
25 - 33	400	545	2.327×10^{-3}
34 - 37	300	544	3.131×10^{-3}
38 - 43	700	684	2.11×10^{-3}
44 - 50	1000	680	1.73×10^{-3}
51 - 55	600	681	2.52×10^{-3}
57 - 63	500	679	2.916×10^{-3}
64 - 66	400	679	3.572×10^{-3}

The value listed in the Vukalovich Steam Tables at 300 at. 544°C. is $\nu = 3.59 \times 10^{-3}$. This is 14.7% higher than the value derived from runs No. 34 - 37. Hence, if the Vukalovich values are assumed correct, the viscosities at the higher pressures should be obtained by multiplying the above values by 1.147. The values for viscosity then become:-

Pressure (at)	Temperature (°C)	Kinematic Viscosity
1000	547	1.418×10^{-3}
700	547	1.588×10^{-3}
500	546	2.057×10^{-3}
400	545	2.670×10^{-3}
300	544	3.591×10^{-3}
1000	680	1.98×10^{-3}
700	684	2.42×10^{-3}
600	681	2.89×10^{-3}
500	679	3.42×10^{-3}
400	679	4.10×10^{-3}

As will be seen from the graph of viscosity against temperature, figure 13, these values fit in well with the other results, but since the calibration value is derived from the Vukalovich Steam Tables they should be regarded as showing the variation of kinematic viscosity with pressure rather than absolute values. It is believed that, since the leakage is only approximately 15% the error in this correction due to turbulence in the passage through which the leakage flow is passing is small. This assumption is supported by the close correspondence between the corrected values from runs 1 - 37 and the preliminary results obtained at nearly the same temperature.

APPENDIX II.

CALIBRATION RESULTS.

The factors K for the apparatus can be found by two methods:

1. Calibration of the capillaries to find the capillary constant C and measurement of the drop tube dimensions to find the value of the constant

$$G = \frac{1}{\left(\frac{L}{4} D^2\right)^2 L}$$

for each timed length. The factor $K = CG$ is then calculated. This method has been found to yield results which are less accurate than method 2.

2. In this method the capillary is mounted on the end of the drop tube and both are calibrated together in the calibration apparatus.

By this method the factor K is found directly for each timed fall, but since the flow rates are greater with the air used for calibration than when the drop tube and capillary are used for steam the times recorded may be inconveniently short. The capillary and drop tube used in the series 2 observations were calibrated by method 2, but a modification of this method was found necessary for the drop tube used in the series 3 observations, because the timed lengths were shorter. In this series the drop tube was calibrated with a special narrow-bore stainless capillary, and the ratio of the capillary constants for this capillary and for the platinum capillary used in the steam runs was found by a separate calibration.

The values of the factor K found for the drop tube in

conjunction with the narrow bore capillary was then multiplied by the ratio $\frac{C_p}{C_s}$ to the narrow bore stainless one.

Since the flow rate is required for the evaluation of the Hagenbach correction and the cross-sectional area is required for the correction for the compressibility of air when the apparatus is calibrated, the drop-tube dimensions still need to be measured, but the necessary accuracy for these purposes is less than that required with method 1 since these corrections are both small.

CALIBRATIONS FOR SERIES 2.

Test No.	Temp. °C	Contact No.				No. of Pellets
		1	2	2'	1'	
1	21	5.225	5.050	5.000	5.450	1
2	21	5.250	5.050	5.050	5.500	1
3	21	5.250	5.050	5.050	5.525	1
4	21	5.250	5.050	5.050	5.525	1
5	21	6.100	5.875	5.850	6.300	2
6	21	6.100	5.800	5.850	6.275	2
7	21	6.100	5.850	5.825	6.350	2
8	21	6.100	5.800	5.825	6.300	2
9	21	6.100	5.775	5.825	6.275	2
10	21.2	5.275	5.050	5.100	5.600	1
11	21.2	5.250	-	-	-	1
12	21.2	5.275	5.050	5.050	5.525	1
13	21.2	5.275	5.050	5.050	5.525	1
14	21.7	6.300	5.800	5.850	6.350	2
15	21.7	6.275	5.825	5.850	6.400	2
16	21.7	6.200	-	5.850	-	2
17	21.7	6.250	5.800	5.800	6.375	2
18	21.7	5.250	5.050	5.050	5.550	1
19	21.7	5.275	5.050	5.050	5.525	1

Pellet weight
1.3360 grams

Average times:

	1 pellet	2 pellets	$\frac{a}{W}$
1	5.260	6.178	0.1295
2	5.050	5.810	0.116
2'	5.050	5.830	0.1185
1'	5.525	6.337	0.1137

$$\eta = 1820 \times 10^{-7} \text{ for air at } 21^{\circ}\text{C.}$$

When the times for contacts 1 and 2 are recorded, the pellet is moving away from the capillary, and the specific volume of the air between the drop tube and capillary is greater by the factor $(1 + \frac{\Delta p}{p})$ than the specific volume of the atmospheric air. Conversely, when the times 2' and 1' are recorded, the specific volume of the air in the drop tube is decreased, as it is comprised by the differential pressure exerted by the pellet.

For contacts 1 and 2 therefore

$$\eta = Kt \left(1 - \frac{a}{W}\right) Wg \left(1 + \frac{\Delta p}{2p}\right)$$

and for contacts 2' and 1'

$$\eta = Kt \left(1 - \frac{a}{W}\right) Wg \left(1 - \frac{\Delta p}{2p}\right)$$

The length of the mercury pellet was 2.4 cm., so that

$$\Delta p = 2.4 \times 13.6 \left(1 - \frac{a}{W}\right) \text{ grams/cm}^2$$

$$p = 1000 \text{ grams/cm}^2$$

The K values were calculated and found to be

$$K_1 = 293.13 \times 10^{-7}, \quad K_2 = 300.83 \times 10^{-7}, \quad K_{2'} = 310.56 \times 10^{-7}, \\ K_{1'} = 281.1 \times 10^{-7}.$$

Series 3

Calibration of the drop tube in conjunction with the narrow-bore stainless capillary:

Test No.	Temp. °C	Contact No.						No. of Pellets	
		2	3	4	3'	2'	1'		
1	22.9	11.175	8.800	11.300	9.300	11.900	9.500	1	Pellet weight 1.9551 grams.
2	23	12.100	9.650	12.200	10.025	12.800	10.350	2	
3	23.1	11.025	8.825	11.225	9.200	-	9.325	1	
4	23.2	11.050	8.825	11.275	9.225	11.700	9.325	1	
5	23.4	12.050	9.750	12.250	10.150	12.800	-	2	
6	23.5	11.125	8.875	11.350	9.400	11.800	9.450	1	
7	23.5	11.100	8.850	11.350	9.350	11.775	9.400	1	
8	23.6	11.100	8.850	11.300	9.350	11.750	9.425	1	
9	23.6	12.200	9.800	12.550	-	12.875	10.500	2	
10	23.6	11.175	8.950	11.350	9.425	11.775	9.500	1	
11	26.3	9.850	7.775	10.000	8.750	10.725	8.550	1	Pellet weight 2.1578 grams.
12	26.3	9.850	7.900	10.050	8.725	10.725	8.475	1	
13	26.4	9.850	7.800	10.025	8.525	10.600	8.400	1	
14	26.4	9.850	7.775	10.050	8.500	10.550	8.350	1	
15	26.5	9.850	7.800	10.050	8.600	10.625	8.400	1	
16	26.5	9.825	7.800	10.250	8.525	10.575	8.325	1	
17	26.5	10.750	9.050	11.350	9.350	-	-	2	
18	26.5	10.775	9.150	-	9.500	-	9.100	2	
19	26.5	10.900	9.125	11.225	9.400	11.475	9.175	2	

CALIBRATION OF CAPILLARIES

Using a special drop tube of approximately 3.25 mm. bore diameter, giving one timing in either direction.

Test No.	Temp. °C	Times Towards Capillary t_1	Times Away from Capillary t_2	No. of Pellets	
1	25.3	22.375	20.750	1	Platinum Capillary
2	25.3	22.075	-	1	" "
3	25.3	22.325	20.275	1	" "
4	25.3	22.100	20.250	1	" "
5	25.3	22.050	20.250	1	" "
6	25.4	22.975	21.150	2	" "
7	25.4	22.900	21.150	2	" "
8	25.4	22.075	20.250	1	" "
9	25.4	-	20.200	1	" "
10	26	95.050	83.750	1	Narrow bore Stainless
11	23.1	92.625	84.700	1	" " " Capillary
12	23.5	-	88.600	2	" " " "
13	23.7	95.950	88.350	2	" " " "
14	24.7	94.000	85.600	1	" " " "
15	24.7	93.275	85.600	1	" " " "
16	24.8	97.275	89.450	2	" " " "
17	24.8	96.900	89.575	2	" " " "
18	25.3	93.500	85.800	1	" " " "
19	25.4	93.550	85.800	1	" " " "

Pellet weight 7.5493 grams.

For the platinum capillary:

At 25.4°C. viscosity of air = 1840×10^{-7}

Hence

$$1840 \times 10^{-7} = G C W g t \left(1 - \frac{a}{W}\right) (1 + 3) \left(1 - \frac{\Delta p}{2p}\right)$$

where the slip correction

$$s = \frac{0.33 \times 10^{-4}}{r}$$

and $r =$ capillary radius $\doteq 0.012$ cm.

For this calibration drop tube

$$G_1 = 4.649$$

$$G_2 = 4.657$$

Using the averages of t_1 and t_2 it was calculated that for the platinum capillary

$$C = \frac{2.657 \times 10^{-10}}{}$$

For the narrow bore stainless capillary

$$r = 0.0075 \text{ cm.}$$

and

$$C = 0.6207 \times 10^{-10}$$

so that the ratio

$$\frac{C_p}{C_s} = 4.28$$

Using the same procedure on the results of the calibration tests with the narrow bore stainless capillary and the drop tube used for steam, the following values of K were calculated:

$$K_2 = 0.386 \times 10^{-7}, \quad K_3 = 0.488 \times 10^{-7}, \quad K_4 = 0.3196 \times 10^{-7},$$

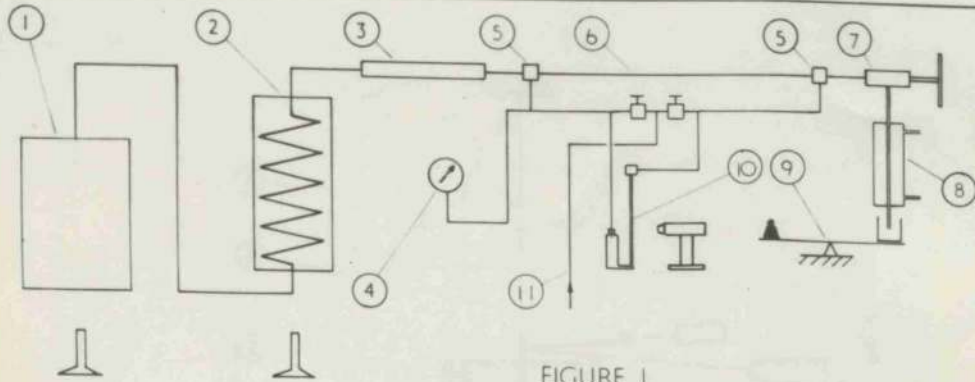
$$K_{3,1} = 0.4853 \times 10^{-7}, \quad K_{2,1} = 0.3858 \times 10^{-7}, \quad K_{1,1} = 0.4894 \times 10^{-7}$$

Tests on Leakage of Water between the Mercury Pellet
and the Drop Tube Wall.

The procedure used is described on page 46.

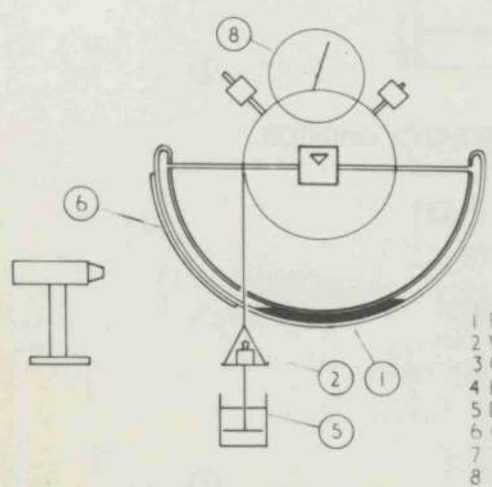
Test No.	Tube dia. mm.	Length of fall cm.	Distance between pellets		Difference mm.	Corr- ection mm.	% Leak- age	Flow rate cc/sec.
			Start mm.	Finish mm.				
1	2.14	110	15.8	15.8	0	0	0	4×10^{-3}
2	2.14	110	19.0	18.5	0.5	0	0.045	4×10^{-3}
3	2.14	110	13.3	10.6	2.7	0	0.25	30×10^{-3}
4	2.14	110	10.3	10.3	0	0	0	7.2×10^{-3}
5	2.14	110	17.1	17.1	0	0	0	22×10^{-3}
6	2.14	110	7.4	7.3	0.1	0	0.009	17.4×10^{-3}
7	2.14	110	9.4	9.3	0.1	0	0.009	11.6×10^{-3}
8	2.14	110	8.4	8.4	0	0	0	19×10^{-3}
9	2.14	110	15.0	13.9	1.1	0	0.1	24.7×10^{-3}
10	2.14	110	6.4	5.6	0.8	0	0.072	25.8×10^{-3}
11	2.14	110	7.2	5.7	1.5	0	0.135	23.6×10^{-3}
12	1.56	100	7.6	5.6	2	+0.22	0.22	19.5×10^{-3}
13	1.56	100	5.8	5.3	0.5	+0.17	0.067	9.3×10^{-3}
14	1.56	100	10.9	10.8	0.1	0.33	0.043	3.35×10^{-3}
15	1.56	100	3.9	3.8	0.1	0.1	0.02	4.0×10^{-3}
16	1.56	100	2.0	0.585	1.415	0.06	0.148	18.3×10^{-3}
17	1.56	100	2.43	2.0	0.43	0.07	0.05	9.3×10^{-3}
18	1.56	100	4.73	2.34	1.39	0.13	0.152	10.5×10^{-3}
								Cont'd

Test No.	Tube dia. mm.	Length of fall cm.	Distance between pellets		Difference mm.	Corr- ection mm.	% Leak-	Flow rate cc/sec.
			Start mm.	Finish mm.				
19	2.34	80	2.45	0.1	2.35	0	0.29	41×10^{-3}
20	2.34	80	3.26	3.16	0.1	0.04	0.017	20×10^{-3}
21	2.34	80	2.97	1.65	1.32	0.037	0.17	18.8×10^{-3}
22	2.34	80	3.7	2.92	0.78	0.04	0.103	19.5×10^{-3}
23	2.34	80	5.12	4.8	0.32	0.06	0.0475	8.7×10^{-3}
24	2.34	80	2.14	1.92	0.22	0.02	0.027	12.2×10^{-3}
25	2.34	80	3.51	3.12	0.39	0.04	0.054	15.8×10^{-3}
26	2.34	80	5.60	5.10	0.50	0.06	0.070	15×10^{-3}
27	2.34	80	2.73	2.58	0.15	0.03	0.023	14.6×10^{-3}
28	2.34	80	3.90	3.40	0.50	0.05	0.07	19×10^{-3}
29	2.34	80	3.07	2.20	0.87	0.038	0.114	24×10^{-3}
30	2.34	80	2.92	2.87	0.05	0.036	0.01	13.2×10^{-3}



- 1 BOILER
- 2 PRIMARY SUPERHEATER
- 3 SECONDARY SUPERHEATER
- 4 PRESSURE GAUGE
- 5 PRESSURE TAPPINGS
- 6 CAPILLARY
- 7 THROTTLE VALVE
- 8 CONDENSER
- 9 BALANCE
- 10 ALCOHOL IN GLASS MANOMETER
- 11 COMPRESSED AIR SUPPLY

FIGURE 1
CAPILLARY VISCOMETER
AS USED BY SPEYERER



- 1 RING BALANCE
- 2 WEIGHTS
- 3 CAPILLARY
- 4 KNIFE EDGE SUSPENSIONS
- 5 DASHPOT
- 6 GRADUATED SCALE
- 7 THERMOCOUPLES
- 8 PRESSURE GAUGE

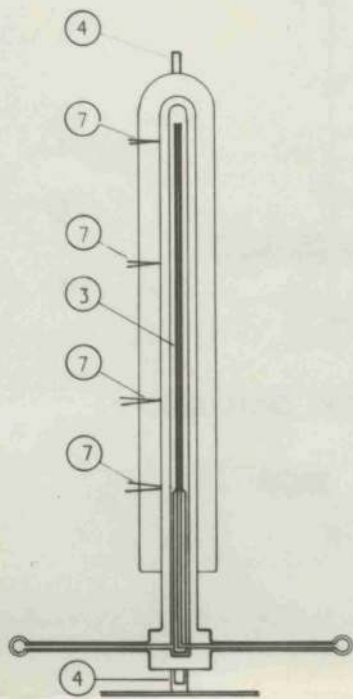
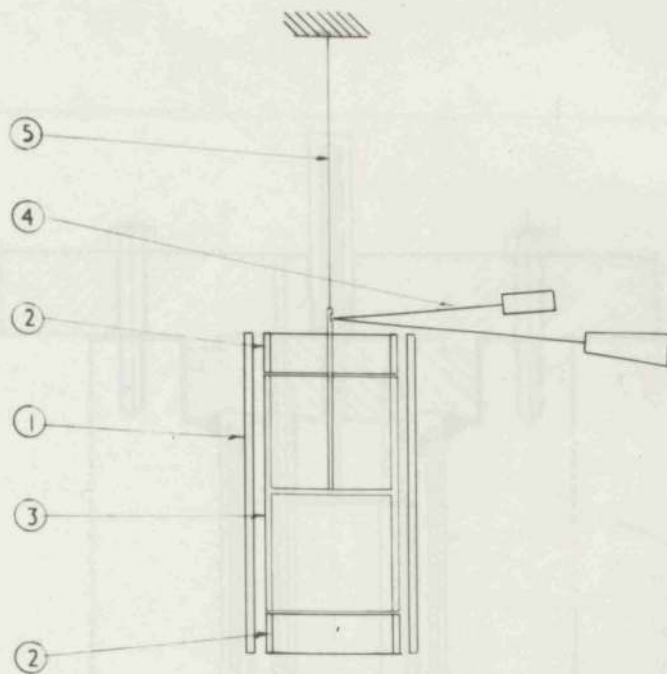


FIGURE 2
TIMROTH'S VISCOMETER



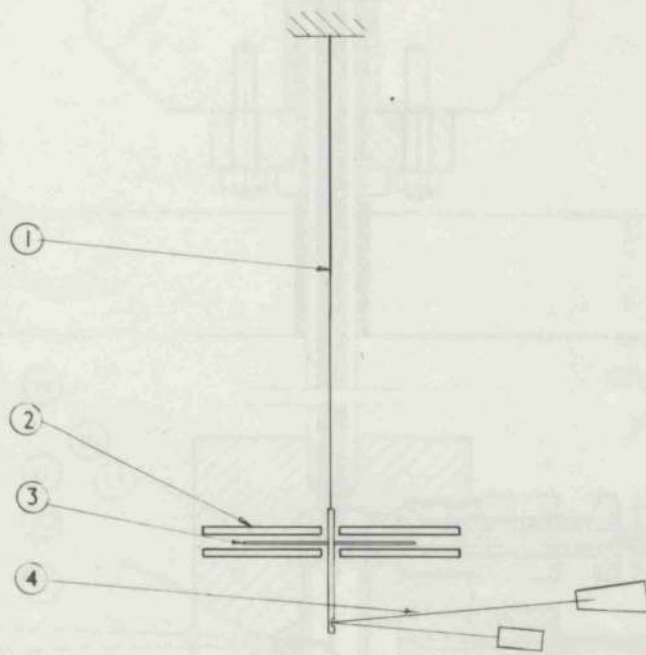
FIGURE 3
RANKINE VISCOMETER



- 1. ROTATING CYLINDER.
- 2. GUARD CYLINDER.
- 3. SUSPENDED CYLINDER.
- 4. DEFLECTION MEASUREMENT SYSTEM.
- 5. SUSPENSION WIRE.

ROTATING CYLINDER VISCOMETER.

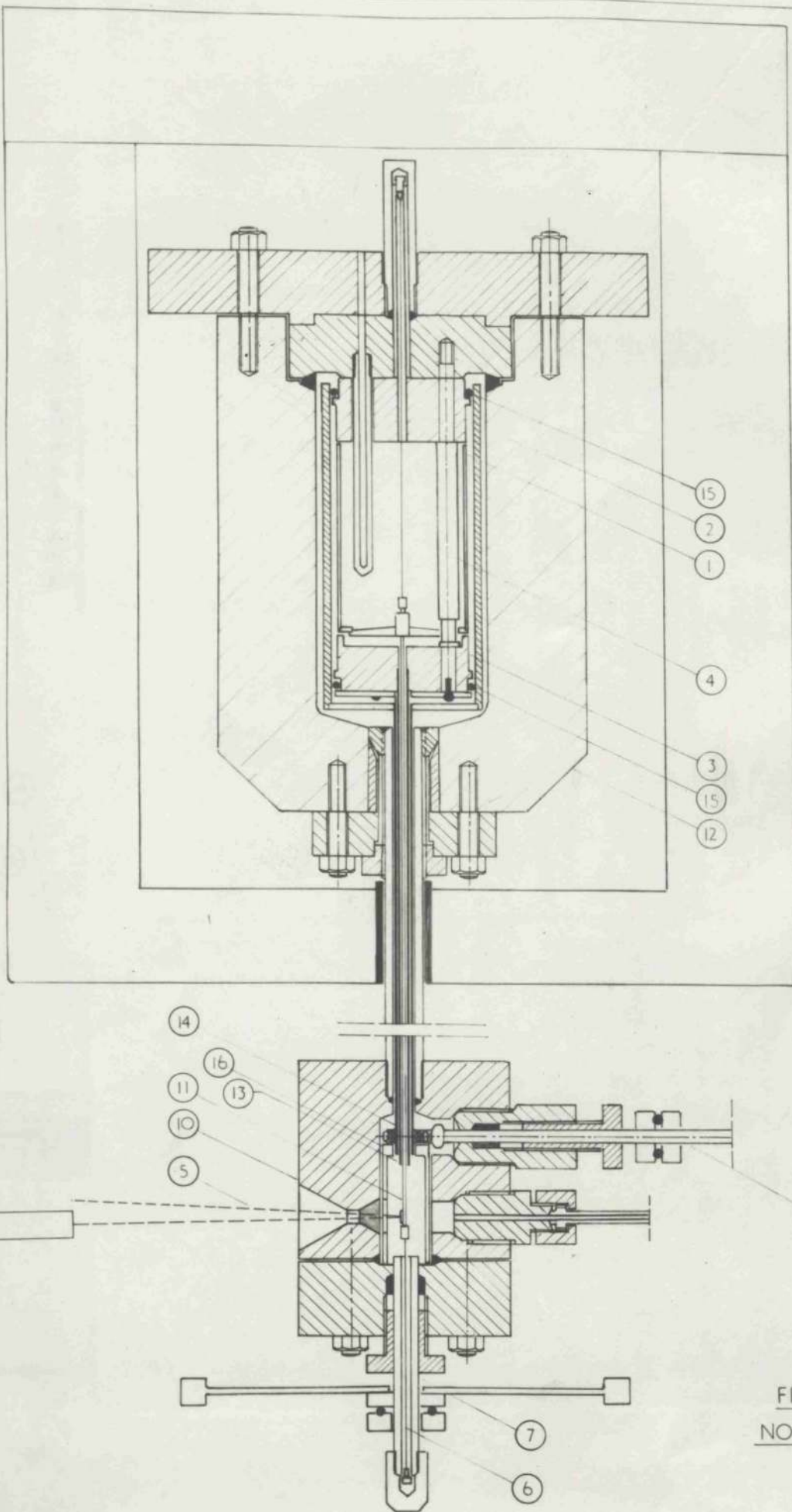
FIGURE 4.



- 1. SUSPENSION WIRE.
- 2. GUARD DISC.
- 3. OSCILLATING DISC.
- 4. DEFLECTION MEASUREMENT SYSTEM.

OSCILLATING DISC VISCOMETER.

FIGURE 5.



- 1 SUSPENDED CYLINDER
- 2 GUARD CYLINDER
- 3 ROTATING CYLINDER
- 4 SUSPENSION WIRE
- 5 DEFLECTION MEASURING SYSTEM
- 6 TORSION WIRE
- 7 SHAFT FOR ROTATING LOWER END OF TORSION WIRE
- 8 DRIVE FOR ROTATING CYLINDER
- 9 CONNECTING SHAFT
- 10 COLD PRESSURE VESSEL
- 11 CONNECTING TUBE
- 12 HOT PRESSURE VESSEL
- 13 GUARD TUBE
- 14 DRIVE TUBE
- 15 BALL OR ROLLER BEARING
- 16 NYLON THRUST BEARING

FIGURE 6
NOT TO SCALE

ROTATING CYLINDER VISCOMETER FOR STEAM. PRELIM. DESIGN.

B 7
DRAWN BY
TRACED BY

CAPILLARY VISCOMETER

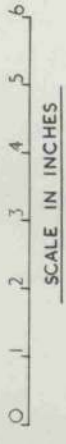
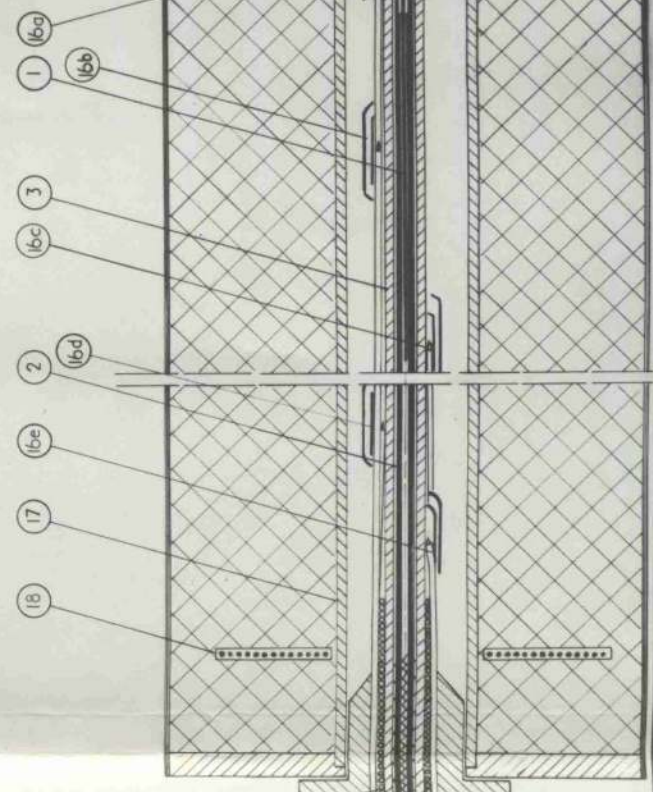
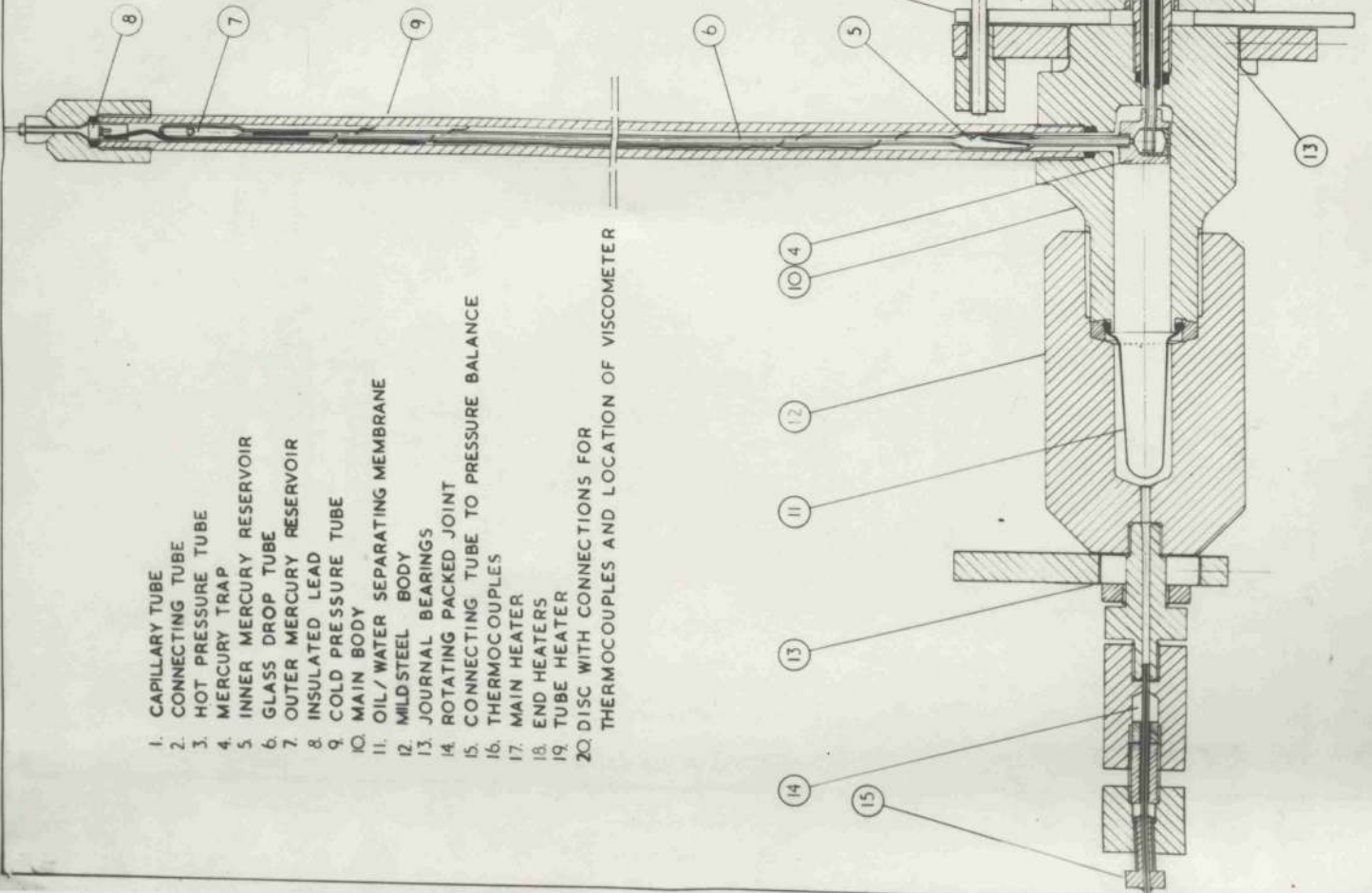
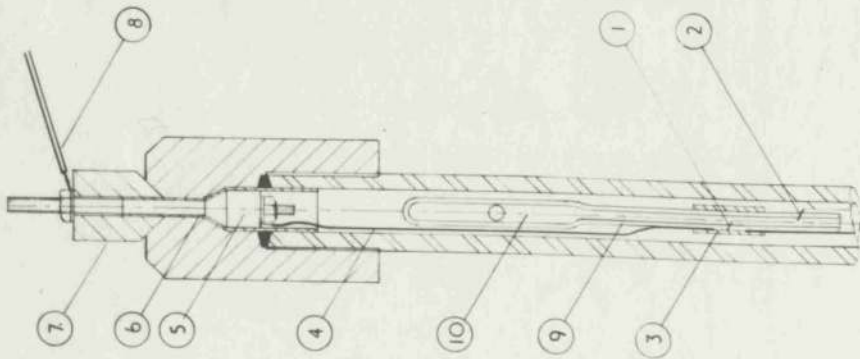


FIGURE 7

- 1. CAPILLARY TUBE
- 2. CONNECTING TUBE
- 3. HOT PRESSURE TUBE
- 4. MERCURY TRAP
- 5. INNER MERCURY RESERVOIR
- 6. GLASS DROP TUBE
- 7. OUTER MERCURY RESERVOIR
- 8. INSULATED LEAD
- 9. COLD PRESSURE TUBE
- 10. MAIN BODY
- 11. OIL/WATER SEPARATING MEMBRANE
- 12. MILD STEEL BODY
- 13. JOURNAL BEARINGS
- 14. ROTATING PACKED JOINT
- 15. CONNECTING TUBE TO PRESSURE BALANCE
- 16. THERMOCOUPLES
- 17. MAIN HEATER
- 18. END HEATERS
- 19. TUBE HEATER
- 20. DISC WITH CONNECTIONS FOR THERMOCOUPLES AND LOCATION OF VISCOMETER





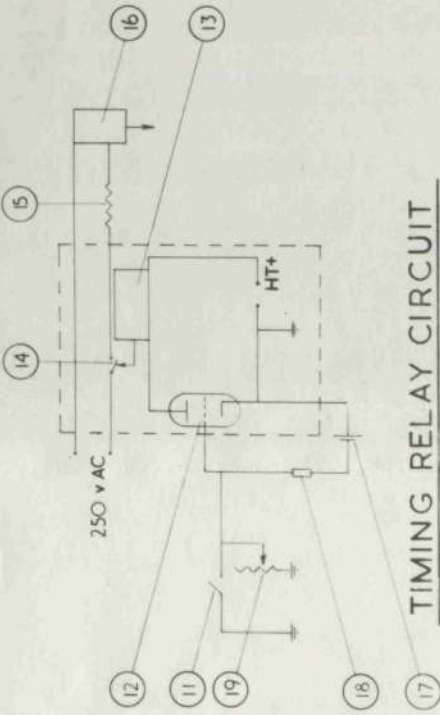
DETAIL OF DROP TUBE

- 1 INSULATED CONTACT WIRE
- 2 EARTHED CONTACT WIRE
- 3 RUBBER INSULATING SLEEVE
- 4 INSULATED LEAD
- 5 BRASS TERMINAL
- 6 PERSPEX INSULATING SLEEVE
- 7 PERSPEX SPACER
- 8 LEAD TO TIMING RELAY
- 9 GLASS DROP TUBE
- 10 OUTER GLASS MERCURY RESERVOIR

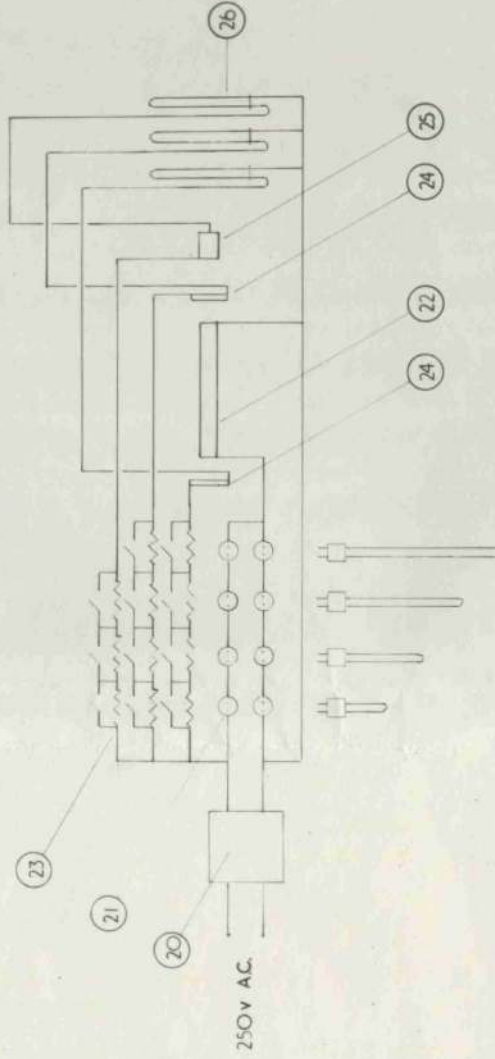
FIGURE 8

- 11 DROP TUBE CONTACT
- 12 TRIODE VALVE
- 13 SWITCH SOLENOID
- 14 MAINS SWITCH
- 15 SERIES RESISTANCE
- 16 STOPWATCH SOLENOID
- 17 BIAS BATTERY 6VOLT
- 18 SERIES RESISTANCE 4000 OHMS
- 19 ADJUSTABLE RESISTANCE

FIGURE 9



TIMING RELAY CIRCUIT

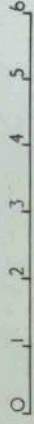


FURNACE HEATER CIRCUIT

- 20 CONSTANT VOLTAGE TRANSFORMER
- 21 PLUG IN RESISTANCES
- 22 MAIN HEATER
- 23 SERIES RESISTANCES
- 24 END HEATERS
- 25 TUBE HEATER
- 26 SLIDE WIRE RESISTANCES

FIGURE 10

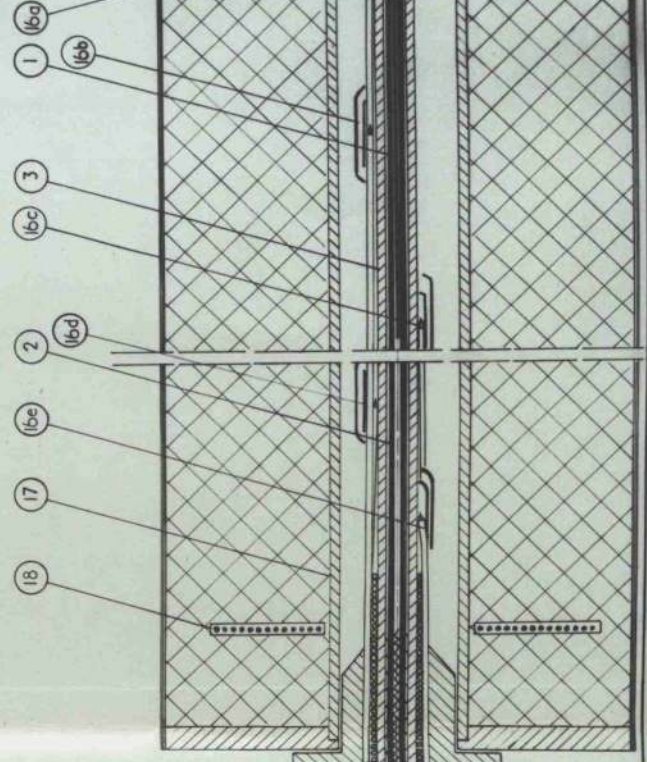
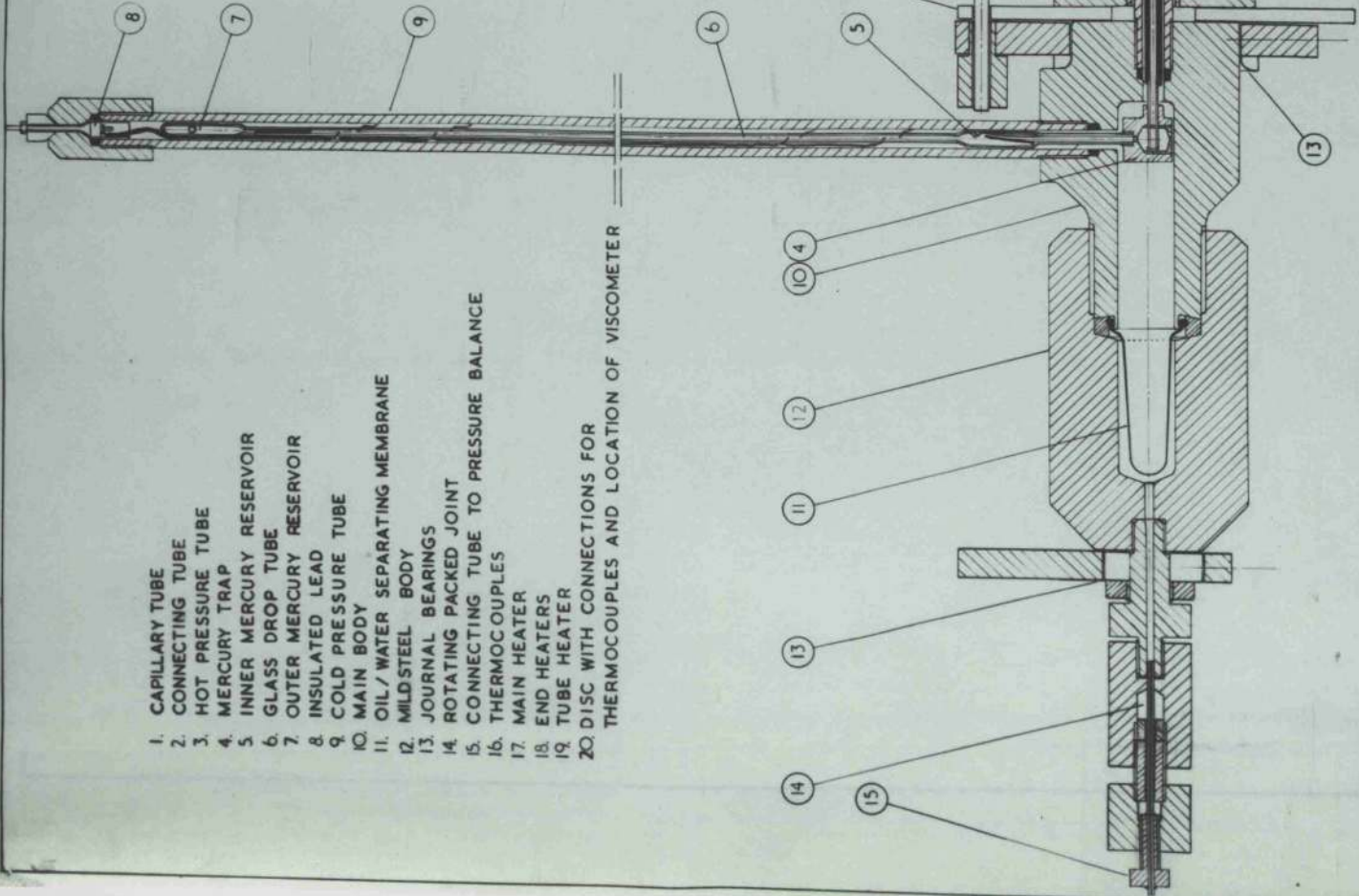
CAPILLARY VISCOMETER

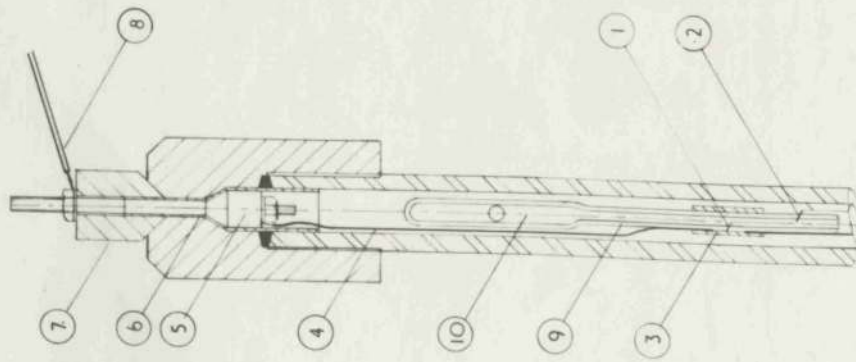


SCALE IN INCHES

FIGURE 7

- 1. CAPILLARY TUBE
- 2. CONNECTING TUBE
- 3. HOT PRESSURE TUBE
- 4. MERCURY TRAP
- 5. INNER MERCURY RESERVOIR
- 6. GLASS DROP TUBE
- 7. OUTER MERCURY RESERVOIR
- 8. INSULATED LEAD
- 9. COLD PRESSURE TUBE
- 10. MAIN BODY
- 11. OIL/WATER SEPARATING MEMBRANE
- 12. MILD STEEL BODY
- 13. JOURNAL BEARINGS
- 14. ROTATING PACKED JOINT
- 15. CONNECTING TUBE TO PRESSURE BALANCE
- 16. THERMOCOUPLES
- 17. MAIN HEATER
- 18. END HEATERS
- 19. TUBE HEATER
- 20. DISC WITH CONNECTIONS FOR THERMOCOUPLES AND LOCATION OF VISCOMETER

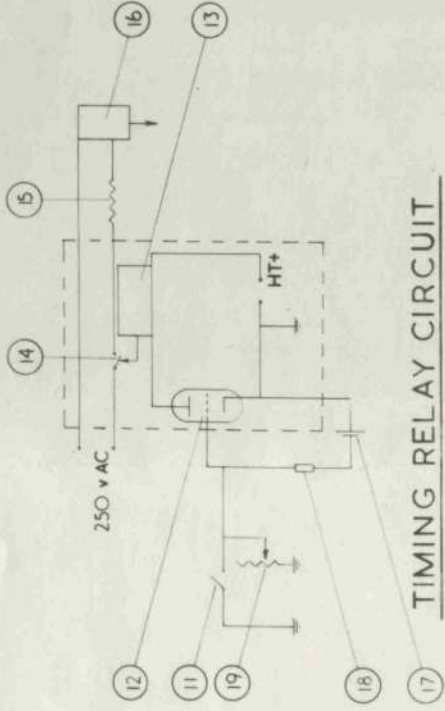




DETAIL OF DROP TUBE

- 1 INSULATED CONTACT WIRE
- 2 EARTHED CONTACT WIRE
- 3 RUBBER INSULATING SLEEVE
- 4 INSULATED LEAD
- 5 BRASS TERMINAL
- 6 PERSPEX INSULATING SLEEVE
- 7 PERSPEX SPACER
- 8 LEAD TO TIMING RELAY
- 9 GLASS DROP TUBE
- 10 OUTER GLASS MERCURY RESERVOIR

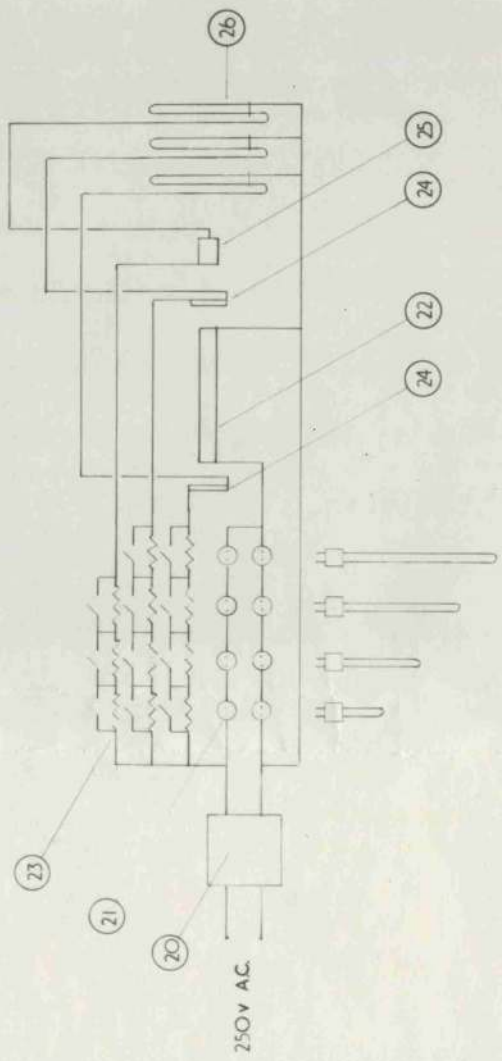
FIGURE 8



TIMING RELAY CIRCUIT

- 11 DROP TUBE CONTACT
- 12 TRIODE VALVE
- 13 SWITCH SOLENOID
- 14 MAINS SWITCH
- 15 SERIES RESISTANCE
- 16 STOPWATCH SOLENOID
- 17 BIAS BATTERY 6VOLT
- 18 SERIES RESISTANCE 4000 OHMS
- 19 ADJUSTABLE RESISTANCE

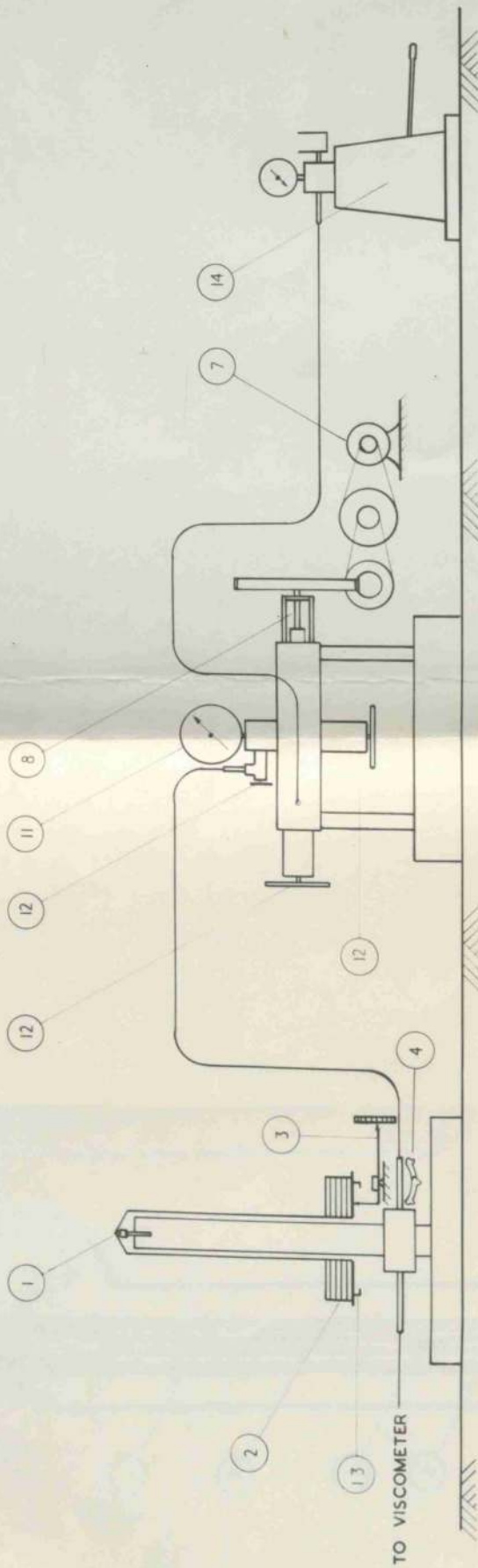
FIGURE 9



FURNACE HEATER CIRCUIT

- 20 CONSTANT VOLTAGE TRANSFORMER
- 21 PLUG IN RESISTANCES
- 22 MAIN HEATER
- 23 SERIES RESISTANCE S
- 24 END HEATERS
- 25 TUBE HEATER
- 26 SLIDE WIRE RESISTANCES

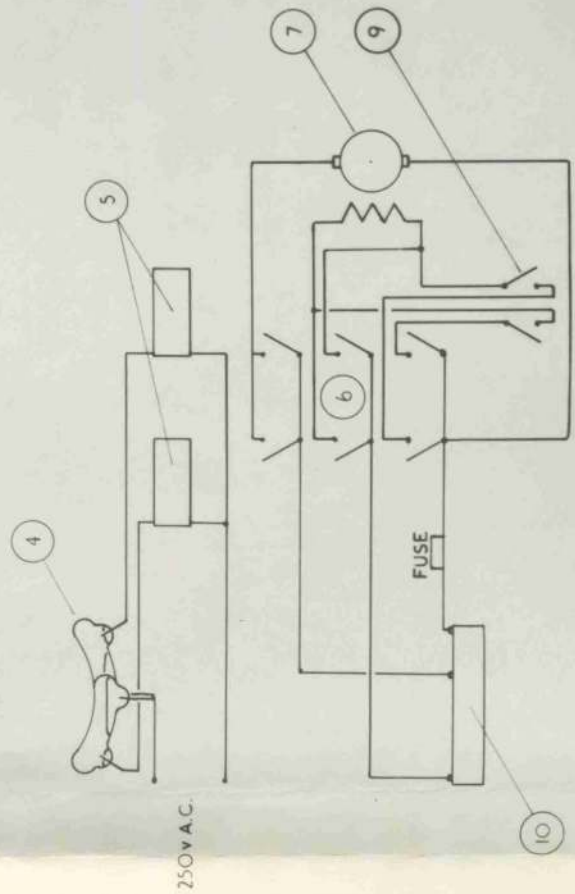
FIGURE 10



PRESSURE BALANCE

- 1 PRESSURE BALANCE PISTON
- 2 OVERHUNG WEIGHTS
- 3 POINTER SHOWING PISTON POSITION
- 4 MERCURY SWITCHES TO ACTUATE 5
- 5 AC SOLENOIDS
- 6 MICROSWITCHES
- 7 MOTOR
- 8 RAM PUMP DRIVEN BY MOTOR 7
- 9 LIMIT SWITCHES FOR RAM 8
- 10 24 V BATTERY
- 11 BOURDON TEST GAUGE
- 12 VALVES
- 13 SPROCKET FOR MOTOR DRIVE

FIGURE 11

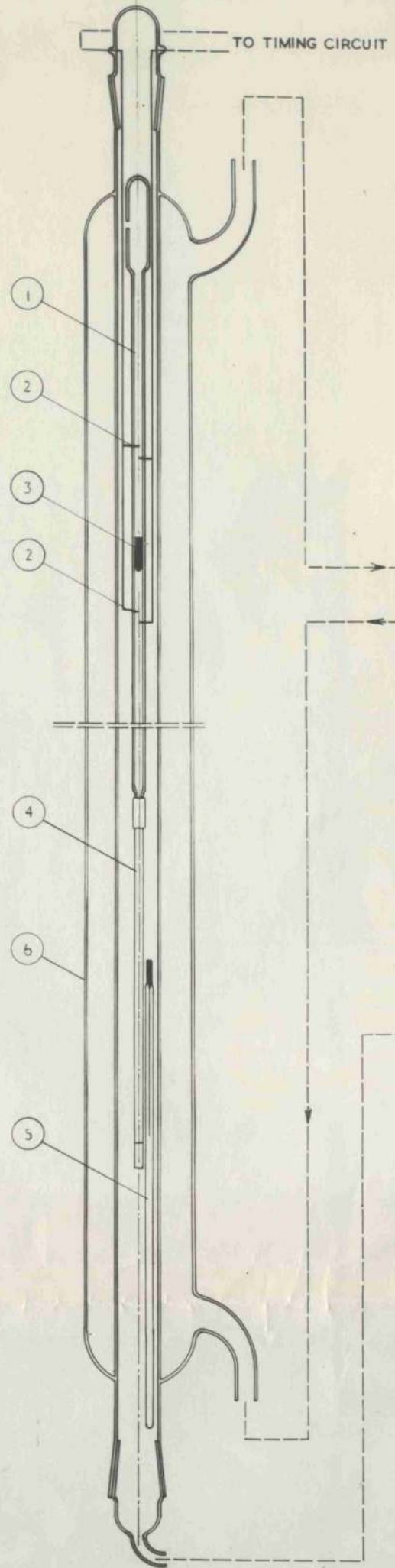


WIRING DIAGRAM

CALIBRATION APPARATUS FOR CAPILLARY VISCOMETER

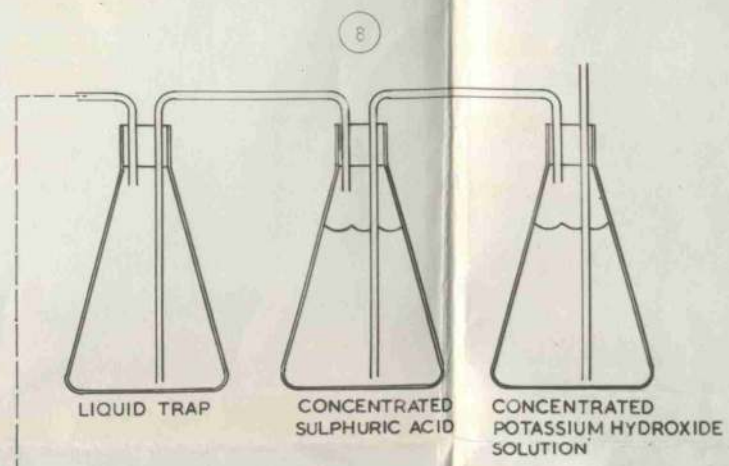
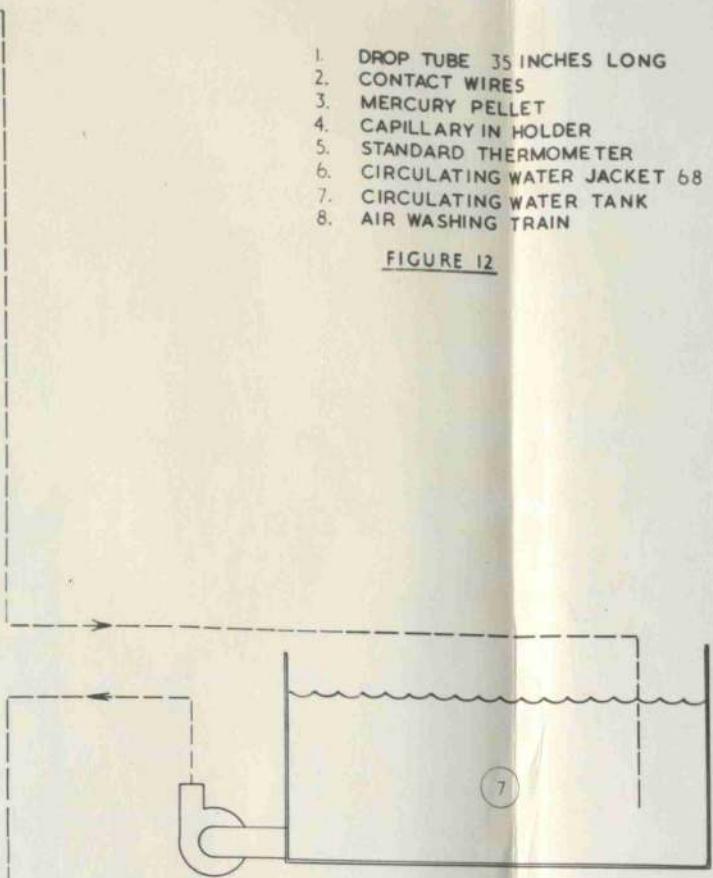
DRAWN: E.F.F.
TRACED: E.M.A.
5/58

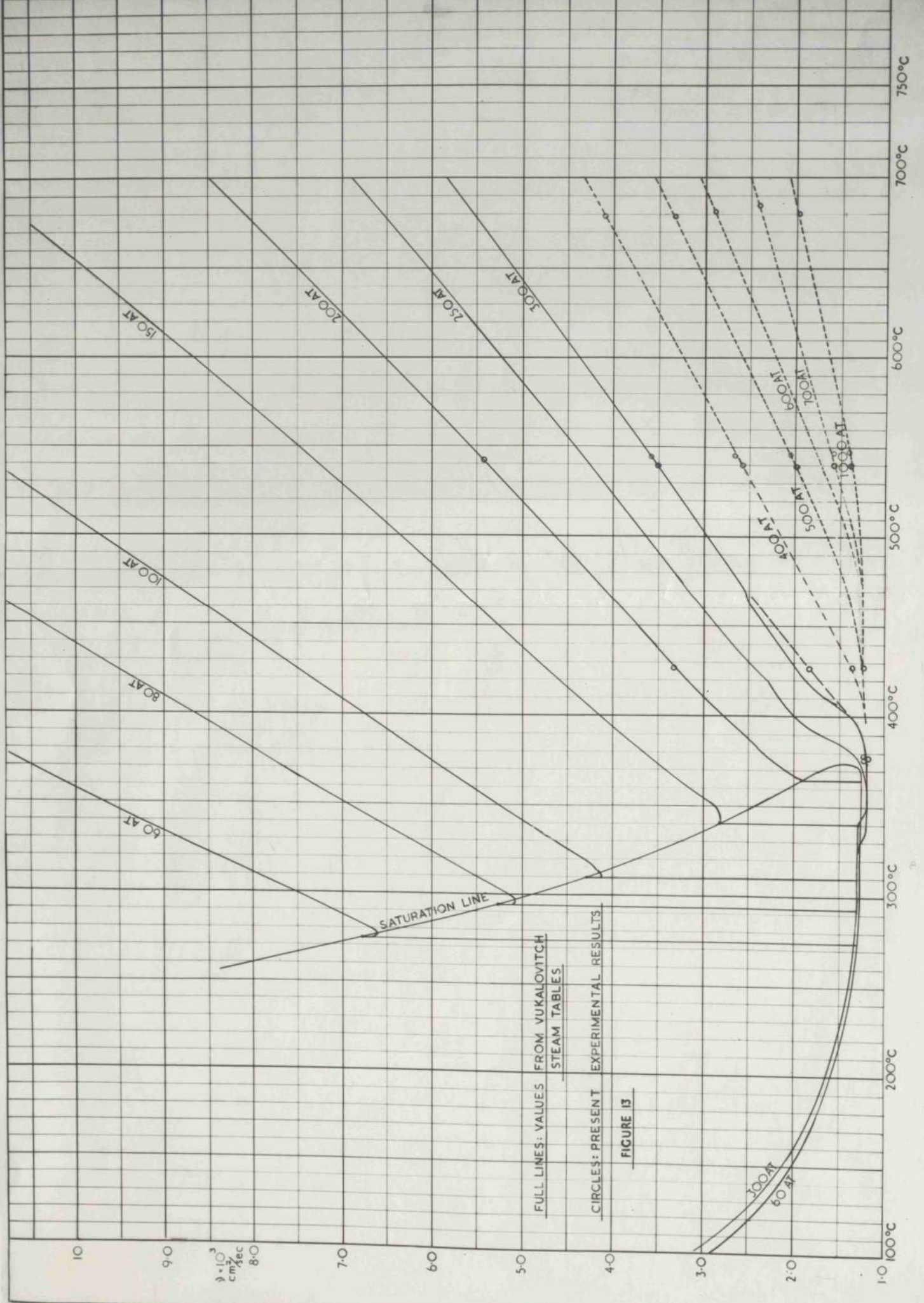
B 6



1. DROP TUBE 35 INCHES LONG
2. CONTACT WIRES
3. MERCURY PELLET
4. CAPILLARY IN HOLDER
5. STANDARD THERMOMETER
6. CIRCULATING WATER JACKET 68 INCHES LONG
7. CIRCULATING WATER TANK
8. AIR WASHING TRAIN

FIGURE 12





FULL LINES: VALUES FROM VUKALOVITCH STEAM TABLES

CIRCLES: PRESENT EXPERIMENTAL RESULTS

FIGURE 13

KINEMATIC VISCOSITY OF STEAM

DRAWN E.H.F.
 TRACED E.H.F.
 2/12/58