Viscosity of Water and Steam at High Pressures and Temperatures Up to 800 Atmospheres and 700°C

ERNST H. W. SCHMIDT AND F. MAYINGER

Technische Hochschule, Munich, Germany

Pressures and temperatures of water and steam in modern power plants increase more and more and reliable values are necessary not only for thermodynamic properties, but also for the so-called transport properties, i.e., viscosity and heat conductivity. Therefore, as early as 1936, the first author while at his former institute at the Technische Hoschschule Danzig encouraged K. Sigwart, his collaborator at that time, to measure the viscosity of water and steam at high pressure. These experiments were successful at pressures up to 270 at* and at temperatures up to 380°C, which at that time was by far the widest range of pressures and temperatures covered. This paper will not give a survey of all the papers dealing with the viscosity of water and steam. Mention here of Sigwart (*4*) is made only to show our early interest in this field and because his results, as later investigators have confirmed, were very good.

Because there are still great discrepancies between the results of different investigators we started new measurements with the additional intention of expanding the range of temperature and pressure as far as possible. For these experiments we chose the capillary method. The pressure drop was measured by a column of mercury, and the mass flow of steam after condensation and cooling was measured with the help of a balance. Two platinum capillaries each about 50 cm long were used. The inner diameter of the first was 0.3 mm; of the second 0.5 mm.

Since it is difficult to measure exactly the inner diameter of such a

* In this paper 1 at = 1 kp/cm² = 14,2234 lb/in.² means the metric atmosphere equal to the force exerted on 1 cm² by the weight 1 kilopond of the mass 1 kilogram at an acceleration of gravity of 9.80665 m/s².

capillary and to ensure that it has a circular cross-sectional area, we determined its effective diameter with the help of a fluid whose viscosity is well established by sufficiently coinciding experimental results of different investigators. Nitrogen gas, which was used at atmospheric pressure and near room temperature, is that kind of fluid.

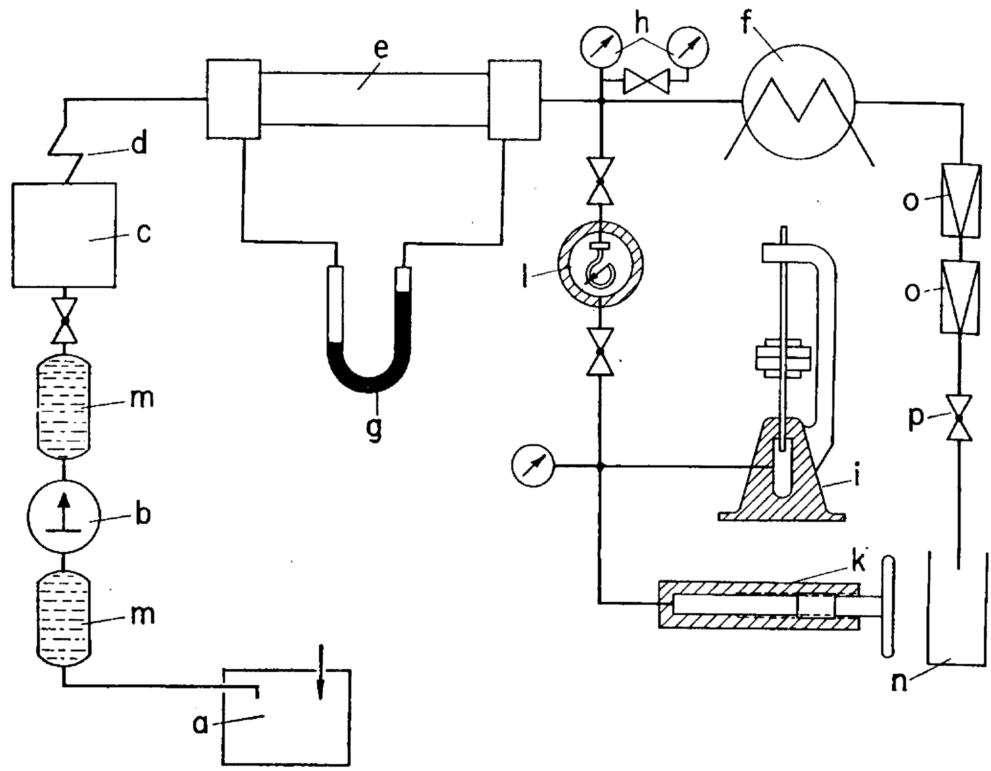

FIG. 1. Schematic of the experimental installation.

(a) Thermostat (100°C)
(b) High pressure pump
(c) Boiler
(d) Superheater
(e) High pressure cylinder
(f) Condenser
(g) Manometer for pressure differences
(h) Conventional manometers
(i) Piston pressure balance
(k) Screw pump
(l) Bourdon gage separating oil and water
(m) Filter
(n) Vessel for measuring mass flow
(o) Throttle valves
(p) Valves

It is well known that the viscosity μ of a fluid is related to the diameter d of the capillary, the pressure drop Δp_0, and other parameters by the equation

$$\mu = \Delta p_0 \frac{\pi d^4 z}{128 L V}$$

where z represents the time in which the volume V passes through a capillary of length L under a pressure drop Δp_0. This pressure drop is measured between two points where the flow has already developed the final parabolic distribution of velocity. The actual difference of pressure Δp between the two ends of a capillary is somewhat different

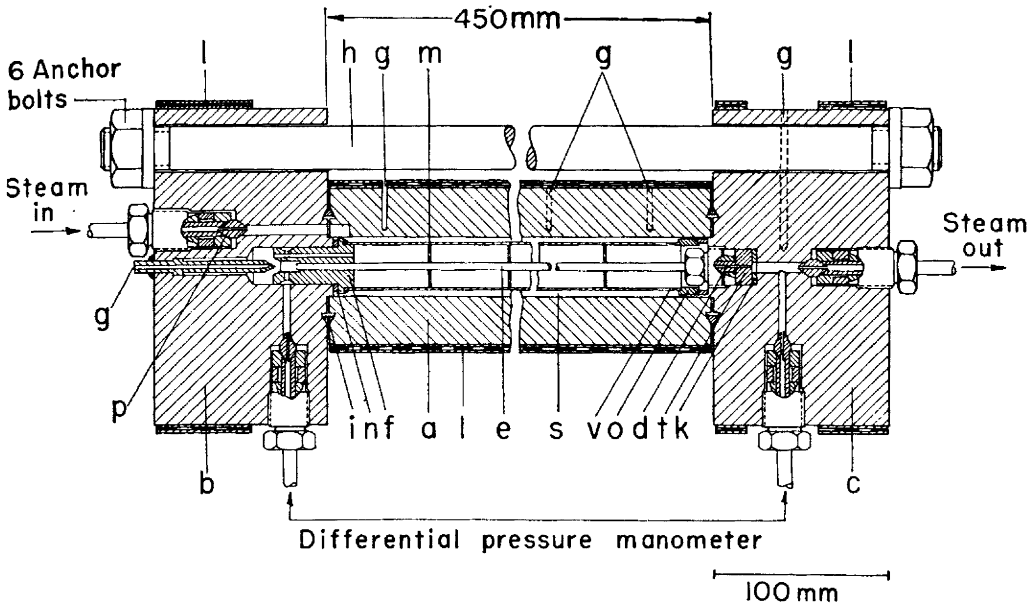

FIG. 2. Cylinder containing the capillary.

(a) High pressure cylinder
(b) and (c) Covers of the high pressure cylinder. The steam enters through cover (b) and leaves through cover (c).
(d) Capillary of platinum
(e) Tube surrounding and protecting the platinum capillary
(f) Support for the tube (e)
(g) Holes for thermocouples
(h) Bolts for pressing the covers (b) and (c) against the cylinder (a)
(i) Sealings
(k) Sealing for the capillary
(l) Heatings
(m) Disks with holes
(n) Sealings
(o) Ring for supporting the tube (s)
(p) Sealings for self tightening
(s) Tube for guiding the steam
(t) Support for holding the end of the capillary
(v) Holes in the guiding tube for the entrance of steam

from Δp_0 and the so-called Hagenbach-correction has to be accounted for.

A scheme of the experimental installation is given in Fig. 1. Carefully distilled and degassed water, taken from a thermostat (a) at boiling temperature, passes two filters (m) and is brought to high pressure by the pump (b), the mass flow of which can be changed at will. The compressed water is evaporated in the boiler (c) and the steam is brought to the temperature intended for measurement in the superheater (d). The fluid then passes through the capillary placed in the high pressure cylinder (e), whose construction is later described in detail. The pressure drop between both ends of the capillary is measured with the help of the mercury column (g). After leaving the capillary the absolute pressure of the fluid is measured by the pressure gages (h) and this pressure is measured with greater precision by the piston pressure balance (i). The steam does not enter the pressure balance but imparts its pressure to the oil in the Bourdon manometer

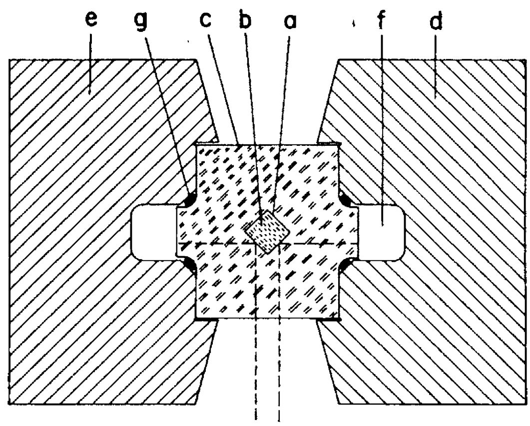

FIG. 3. Cross-section of the device for measuring small differences of pressure at high absolute pressures.

(a) Coating of silver
(b) Quadratic rod of araldite coated with silver
(c) Body of clear araldite
(d) and (e) Bars of steel
(f) Holes for the mercury columns
(g) Sealing stripes

(1), whose flat tube separates the steam or water from the oil of the piston balance. In the cooler (f) the steam is condensed and cooled to room temperature. Then the water passes through two throttle valves (o), a closing valve (p), and enters a container (n), which is used to weigh the water that has collected in a measured time.

The high pressure cylinder wherein the capillary is placed (Fig. 2) is built for temperatures up to 800°C and for pressures up to 1000 at. To withstand the high pressures at high temperatures, the cylinder, its covers at both ends, and the screw bolts pressing together the assembly are made of nimonic 90. In order to prevent the self welding of the screws of the bolts with the nuts, molybdenum bisulfite is applied as a lubricant with good results. The sealings (i) between

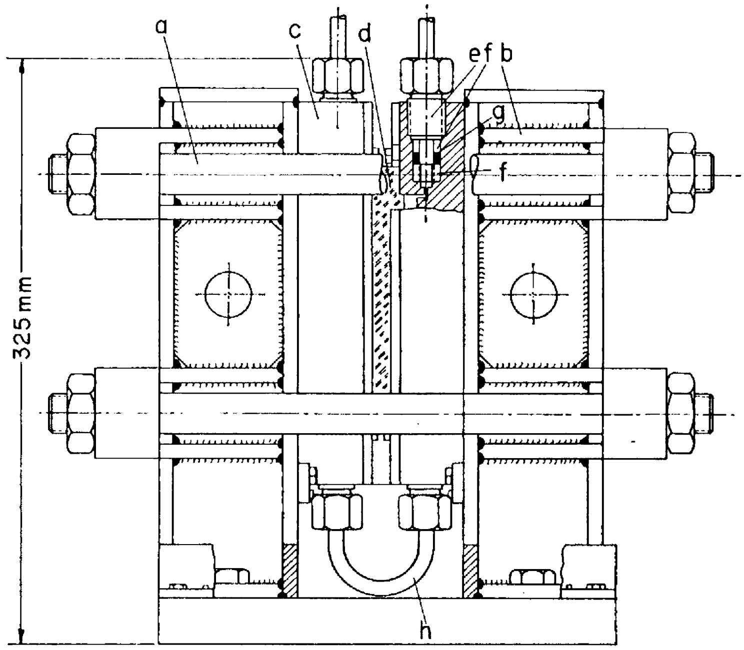

FIG. 4. Vertical section of the instrument for the measurement of small pressure differences at high absolute pressures.

(a) Bolts of steel
(b) Additional steel beams
(c) Steel bars
(d) Body of araldite
(e) Screw for fixing the connecting tube from the capillary
(f) Ring compressing the sealing
(g) Sealing
(h) Tube connecting both mercury columns

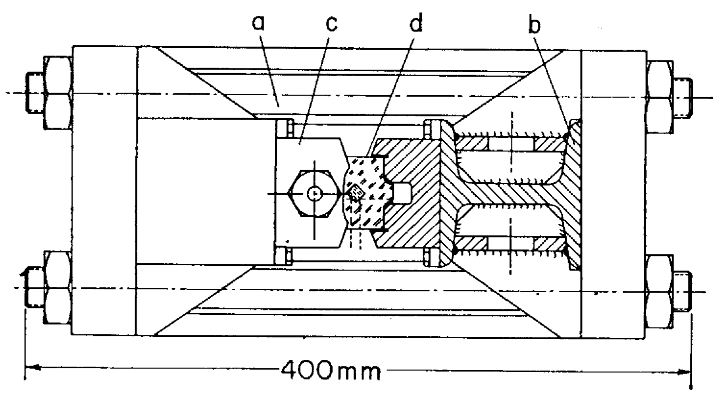

FIG. 5. Cross-section of the instrument for the measurement of small pressure differences at high absolute pressures.

(a) Bolts of steel
(b) Additional steel beams
(c) Steel bars
(d) Body of araldite

the cylinder and its covers have the form of conical rings and are self tightening.

The steam enters the high pressure cylinder (a) from the left-hand side and flows along its inner surface guided by a thin cylinder (s) of

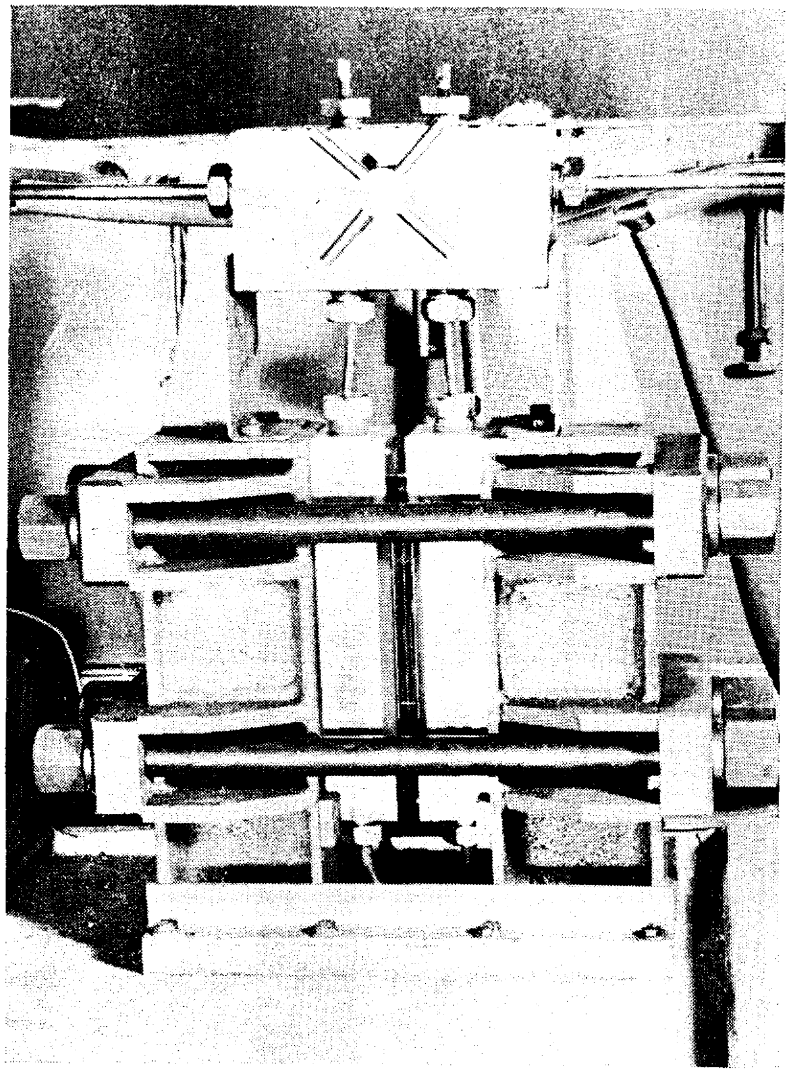

FIG. 6. Photo of the instrument for the measurement of small pressure differences at high absolute pressures up to 1000 at.

somewhat smaller diameter. The steam then returns inside this thin guiding cylinder and then enters the capillary (d) from the left-hand side. Finally, the steam leaves the high pressure cylinder at the right-hand side.

The pressure difference at both ends of the capillary is taken by two connections and tubes leaving the covers of the cylinder horizontally at the same level.

One of the essential problems of our method is to measure small

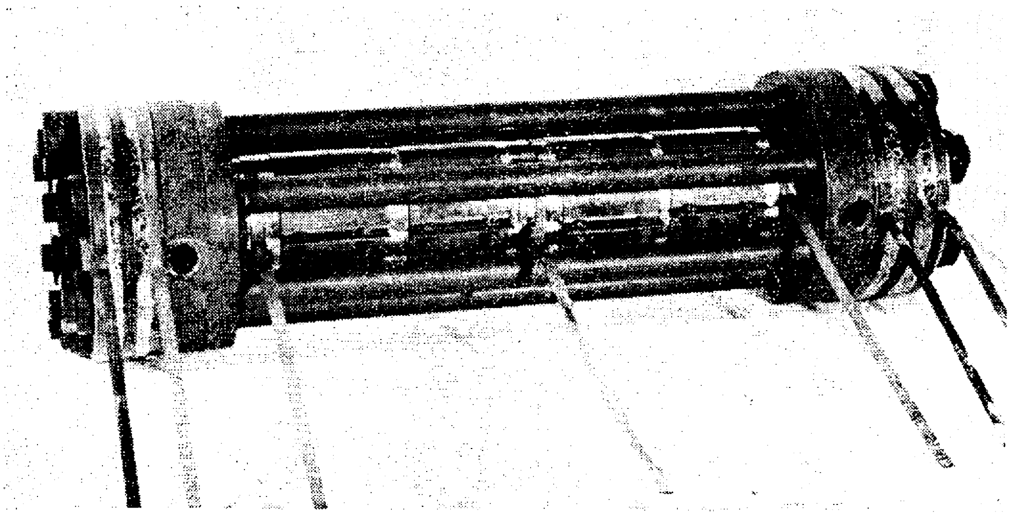

FIG. 7. Photo of the high pressure cylinder containing the platinum capillary.

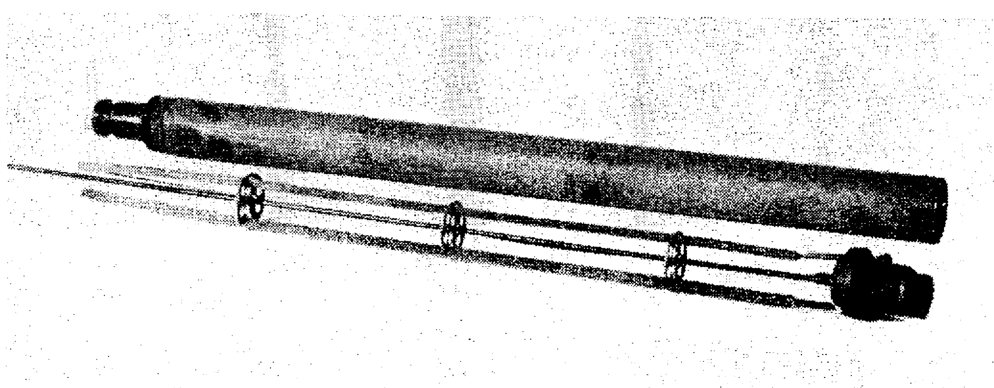

FIG. 8. Photo of the platinum capillary with its supports and the thin steel cylinder surrounding it.

pressure differences whose order of magnitude is a few inches of mercury column. These differences are measured at high absolute pressure levels of up to about 1000 at. The principle of the installation used for this purpose is shown in Fig. 3. Two very solid steel bars (d and e) extending vertically to the plane of the drawing have two holes (f) of about 1 cm^2 cross-sectional area. These holes contain two mercury columns which communicate with each other at their lower ends. The two different pressures at both ends of the capillary act from above upon the menisci of the mercury columns. The two steel bars

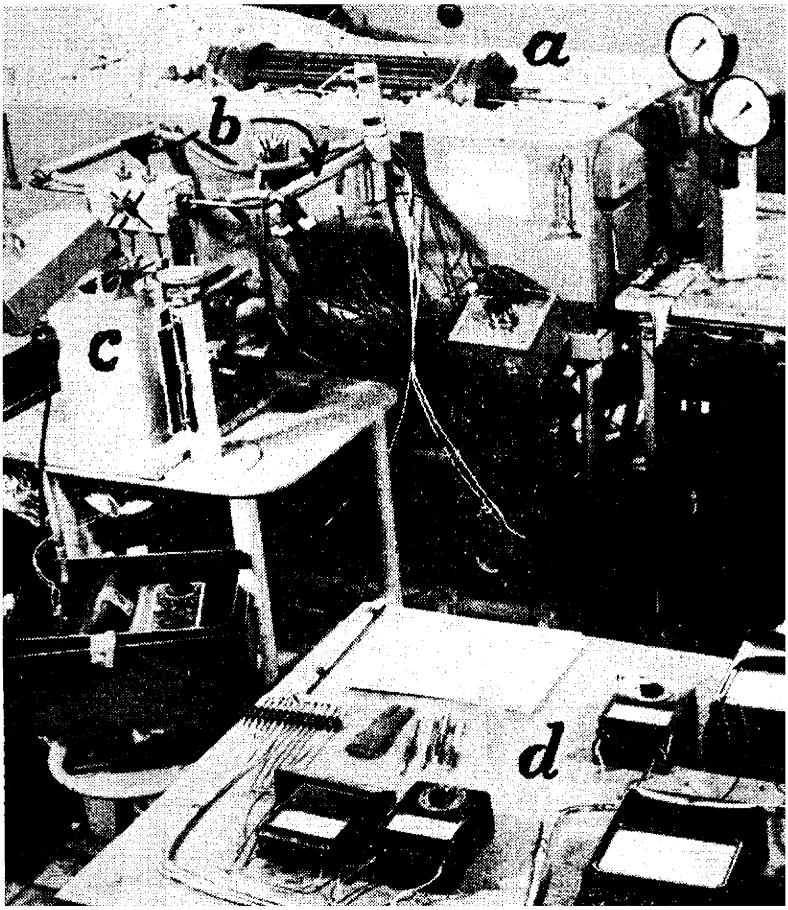

FIG. 9. Photo of the whole installation.

(a) Steel cylinder with the platinum capillary
(b) Horizontal water cooled tubes connecting the capillary with the instrument for measuring the pressure differences
(c) Instrument for measuring small pressure differences
(d) Electrical instruments

press together the body of clear araldite (c) between them. This action closes the open sides of the holes in the steel bars.

In order to observe the menisci, the clear araldite body (c) contains a rod (b) of quadratic cross-section whose silver coated surfaces act as mirrors in the transparent araldite. In this way it is possible to observe both menisci, one immediately beside the other, from the same direction when these menisci are illuminated from the opposite direction by way of the silver mirrors. Details of the construction of this device are shown in Figs. 4 and 5.

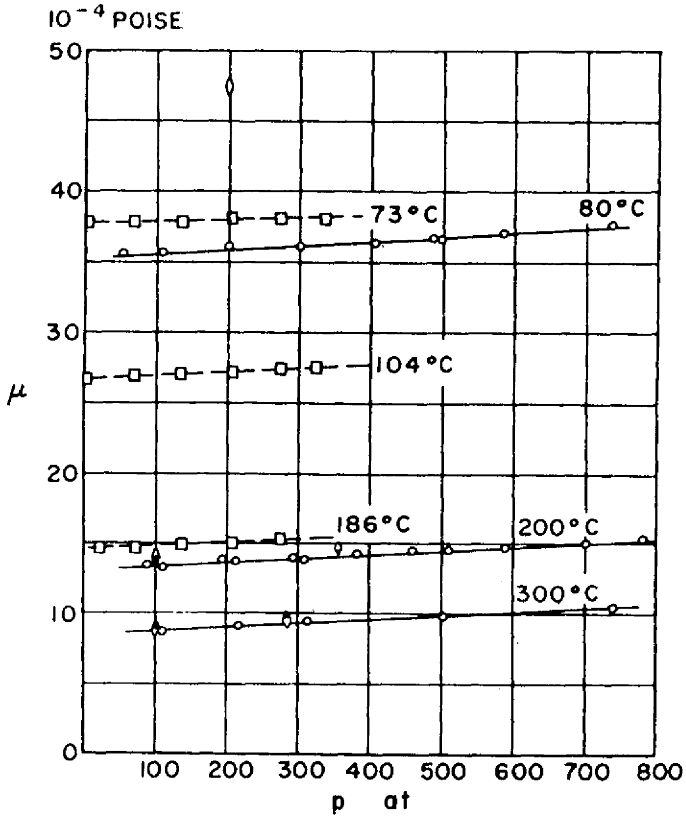

FIG. 10. Dynamic viscosity of water.

KEY: o = Author's measured values
— = Smoothed curve
For comparison:
Timroth: ◊ Measured values at 60°C
◊ Measured values at 200°C
◊ Measured values at 300°C
Kestin: □ Measured values
--- Smoothed lines for three temperatures

Because the araldite closing the holes containing the mercury columns is compressed mainly in one direction, the araldite withstands pressures up to 1200 at and thanks to its transparency allows an immediate observation. The difference in height of both mercury menisci can be measured with the help of a cathetometer to an exactness of 0.1 mm mercury, that is one part per thousand for a pressure difference of 100 mm mercury. The tubes connecting the ends of the capillary with the measuring device are placed horizontally at the same level. Since these tubes are very hot at one end they are cooled with the help of water jackets before they reach the difference manometer. In this way only water at room temperature is above the mercury

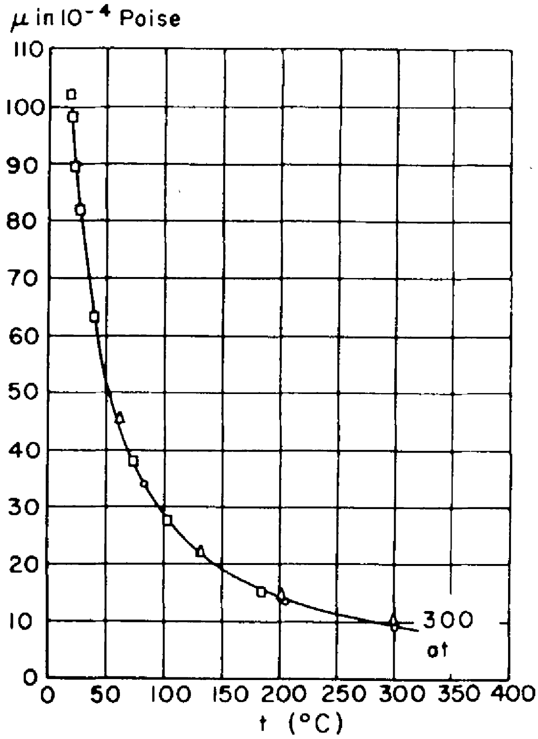

FIG. 11. Dynamic viscosity μ of water at 300 atm.

KEY: o = Author's measured values
— = Smoothed curve
For comparison:
△ Measured values of Timroth
□ Measured values of Kestin

menisci and the change from steam to water takes place in the horizontal part of the cooled tubes. Thus the measurements of the pressure difference are not influenced if the water menisci of the tubes do not always have exactly the same position.

Some photographs of the installation are shown in the following figures: Figure 6 shows the instrument that measures small pressure differences and the figure indicates the heavy construction, bolts, and the slit in the middle of the instrument for the observation of the mercury menisci. Figure 7 shows the cylinder of nimonic containing the platinum capillary. Figure 8 shows the capillary with its supports and the thin steel cylinder for guiding the steam in one direction and

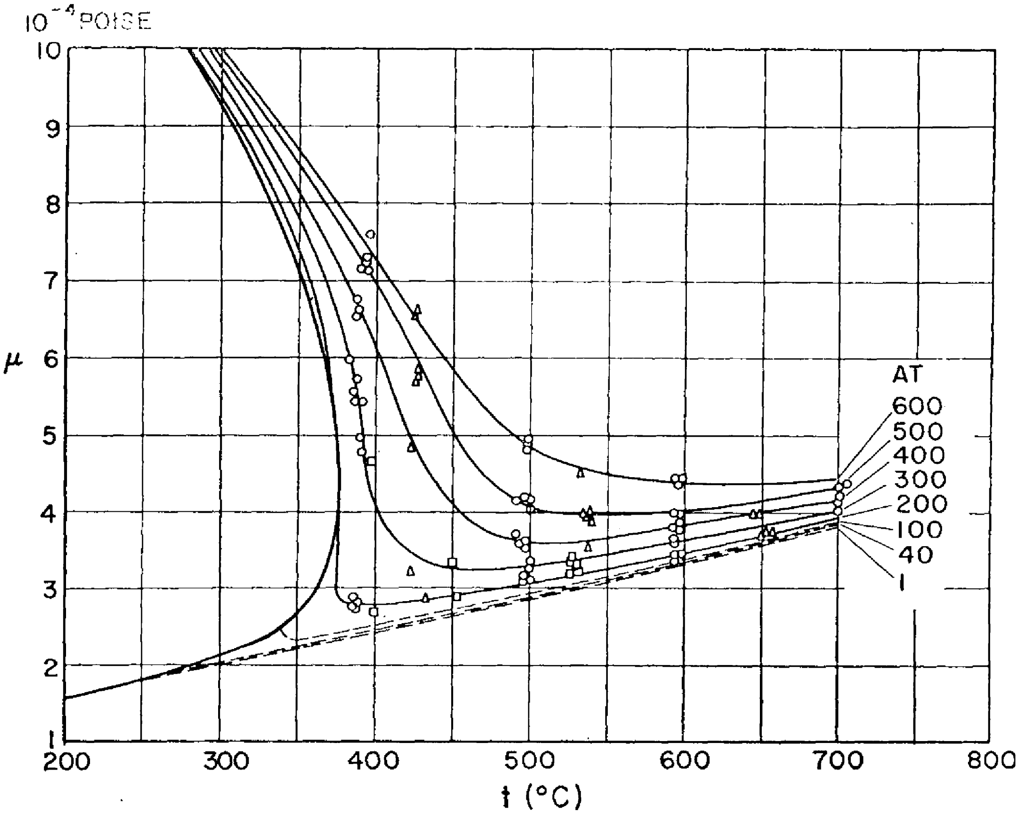

FIG. 12. Dynamic viscosity μ of steam.

KEY: o = Author's measured values
— = Smoothed isobars
For comparison:
△ Measured values of Whitelaw, at the pressures of the isobars.
□ Measured values of Timroth, at the pressures of the isobars.
--- Russian steam table (1958)

returning the steam in the other direction. Figure 9 is a photo of the whole installation. In the background at the left-hand side the steel cylinder (a) containing the platinum capillary is to be seen in a bed of quartz wool; the latter is required because at temperatures up to 700°C a good thermal insulation is necessary. (In the photograph the upper half of the bed has been removed.) The two horizontal tubes

(b) with a water jacket for cooling connect the ends of the capillary with the instrument (c). This instrument, which is placed on a small table, measures the pressure difference.

The results of our experiments compared with those of other investigators are given in the following figures: Figure 10 shows the results

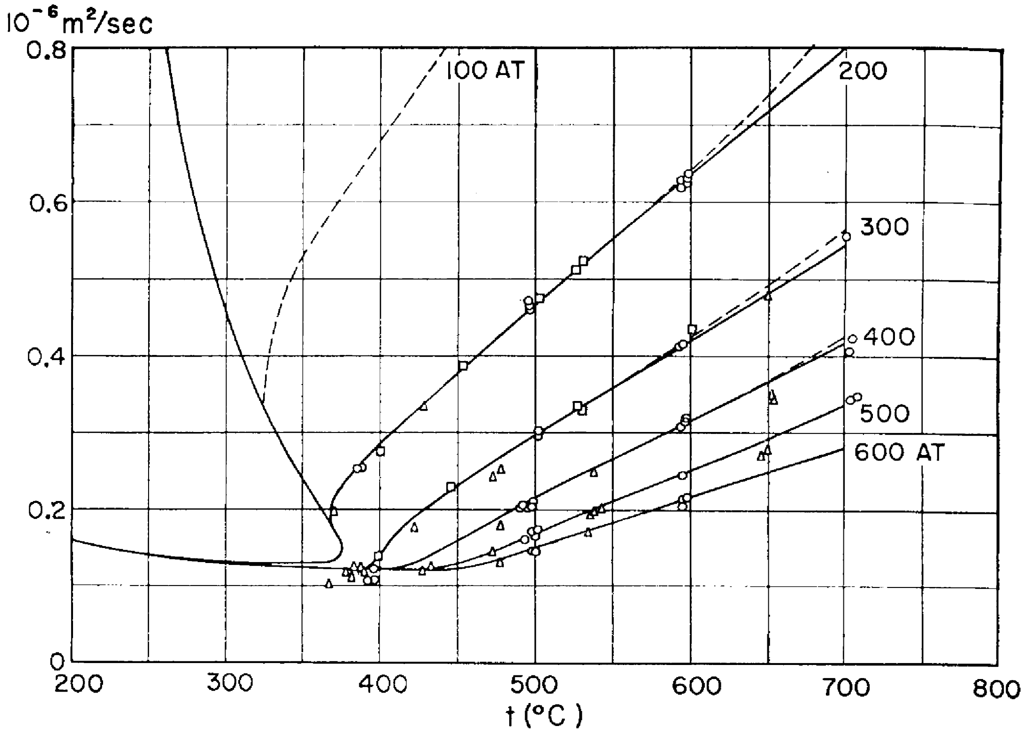

FIG. 13. Kinematic viscosity $\nu = \eta/\rho$ of steam.

KEY: o = Author's measured values
---- = Smoothed isobars
For comparison:
△ Measured values of Whitelaw, at the pressures of the isobars.
[ ] Measured values of Timroth, at the pressures of the isobars.
. Russian steam table (1958)

of our measurements of the dynamic viscosity μ of liquid water at 80, 200, and 300°C plotted against pressures of up to 800 at. Also included in this figure are the results of Timroth (*5*), Kestin (*1*), and Moszynski (*2*); these results however, cover only the range of pressures up to 350 at. For better comparison Fig. 11 illustrates the dynamic viscosity of water at 300 at plotted against temperature.

At temperatures up to 150°C the agreement is very good. At temperatures of 200 and 300°C Timroth's results are 3 to 8% higher.

The values of the Russian steam tables (1958) exceed our own values in this region only by 1 to 2% *(6)*.

The measurements in the area of superheated steam are given in Figs. 12–14. Figure 12 shows the dynamic viscosity μ of steam. In this figure the smoothed curves of our measurements are compared with some values of Timroth *(5)* and Whitelaw (Univ. of Glasgow) *(7)*. At temperatures of 400 to 500°C we are in good agreement with Timroth's measurements and also with Sigwart's old measurements; at

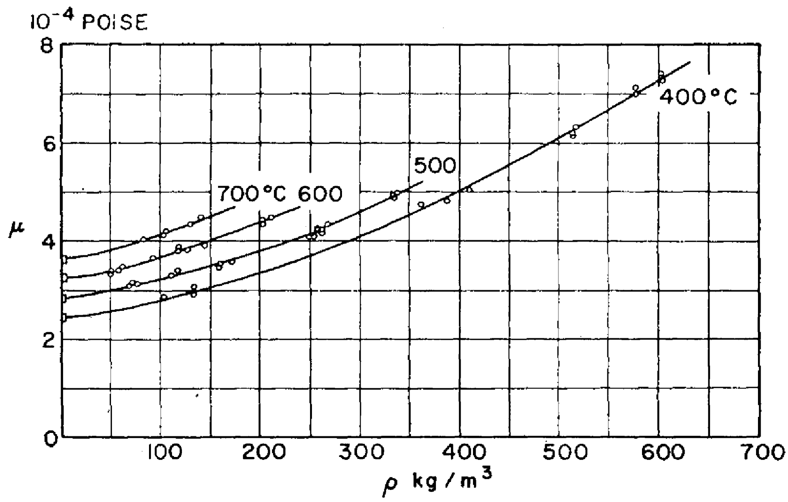

FIG. 14. Dynamic viscosity μ of steam as a function of the density ρ.

KEY: o = Author's measured values
— = Smoothed isobars
For comparison:
□ Measured values of Shifrin at atmospheric pressure

600°C Timroth's values are higher and Whitelaw's results are lower with the greatest deviation at 500 at and 650°C.

In Fig. 13 the values of the kinematic viscosities $\nu = \mu/\rho$ are plotted in the same way.

In Fig. 14 our measurements of the dynamic viscosity at temperatures of 400, 500, 600, and 700°C are plotted against the density. This way of representation with its smooth curves is best suited for interpolation and extrapolation. If we extrapolate the isotherms to the low densities of 1 at, they are in excellent agreement with Shifrin's measurements *(3)* at atmospheric pressure.

References

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