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TECHNICAL NOTE 3180

DETERMINATION OF VISCOSITY OF EXHAUST-GAS MIXTURES
AT ELEVATED TEMPERATURES

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National Bureau of Standards

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DETERMINATION OF VISCOSITY OF EXHAUST-GAS MIXTURES

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SUMMARY

The viscosities of five samples of dry-exhaust-gas mixtures at approximately atmospheric pressure and at temperatures from 0° to $1,100^{\circ}$ C are presented. A method of analysis and correlation proposed by Sutherland has been applied to the data and equations were derived therefrom for representing the results. It is believed that these equations may be used for computing viscosities of all mixtures having compositions within the range of the five studied at any temperature up to about 1300° C. The effect of moisture upon the viscosity of exhaust gas was computed by a relation developed from experimental values for moist air. In a check determination on moist exhaust gas, the experimental viscosity differed less than 1 percent from the calculated value.

INTRODUCTION

Accurate data on the viscosity of gases are required in the design of transmission and measurement systems for fuel gases and in the construction of gas-flow systems in chemical plants. Because the viscosity of a gas is an important factor in the rate of heat transfer between gases and metals, viscosity data are also useful in the design of gas turbines and jet engines. With the continued development of engines of this kind, there is an increasing need for information on the viscosity of the exhaust gases at high temperatures.

Heretofore, available data on the viscosity of exhaust gases were very meager, particularly at temperatures above 500° C. To meet this need, this investigation was initiated to determine the viscosity of exhaust gas mixtures over the temperature range from 0° to $1,800^{\circ}$ C and at pressures ranging from 1 atmosphere to 50 atmospheres. The present results cover only portions of these ranges, being for a pressure of 1 atmosphere and for temperatures from 0° to $1,100^{\circ}$ C. As it would be too extensive a program to cover every mixture variation that may be encountered in practice, it was decided to cover the extreme mixture proportions with only five gas samples and provide a method of correlation to cover intermediate mixture ratios.

The technical difficulties involved in measuring the volume flow of supersaturated gases at room temperatures limited the determinations of wet gases to those presaturated at approximately atmospheric conditions. It was felt that these data would be sufficient for providing equations that would express the viscosity of a wet gas as a function of the specific humidity and the individual viscosities of the dry gas and water vapor.

In this investigation, viscosities are measured by timing the flow of the gas under study through a very fine capillary tube. Viscosities were computed by the Hagen-Poiseuille law from the known dimensions of the tube, the volume rate of flow, and the pressure drop across the tube.

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SYMBOLS

A_1, A_2	constants which involve only molecular constants of individual gases
b	barometric pressure, cm Hg
C	Sutherland constant, $^{\circ}K$
\bar{c}	average molecular velocity, cm/sec
L	length of capillary tube, cm
λ	mean free path, cm
P_i	absolute pressure at inlet of capillary, dynes/sq cm
P_0	absolute pressure at outlet of capillary, dynes/sq cm
Q_m	volume rate of gas flow at T_m and $\frac{P_i + P_0}{2}$, cu cm/sec
r	radius of capillary tube, cm
T	absolute temperature, $^{\circ}K$

T_a	absolute temperature of room, °K
T_m	absolute temperature of capillary tube, °K
t	transpiration time of gas volume V , sec
V	volume of gas metered at P_2 and T_a , cu cm
W	specific humidity
α	coefficient of thermal expansion
ϵ	thickness of slippage, cm
η	absolute viscosity of gas at T_m , poise
λ	mean free path of gas mixture, cm
ρ	mass density of gas, gm/cu cm
ρ_m	mass density of gas at T_m and $\frac{P_i + P_0}{2}$, cu cm/sec

Subscripts

1	exhaust gas
2	water vapor
o	at 0° C
dry	dry
exp	experimental
ref	reference
wet	wet

THEORETICAL CONSIDERATIONS

The Hagen-Poiseuille law in the following form was employed in calculating the viscosity from the test data:

$$\eta = \left(1 + \frac{4\epsilon}{r}\right) (P_i - P_0) \left(\frac{\pi r^4}{8L}\right) / Q_m \quad (1)$$

where

$$Q_m = \rho_0 V / \rho_m t \quad (2)$$

In considering the flow of gas through a cylindrical tube, the flow must occur in the laminar regime in order for a Poiseuille analysis to be appropriate. When the tube is coiled in a ring, experiments have shown that the transition between turbulent flow and laminar flow occurs at a higher value of Reynolds number. A higher internal fluid friction is also observed in a coiled tube and these phenomena are attributed to a longer flow path traversed by the fluid particles than the actual mechanical length of the tube. This increased flow path is due to a tendency for the gas to spiral along the periphery of the tube.

White found that the increase in internal fluid friction due to coiling a tube is equal to the Reynolds number multiplied by the square root of the ratio of the internal diameter to the diameter of the coil and that the increase in fluid friction is negligible when this product does not exceed 11.6 (ref. 1). The corresponding limiting value of Reynolds number for these experiments is 232, a value which was never exceeded in the present tests. Following a procedure outlined in reference 2, the corrections to the measured pressure loss across the capillary due to end effects and acceleration of the gas were computed and found to be negligible over the experimental temperature range and at 1 atmosphere.

Experiment has shown that the flow of gas in tubes of very small diameter is greater than that predicted by the Poiseuille expression and this increase in flow is attributed to slippage at the wall. In effect, this excess in gas flow over that obtained by Poiseuille's relationship represents the drifting of the gas molecules through the capillary without any net transport of momentum occurring in the direction of drift, which is parallel to the axis of the tube.

To take account for this increase in flow, it is assumed that the speed cancels out at the distance $(r + \epsilon)$ from the axis of the tube, the quantity ϵ being called the "thickness of slippage." The increase in discharge is obtained by the multiplying factor $(1 + \frac{4\epsilon}{r})$.

In determining the quantity ϵ Knudsen has given the formula (ref. 3)

$$\epsilon = \frac{8\sqrt{2}}{3\pi} \frac{\eta}{\sqrt{Pp}} \frac{C_1}{C_2} \quad (3)$$

where the term C_1/C_2 is equal to 0.81 as determined experimentally. In substituting for η its equivalent in terms of ρ , \bar{c} , and λ as proposed by Chapman (ref. 4) $\epsilon = 1.41\lambda$.

In calculating the slip correction for the exhaust gases tested the properties of dry air were used. This procedure was adopted after comparing the maximum deviation in slip correction for carbon dioxide, nitrogen, and air at $1,800^\circ\text{K}$. The slip correction for carbon dioxide at this temperature was only 3 parts in 1,000 lower than that for air and 1 part in 1,000 lower than that for nitrogen. It was believed that the uncertainty in the use of $C_1/C_2 = 0.81$ for these experiments was much greater than this.

The correction for the expansion of the capillary tube at elevated temperature was obtained by the following equation, where the general tube constant at temperature T is given by

$$\frac{\pi r^4}{8L} = \frac{\pi r_0^4}{8L_0}(1 + 3\alpha t) \quad (4)$$

The coefficient of thermal expansion α for Inconel was taken as $11.5 \times 10^{-6}/^\circ\text{C}$ up to 100°C and $16.1 \times 10^{-6}/^\circ\text{C}$ up to 700°C ; $\frac{\pi r_0^4}{8L_0}$ is the tube constant at the calibration temperature.

Maxwell predicted from simple kinetic theory that the viscosity of a gas is $\eta = \rho \bar{c} \lambda / 3$ and that if this expression were rigorously correct the viscosity would be independent of pressure (ref. 5). Although it has since been shown that pressure has some effect (ref. 6), the present tests were made at pressures so nearly the same that the small changes which did exist were certainly without significant influence upon the observed values of viscosity.

According to the Sutherland equation (ref. 7), which is convenient for formulating results on the effect of temperature upon the viscosity of a gas, the viscosity η at temperature T may be expressed as

$$\eta = \eta_0 \left(\frac{T}{273.2} \right)^{3/2} \frac{C + 273.2}{C + T} \quad (5)$$

when η_0 is the viscosity at a temperature of 0°C (273.2°K).

As a basis for considering the effects of water vapor on the viscosity of a gas, it may be assumed that the mixture represents a simple binary system consisting of water vapor and exhaust gas. On the basis of

this assumption, a close approximation of the effective viscosity is obtained by considering that the viscous transfer of momentum in the mixture is equal to the sum of the transfers of the individual molecules separately. Thus, if ρ_1 and ρ_2 are the densities of exhaust gas and water vapor, respectively, \bar{c}_1 and \bar{c}_2 are the respective average velocities, and λ_1 and λ_2 are the average free paths, then the viscosity of the mixture may be expressed by

$$\eta_{12} = \frac{\rho_1 \bar{c}_1 \lambda_1}{3} + \frac{\rho_2 \bar{c}_2 \lambda_2}{3} = \frac{\eta_1 \lambda_1}{\lambda_1} + \frac{\eta_2 \lambda_2}{\lambda_2} \quad (6)$$

It can be shown from kinetic considerations that equation (6) reduces to

$$\eta_{12} = \frac{\eta_1}{1 + \left(\frac{A_1 \rho_2}{\rho_1} \right)} + \frac{\eta_2}{1 + \left(\frac{A_2 \rho_1}{\rho_2} \right)} \quad (7)$$

in which A_1 and A_2 are constants which involve only molecular constants of the individual gases.

APPARATUS

The apparatus used in the present experiments is shown photographically in figure 1 and diagrammatically in figure 2. An essential part is the flowmeter regulator shown schematically in figure 3 and described in detail in reference 8. Briefly, it was used as follows in the present measurements.

The flowmeter consists of a calibrated volume chamber, a float-valve chamber, and a gas-mercury reservoir. These are connected in with the calibrated capillary tube to form a closed system in which the gas under study flows out of the reservoir and through the capillary tube to displace mercury in the volume chamber. The float valve regulates the flow of mercury out of the volume chamber as it is displaced by the incoming gas and at the same time maintains constant the height of a mercury column which provides a hydrostatic pressure causing the gas to flow through the capillary tube. As the mercury passes out of the volume chamber, it breaks electrical contact with successive platinum electrodes, activating relays which start and stop a clock. In this way the time required for the measured volume of gas to flow through the capillary tube is ascertained.

No energy from the gas stream is employed in replacing the mercury, which is made to flow by gravity out of the calibrated container through the float-valve chamber at a rate equal to the rate of gas inflow. The replaced mercury is then added to the top of the hydrostatic column, replacing mercury which passes out of the small-diameter tube forming the lower or power part of the column and into the gas-mercury reservoir. The mercury which thus enters the reservoir in turn replaces the gas which is continually leaving the reservoir to pass through the calibrated capillary tube. A pressure-equalization tube which joins the calibrated gas-collection chamber to the float-valve chamber insures that the pressure differential across the capillary tube is only that due to the column of mercury above the gas-mercury reservoir.

The volume chamber, made of glass, is divided into two equal parts, one above the other, with a necked-down section in between and at the base of the lower chamber. The principal purpose of the upper volume is to provide a starting period during which flow conditions may become stabilized. The necked sections make the cross-sectional area small in the place of the contact break.

The entire flowmetering equipment was enclosed in a thermostat, shown at the left of figure 1, which was constructed of 5/8-inch-sheet Celotex and Lucite. This enclosure insured a fairly stable temperature during operation of the flowmeter.

The capillary tubes employed in these experiments were drawn on a soft iron mandrel from Inconel tubing to approximately 0.038-centimeter internal diameter and a length of about 433 centimeters. These tubes were coiled into a 15.24-centimeter ring and mounted on a stainless-steel plate 10 inches square and 1/4 inch thick. This type of mounting facilitated uniform heating and temperature control.

The ends of the capillary tube were silver-soldered to stainless-steel preheating and after-cooling connections. The temperatures of these connections were measured with Chromel-Alumel thermocouples and were never allowed to exceed the fusion temperature of silver solder.

The high-temperature furnace shown in the center of figure 1 was constructed of 3/8-inch-thick Transite and 2-inch angle iron. This structure was 2 feet square and approximately 18 inches high. The heating element was of the standard muffle furnace design, consisting of coiled Nichrome wire embedded in a high-temperature ceramic material. The thermal output of the unit was such that when the capillary mounting was installed and fully insulated with diatomaceous earth the temperature could be sustained for a long period of time at a 1,100° C maximum.

The voltage input to the furnace was regulated by a 2,000-volt-ampere autotransformer and the temperature was maintained by manual adjustment.

The maximum output voltage which could be obtained from the transformer was 250 volts although the actual voltage supplied the furnace never exceeded 100 volts. By regulation of the voltage, it was possible to maintain the temperature of the capillary tube within 1° C at 500° C and 2° C at $1,000^{\circ}$ C.

The temperature of the capillary tube was determined by four Chromel-Alumel thermocouples that were wired to four equally spaced points around the periphery of the capillary coil. The smoothing of the capillary coil temperatures was greatly improved by the 1/4-inch stainless-steel mounting plate that was situated directly above the heating unit. The voltage output of the thermocouples was measured with a precision laboratory potentiometer. These voltages were measured with the cold junction of the thermocouples at the ice point and the four measurements agreed within 5° C at approximately 980° C. The average of the temperatures thus determined during a run was used as the temperature of the run.

The Chromel-Alumel thermocouples were made from 22-gage duplex wire and the hot junction was electrically welded. The original coil of thermocouple wire was 1,000 feet long and three representative samples were calibrated from 0° to 600° C by the Temperature Measurements Section of the National Bureau of Standards. The average values were accepted as representative of the thermocouple wire. The calibration of the thermocouples was extrapolated to $1,000^{\circ}$ C by means of the standard centigrade table for Chromel-Alumel thermocouples (ref. 9).

The pressure difference from the inlet to the outlet of the capillary tube was measured with a precision U-tube manometer shown in figure 1. This measurement was made only to define the initial magnitude of the mercury column in the flowmeter and, as this column was constant by design, a continuous observation of this quantity was not necessary. The same type of instrument with one leg open to the atmosphere was employed for measuring the gage pressure at the inlet to the capillary tube. The atmospheric pressure was determined by a mercurial barometer.

In determining the viscosity of saturated gas mixtures the drier at the inlet of the capillary was replaced with a water saturator. Only gas mixtures that were saturated with water vapor at room temperature were used.

The temperatures of the room and of the flowmeter thermostat were determined with calibrated mercury-in-glass thermometers.

TEST PROCEDURE

The prepared gas samples used in these tests were compounded by the method of partial pressures, the principal constituents being nitrogen,

carbon dioxide, oxygen, argon, and water vapor. Actual exhaust-gas samples were collected from an experimental turbojet burner operating at approximately cruising conditions, this sample being designated number 3.

The gas samples 1, 3, and 4 were analyzed by mass spectroscopy in the Gas Chemistry Section of the National Bureau of Standards on a mole-volume basis. Gas samples 2 and 5 were analyzed with an Orsat apparatus. Samples 1 and 2 were tested before and after being saturated with water vapor. In the saturated condition these samples are designated 1-S and 2-S. Compositions of the gas samples studied are listed in table 1.

The tube constant $\pi r^4/8L$ was determined by calibration with gases of known viscosities, such as dry air and nitrogen. The value of tube radius obtained from this constant agreed within 1/2 percent of the average radius of the soft iron mandrel which had been withdrawn from the tube and measured with a micrometer at several different places.

The tube constant was determined at regular intervals throughout these experiments. No change was observed until operations were extended to the temperature range above 760° C. These are plotted in figure 4 in terms of r/r_0 as a function of the time of heating above 540° C. The changes that occurred in this temperature range may be attributed to the effects of nitriding on the radius. Tests with Inconel metal over a temperature range from 538° to 760° C, as reported by the International Nickel Co. (ref. 10), have shown a rate of attack by nitriding gases of 0.00035 inch per 100 hours of operation. Using this rate of attack, in 100 hours of operation the radius would change from 0.00750 to 0.00715 inch, which would alter the tube constant by 17.3 percent. This compared with the observed change of 19.4 percent in tube constant during approximately that period of time.

The test procedure consisted of evacuating the system with a high-vacuum pump and then filling it with the test gas at the operating pressure. The pressure P_i was established at a value that would assure operation of the flowmetering equipment at approximately atmospheric pressure when a long series of runs was anticipated. In this case, there was essentially no pressure difference acting on the flowmeter volume chamber during operation.

The voltage to the furnace was adjusted to establish thermal equilibrium of the capillary tube at the desired temperature. The high thermal lag of the diatomaceous earth in the furnace tended to maintain a stable temperature throughout any one run with a minimum of recourse to manual adjustment of the autotransformer.

Temperature increments of approximately 100° C from room temperature up to 1,100° C were used. The tests at 0° C were made with the mounted

capillary coil removed from the furnace and submerged in an ice bath. Viscosity determinations at the lower temperatures were made in groups of not more than 10 at one temperature level; however, at temperatures above 700° C not more than three runs were made at any one temperature level. This procedure was adopted to reduce the operating time of the capillary tube at elevated temperatures.

When thermal equilibrium was indicated in the furnace, the flowmeter was charged with mercury. After the pressure in the metering chamber increased to atmospheric from the vacuum pressure necessary for charging, the meter discharge valve was opened and a run started.

During a test the following data were recorded:

t	time for flow of gas volume V, sec
$P_i - P_0$	measured pressure difference from inlet to outlet of capillary coil, cm mercury
b	barometric pressure, cm mercury
$P_i - b$	gage pressure at inlet to capillary coil, cm Hg
T_m	average of four capillary thermocouples, °C + 273.2
T_a	ambient temperature, °C + 273.2
V_m	calibrated volume of meter-measuring chamber, cu cm

To determine the effect of water vapor, gas samples 1 and 2 were saturated with water vapor at room temperature. This procedure gave a constant specific humidity over the experimental temperature range and insured the retention of the water vapor in the gaseous state at the outlet of the capillary tube.

RESULTS

The applicability of the Sutherland relationship to a given set of results may be checked by plotting $T_m^{3/2}/\eta$ versus T_m . If the relationship applies to the data, a straight line is obtained. Each of figures 5 to 11 includes the Sutherland plot for one mixture, its viscosity as a function of temperature, and, for comparison, the viscosity of air obtained from reference 11.

The method of least squares was employed to determine the Sutherland constant and η_0 for each gas, and the resulting equations were used for interpolation and extrapolation in preparing table 2.

Table 3 and tables 4 and 5 give some typical data with the magnitude of the corrective terms that were employed.

DISCUSSION

An estimate of the reliability of the values given in table 2 was made by comparing η_0 as computed by a least-square treatment of the averages of all the data against η_0 as determined by experiment. The results of this comparison are shown in table 6.

In establishing the reliability of the method employed and the equipment used, the viscosity of nitrogen was determined during the progress of those experiments. Table 7 shows a comparison of the present experimental values with those listed in reference 12.

Values obtained for the dry-exhaust-gas mixtures, composed almost entirely of nitrogen, oxygen, carbon dioxide, and argon, show a definite relation between the viscosity of the mixture and the percentages of oxygen and carbon dioxide. Figure 12 shows the values of η_0 for various percentages of oxygen and carbon dioxide. Conversely, these charts may be used for obtaining values of η_0 of dry-gas mixtures having known concentrations of oxygen and carbon dioxide (with negligible amounts of carbon monoxide and hydrogen). This procedure has been followed in deriving table 8 for a number of mixtures of arbitrary composition.

The Sutherland constant C in table 8 was based on figure 13, which shows a plot of C versus the oxygen content. The scattering of the C values when plotted against increasing amounts of oxygen is quite noticeable. However, by drawing a straight line between the C value at 0.16 percent oxygen and the C value at 21.0 percent oxygen a good representation of these data is obtained.

In the case of exhaust-gas sample 1, the value $C = 138.3^\circ \text{K}$ was based almost entirely upon the low-temperature data ($T < 1,000^\circ \text{K}$) because, after making some of the high-temperature tests, the capillary was damaged before a check on the tube constant was obtained. This cast a doubt upon the reliability of the high-temperature results. However, if this possible uncertainty is disregarded and the results of the high-temperature tests alone are used, a somewhat higher value of C is obtained.

To express the experimental results on the viscosity of moist air, equation (7) was employed. The constants A_1 and A_2 in equation (7), as determined from the results of the moist-air tests, were found to be

$$A_1 = 0.7380$$

$$A_2 = 0.3862$$

The values used for the viscosity of steam in these calculations and in later determinations are those reported in reference 13.

Using the constants $A_1 = 0.7380$ and $A_2 = 0.3862$, the values of the viscosity of moist air were computed for the experimental values of specific humidity. These values of viscosity are shown as the calculated points in figure 14. Of the experimental results, those at zero and the maximum specific humidity are the most reliable, as the salt-solution method of establishing intermediate humidity values is subject to some uncertainty, because of impurities in the various salts.

In some instances, the properties of exhaust gas and air exhibit the same characteristics which would be expected considering that both gases consist of approximately 79 percent by volume of nitrogen. On the basis of this analysis, equation (7) with the constants A_1 and A_2 as determined from the moist-air experiments was applied to exhaust gases 1 and 2.

$$\eta_{\text{wet}} = \frac{\eta_{\text{dry}}}{1 + (0.7380W)} + \frac{\eta_{\text{H}_2\text{O}}}{1 + (0.3862/W)} \quad (8)$$

where η_{dry} is the experimental dry viscosity of the gas, W is the specific humidity in consistent mass units, $\eta_{\text{H}_2\text{O}}$ is the viscosity of steam as determined earlier, and η_{wet} is the predicted value of the moist gas.

The results of this comparison are shown in tables 9 and 10, where η_{exp} is the experimental value of the viscosity of the moist gas. All the experimental values shown are the average values as determined by a Sutherland analysis. The percent deviation of the predicted value from the experimental value of the moist gas is seen to be less than 1 percent for both gases. This shows that the constants A_1 and A_2 are relatively independent of temperature over the range from 300° to $1,300^\circ$ K, and at present equation (8) is the only known means for estimating the viscosity of exhaust gases at specific humidities above those covered in the present experiments.

It is to be noted that exhaust gas 1 contained 27.10 percent carbon dioxide by volume and exhaust gas 2 contained only 1.99 percent carbon dioxide by volume. This would apparently indicate that the constants A_1 and A_2 are relatively independent of the variations of the principal constituents in the mixture other than nitrogen.

From tables 9 and 10 it is apparent that the ratio of wet viscosity to dry viscosity is approximately the same for mixtures 1 and 2, and as these represent extremes of mixture proportions it seems reasonable that the effect of water vapor on the viscosity of exhaust gases can be taken into account by using the appropriate multiplying factor from tables 9 and 10 or from the curves of figure 15.

CONCLUDING REMARKS

The viscosities of some dry-exhaust-gas mixtures have been determined experimentally over the temperature range from 0° C up to approximately $1,100^{\circ}$ C at pressures so near to 1 atmosphere that the effect of changes in pressure was negligible. Except for moisture content, these mixtures cover the range of compositions encountered in efficient turbojet burners as well as larger variations in the concentration of oxygen and carbon dioxide.

A Sutherland analysis has been made of the results over the experimental temperature range. This analysis shows that the deviation from the Sutherland equation does not exceed 1 percent for any mixture studied. The equations derived from this analysis have been used to extrapolate the results up to $1,300^{\circ}$ C, with an estimated uncertainty of less than 2 percent.

Equations for gas mixtures of intermediate compositions may be derived from the data to take account of the effects of varying proportions of oxygen and carbon dioxide upon the viscosity at 0° C and the Sutherland constant in the Sutherland equation.

Some effects of moisture on the viscosity of the mixtures are predicted from an analysis of results with moist air. However, the total moisture content of these mixtures was so low as compared with actual products of combustion that the application of the present results to the latter is questionable.

To check the utility of this Sutherland equation, it was used to compute the effect of water vapor upon the viscosity of two exhaust-gas samples. The computed values agreed with the results of experimental determinations within less than 1 percent. It is suggested that the

equation may be used for calculating the viscosity of exhaust gases over the temperature range from 0° up to $1,300^{\circ}$ C.

The effect of small amounts of water vapor on the viscosity of exhaust gases was found to be relatively independent of variations in other constituents.

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Washington, D. C., March 3, 1953.

REFERENCES

1. White, C. M.: Streamline Flow Through Curved Pipes. Proc. Roy. Soc. (London), ser. A., vol. 123, Feb. 1, 1929, pp. 645-663.
2. Vasilescu, Virgile: Recherches experimentales sur la viscosite des gaz aux temperatures elevees. Ann. Phys., ser. 11, t. 20, May-June 1945, pp. 137-176, 292-334.
3. Knudsen, Martin: Die Gesetze der Molekularströmung und innere Reibungsströmung der Gase. Ann. Phys., Folge 4, Bd. 28, Heft 1, 1909, pp. 75-130.
4. Chapman, S.: On the Law of Distribution of Molecular Velocities, and on the Theory of Viscosity and Thermal Conduction, in a Non-uniform Simple Monatomic Gas. Phil. Trans. Roy. Soc. (London), ser. A., vol. 216, May 26, 1916, pp. 279-345.
5. Maxwell, J. C.: Illustrations of the Dynamical Theory of Gasses - Part I. On the Motions and Collisions of Perfectly Elastic Spheres. London, Edinburgh, and Dublin Phil. Mag. and Jour. Sci., ser. 4, vol. 19, no. 5, Jan. 1860, pp. 19-32.
6. Maxwell, J. C.: On the Viscosity or Internal Friction of Air and Other Gases. Phil. Trans. Roy. Soc. (London), ser. A, vol. 156, Feb. 1866, pp. 249-268.
7. Sutherland, William: The Viscosity of Gases and Molecular Force. London, Edinburgh, and Dublin Phil. Mag. and Jour. Sci., ser. 5, vol. 36, no. 223, Dec. 1893, pp. 507-531.
8. Westmoreland, J. C.: A Meter for Timing the Flow of Very Small Volumes of a Gas. NACA RM 52I09, 1952.
9. Roeser, Wm. F., Dahl, A. I., and Gowens, G. J.: Standard Tables for Chromel-Alumel Thermocouples. Res. Paper RP767, Jour. Res., Nat. Bur. Standards, vol. 14, no. 3, Mar. 1935, pp. 239-246.
10. Anon.: Engineering Properties of Inconel. Bull. T-7, Development and Res. Div., The Int. Nickel Co., Inc., revised Apr. 1946.
11. Morey, F. C.: Coefficient of Viscosity of Dry Air. NBS-NACA Tables of Thermal Properties of Gases, Table 2.39, Dec. 1950.
12. Touloukian, V. S., and Hilsenrath, J.: Coefficient of Viscosity of Nitrogen. NBS-NACA Tables of Thermal Properties of Gases, Table 11.39, Oct. 1952.

13. Touloukian, Y. S., and Hilsenrath, J.: Coefficient of Viscosity of Steam. NBS-NACA Tables of Thermal Properties of Gases, Table 4.39.

TABLE 1
COMPOSITION OF GAS MIXTURES

Exhaust gas	Nitrogen, percent by volume	Carbon dioxide, percent by volume	Oxygen, percent by volume	Carbon monoxide, percent by volume	Argon, percent by volume
1	71.10	27.10	0.16	---	1.58
2	79.30	1.99	17.72	---	1.00
3	79.30	4.90	14.00	0.8	1.00
4	77.90	10.08	10.50	---	1.58
5	78.77	14.51	5.72	---	1.00

TABLE 2

VISCOSITY OF EXHAUST-GAS SAMPLES

Sample	C, °K	η_0 , poise	η/η_0 for T_m , °K, of -												
			300	400	500	600	700	800	900	1,000	1,100	1,200	1,300	1,400	1,500
1	138.3	$1,628 \times 10^{-7}$	1.080	1.354	1.596	1.814	2.013	2.202	2.370	2.532	2.685	2.831	2.970	3.103	3.232
1-S	170.8	1,590	1.085	1.378	1.639	1.875	2.091	2.292	2.480	2.656	2.823	2.982	3.134	3.279	3.419
2	133.6	1,694	1.080	1.351	1.590	1.805	2.002	2.184	2.353	2.513	2.664	2.808	2.946	3.077	3.204
2-S	132.8	1,724	1.080	1.350	1.589	1.803	2.000	2.181	2.351	2.510	2.661	2.805	2.942	3.073	3.199
3	119.5	1,687	1.077	1.339	1.570	1.710	1.965	2.140	2.303	2.457	2.602	2.740	2.872	2.998	3.120
4	140.5	1,659	1.077	1.356	1.599	1.819	2.019	2.205	2.378	2.541	2.695	2.842	2.982	3.116	3.245
5	161.3	1,637	1.084	1.372	1.618	1.858	2.069	2.265	2.448	2.621	2.796	2.939	3.087	3.229	3.366

TABLE 3
EXHAUST GAS 4

[Viscosimeter No. 23.73-10]

Test	P _i , cm Hg	T _m , °K	η, poise
2	101.14	298.8	1,823 × 10 ⁻⁷
3	101.21	298.7	1,817
4	101.02	298.7	1,814
6	101.39	450.6	2,461
7	101.44	450.0	2,449
8	101.35	449.7	2,425
9	100.64	556.9	2,864
10	100.63	567.2	2,859
11	100.63	567.8	2,870
1	101.84	656.4	3,172
2	101.50	656.7	3,172
3	101.09	656.9	3,169
4	100.30	818.1	3,671
5	101.24	817.4	3,686
6	101.13	816.7	3,679
7	100.72	924.1	4,060
8	101.00	928.8	4,043
9	100.95	930.5	4,080
1	101.18	1,040.8	4,315
2	101.14	1,038.0	4,310
3	100.95	1,035.8	4,299
4	100.53	1,138.9	4,572
5	100.70	1,139.1	4,597
6	100.67	1,140.8	4,622
1	99.38	1,247.8	4,793
2	101.11	1,252.8	4,857
1	76.41	293.6	1,793
2	76.41	293.6	1,792
1	75.54	273.2	1,673
2	75.54	273.2	1,676
3	75.54	273.2	1,675

TABLE 4
VISCOSITY OF NITROGEN

[$P_i = 91.35$ cm Hg]

Test	$T_m,$ °K	Uncorrected viscosity	Slip correction factor	Thermal expansion factor	Viscosity poise
1	881.7	3,625	1.0056	1.0268	$3,743 \times 10^{-7}$
2	884.4	3,640	1.0056	1.0269	3,759
3	886.8	3,662	1.0057	1.0270	3,782
4	889.1	3,693	1.0057	1.0273	3,815

TABLE 5
VISCOSITY OF EXHAUST GAS 4

$$[P_i = 100.70 \text{ cm Hg}]$$

Test	T_m , °K	Uncorrected viscosity	Slip correction factor	Thermal expansion factor	Viscosity, poise
1	1,040.8	4,138	1.0067	1.036	$4,315 \times 10^{-7}$
2	1,038.0	4,133	1.0067	1.036	4,310
3	1,035.8	4,122	1.0067	1.036	4,299
4	1,138.9	4,351	1.0074	1.043	4,572
5	1,139.1	4,375	1.0074	1.043	4,597
6	1,140.8	4,399	1.0074	1.043	4,622

TABLE 6
 EXPERIMENTAL AND CALCULATED VALUES OF η_0

Gas sample	C, °K	Experimental η_0 , poise	Calculated η_0 , poise	Percent deviation
1	138.3	$1,618 \times 10^{-7}$	$1,628 \times 10^{-7}$	0.62
1-S	170.8	Indeterminate	1,590	----
2	133.6	1,706	1,694	-.70
2-S	132.8	Indeterminate	1,724	----
3	119.5	1,691	1,687	-.24
4	140.5	1,675	1,660	-.90
5	161.3	1,649	1,637	-.73

TABLE 7
 VISCOSITY OF NITROGEN AT 1 ATMOSPHERE

$T_m,$ °K	$\eta_{exp},$ poise	$\eta_{ref},$ poise	Percent departure, $\frac{\eta_{exp} - \eta_{ref}}{\eta_{exp}}$
273.2	$1,662 \times 10^{-7}$	$1,662.5 \times 10^{-7}$	-0.03
293.7	1,771	1,777	-.34
357.5	2,058	2,032	1.28
400.3	2,231	2,204	1.23
444.4	2,393	2,374	.80
745.0	3,387	3,368	.56
884.4	3,759	3,773	-.37
978.7	4,027	4,033	.15
1,035.0	4,190	4,185	.12

TABLE 8
 VISCOSITY OF DRY-EXHAUST-GAS MIXTURES FROM
 0° TO 1,300° C

$$\left[\eta = \eta_0 \left(\frac{T}{273.2} \right)^{3/2} \left(\frac{C + 273.2}{C + T} \right) \right]$$

Inert nitrogen and argon, percent by volume	Carbon dioxide, percent by volume	Oxygen, percent by volume	η_0 , poise	C, °K
75.0	23.0	2.0	$1,628 \times 10^{-7}$	166.2
77.8	18.2	4.0	1,640	161.4
79.8	14.2	6.0	1,651	156.6
79.8	12.2	8.0	1,662	151.8
79.6	10.4	10.0	1,672	146.9
80.3	7.7	12.0	1,682	142.0
81.3	4.7	14.0	1,692	137.1
80.7	3.3	16.0	1,698	132.3
80.2	1.8	18.0	1,705	127.5
79.5	.5	20.0	1,713	122.7
79.0	0	21.0	1,716	120.0

TABLE 9

EXHAUST GAS 1

$[W = 0.01456]$

T, °K	η_{dry} , poise	η_{wet} , poise	η_{exp} , poise	Percent deviation	$\frac{\eta_{wet}}{\eta_{dry}}$
300	^a $1,723 \times 10^{-7}$	$1,740 \times 10^{-7}$	$1,732 \times 10^{-7}$	0.462	1.010
500	2,599	2,633	2,606	1.036	1.013
700	3,278	3,331	3,326	.150	1.016
900	3,858	3,932	3,943	-.279	1.019
1,100	4,371	4,469	4,489	-.446	1.022
1,300	4,835	4,952	4,983	-.622	1.024
1,500	5,261	5,393	5,437	-.809	1.025

^aActual datum.

TABLE 10
EXHAUST GAS 2

[W = 0.0154]

$T, \text{ } ^\circ\text{K}$	$\eta_{\text{dry}}, \text{ poise}$	$\eta_{\text{wet}}, \text{ poise}$	$\eta_{\text{exp}}, \text{ poise}$	Percent deviation	$\frac{\eta_{\text{wet}}}{\eta_{\text{dry}}}$
300	$1,829 \times 10^{-7}$	$1,836 \times 10^{-7}$	$1,861 \times 10^{-7}$	-0.806	1.009
500	2,692	2,727	2,739	-.438	1.013
700	3,390	3,445	3,448	-.087	1.016
900	3,986	4,063	4,053	.247	1.019
1,100	4,512	4,614	4,588	.567	1.022
1,300	4,988	5,110	5,072	.749	1.024
1,500	5,426	5,563	5,516	.852	1.025

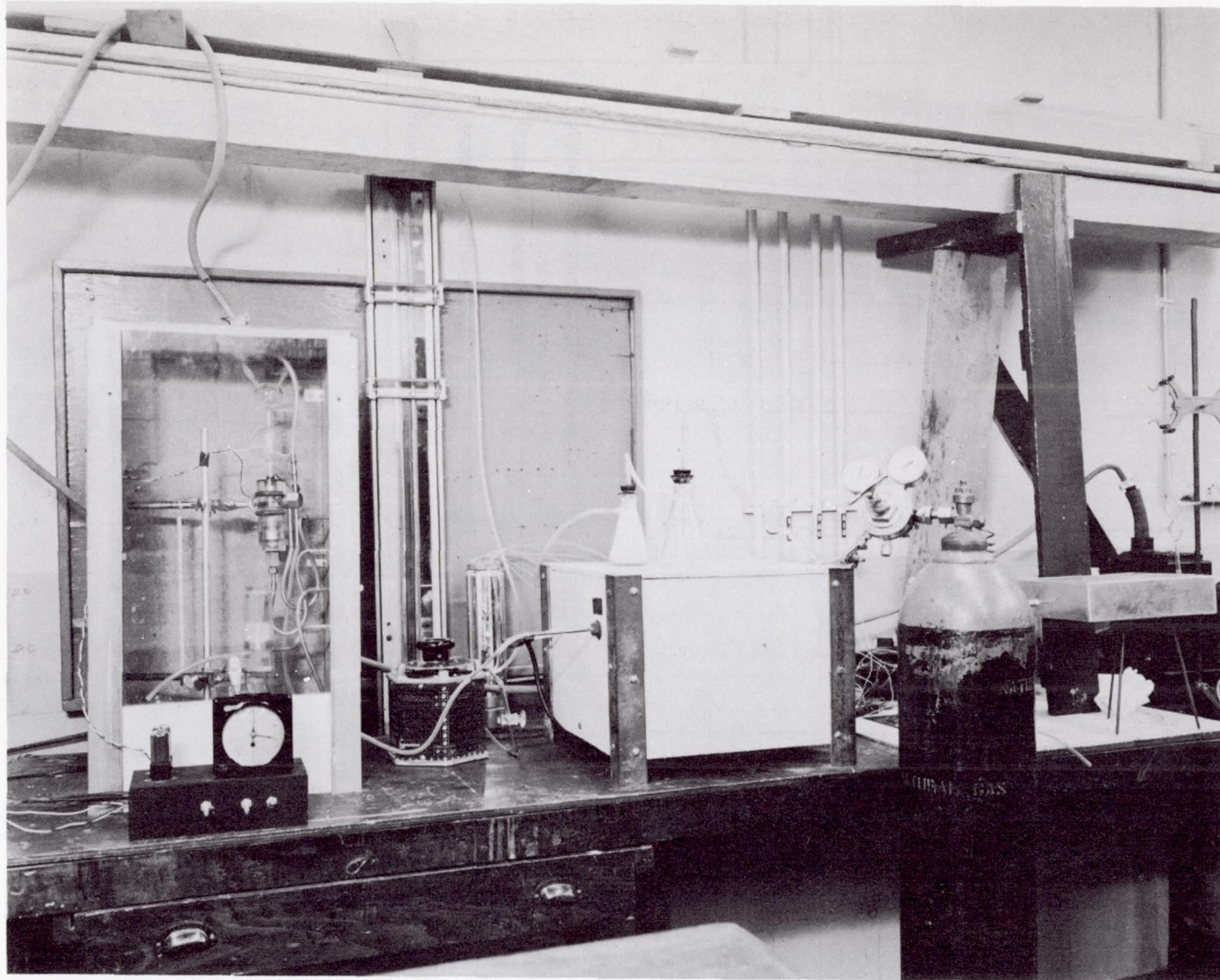


Figure 1.- Apparatus for testing viscosity of high-temperature gases. L-82076

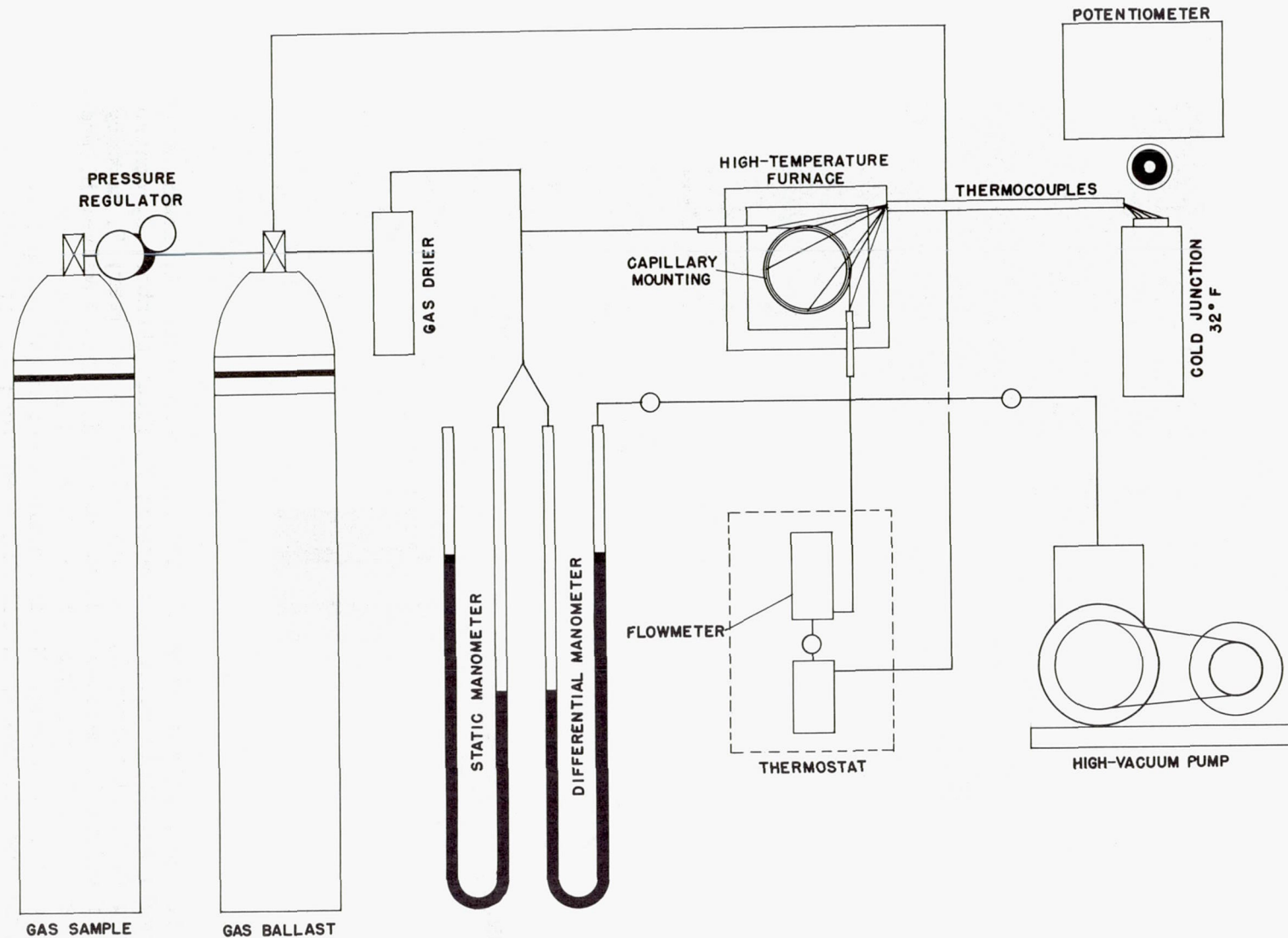


Figure 2.- Schematic diagram of high-temperature viscosimeter.

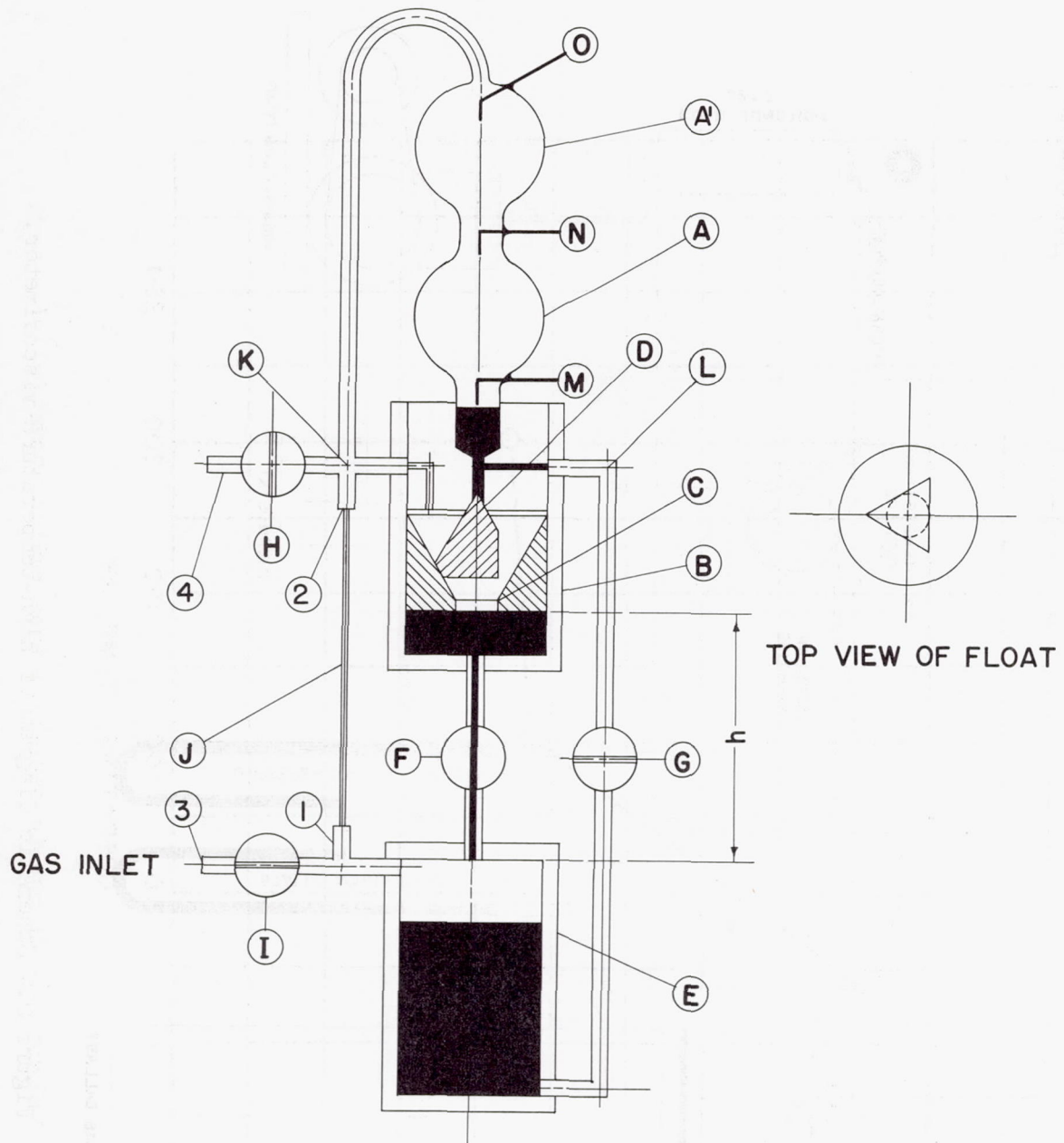


Figure 3.- Schematic diagram of flowmeter regulator. A, lower metering chamber; A', upper metering chamber; B, float chamber; C, control float; D, float valve; E, mercury-collection chamber; F, mercury cutoff valve; G, mercury filling valve; H, exhaust valve; h, pressure differential; I, gas inlet tube; J, capillary tube; K, meter inlet connection; L, mercury filling connection; M, stopping electrode; N, starting electrode; O, filling electrode; 1, capillary inlet; 2, capillary outlet; 3, gas inlet connection; and 4, vacuum connection.

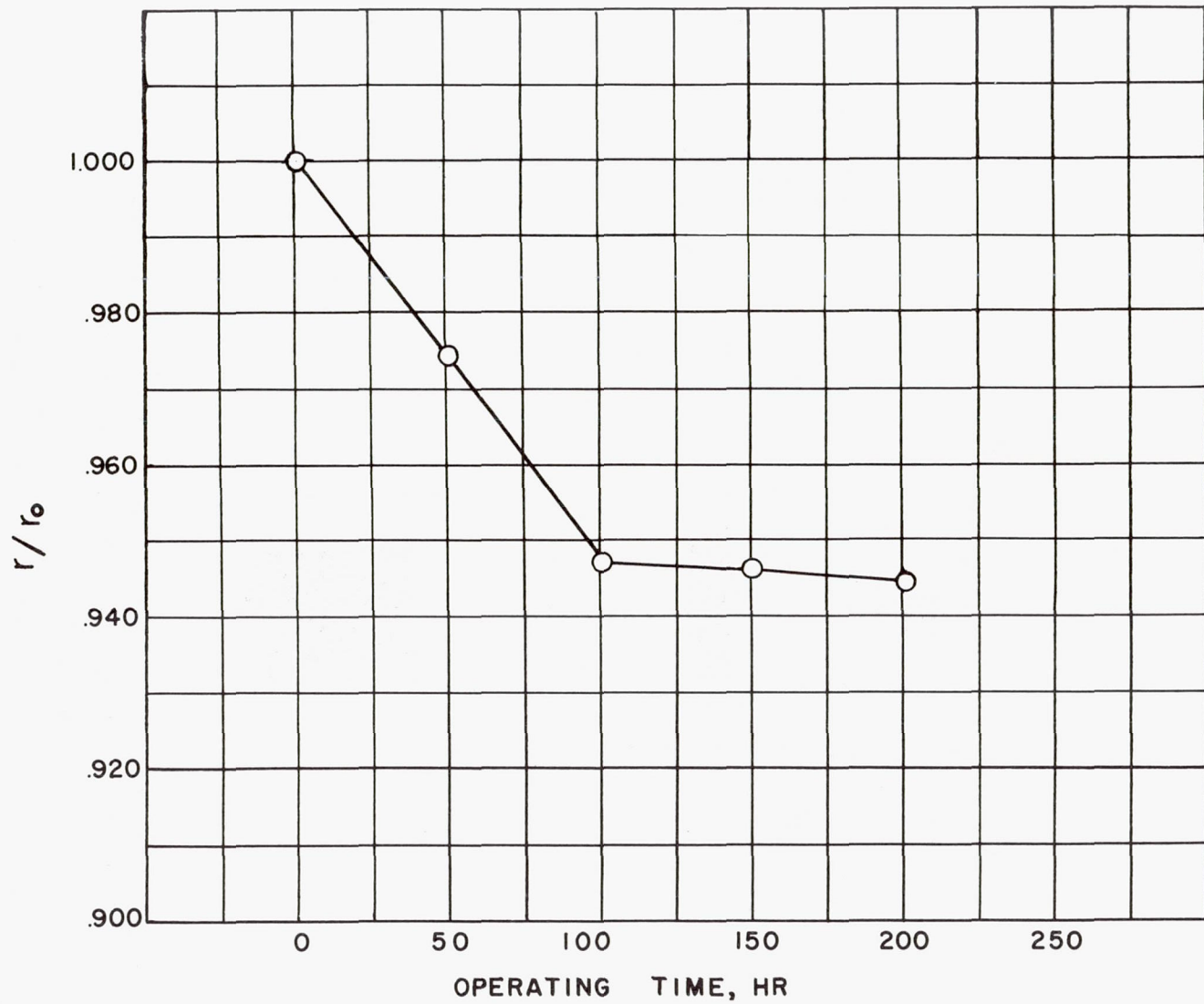


Figure 4.- Change in capillary tube radius above 760° C.

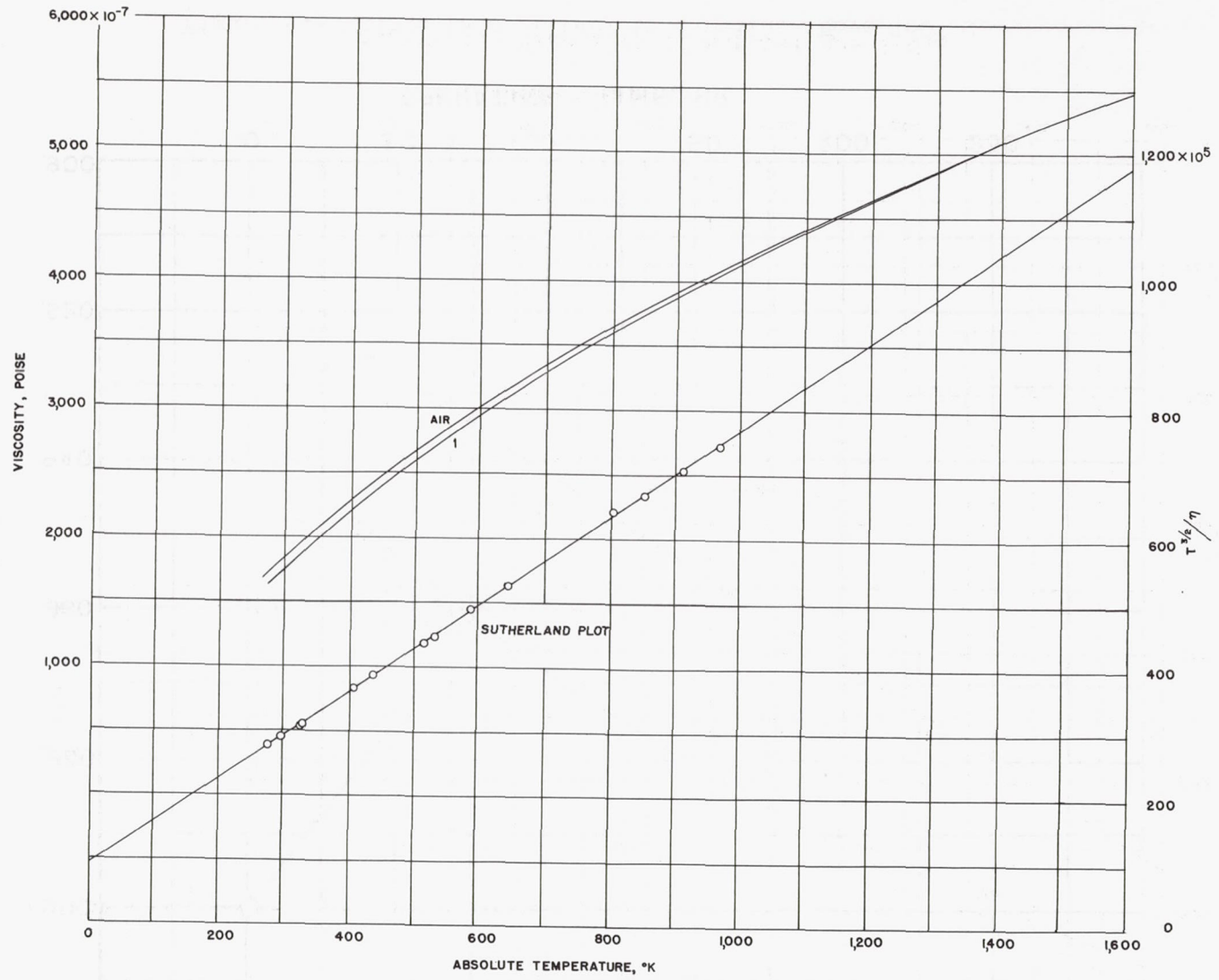


Figure 5.- Viscosity of exhaust gas 1.

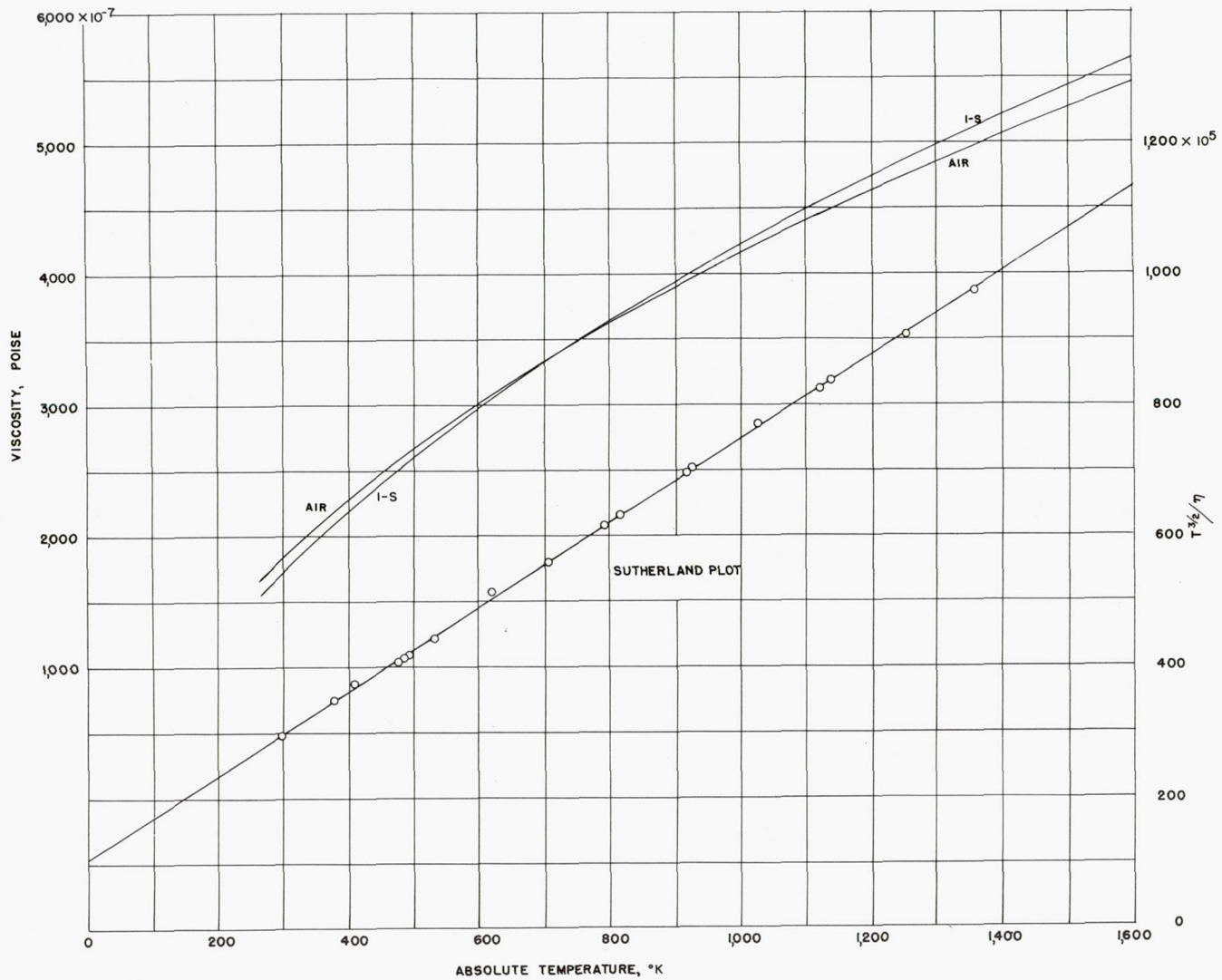


Figure 6.- Viscosity of exhaust gas 1-S.

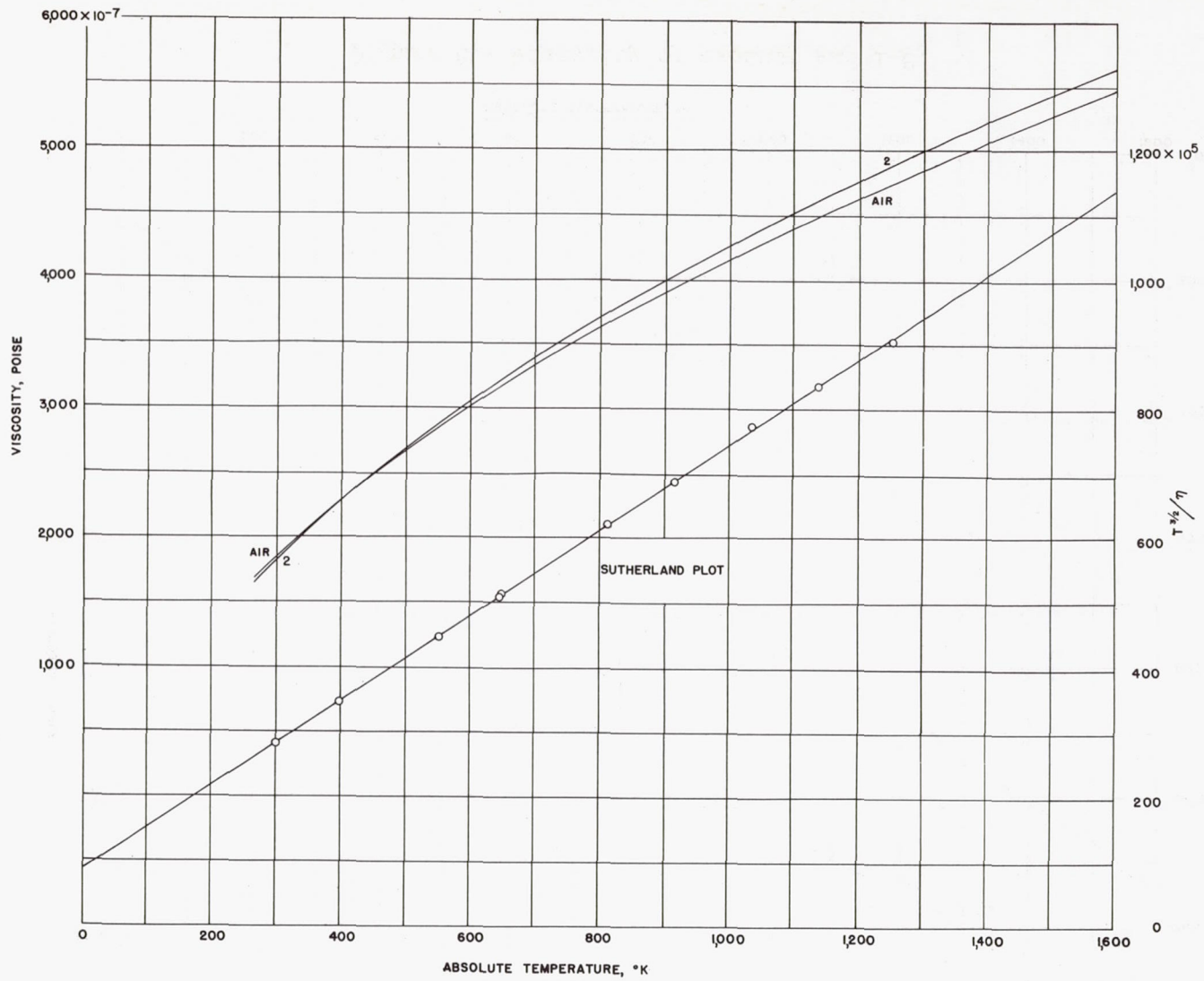


Figure 7.- Viscosity of exhaust gas 2.

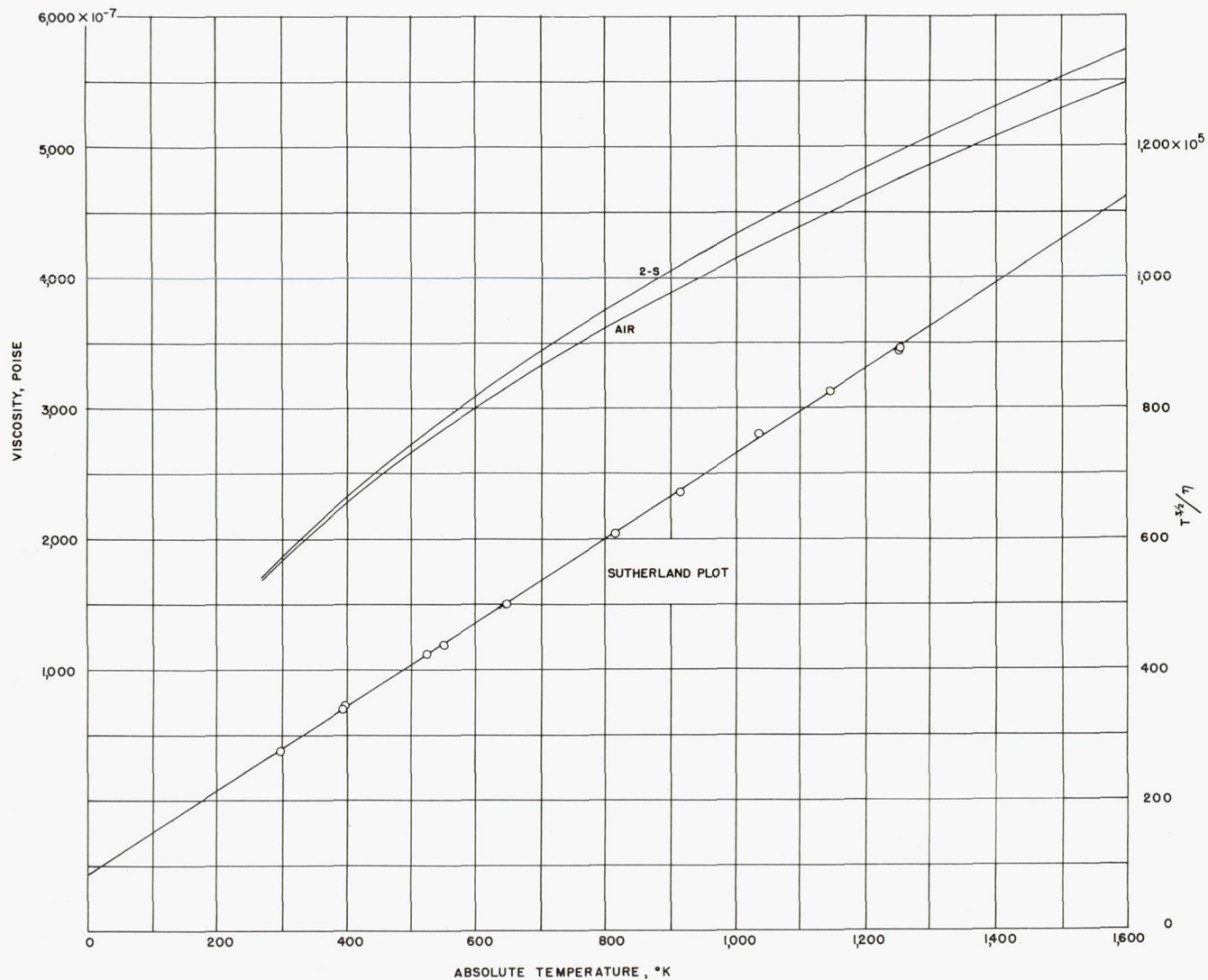


Figure 8.- Viscosity of exhaust gas 2-S.

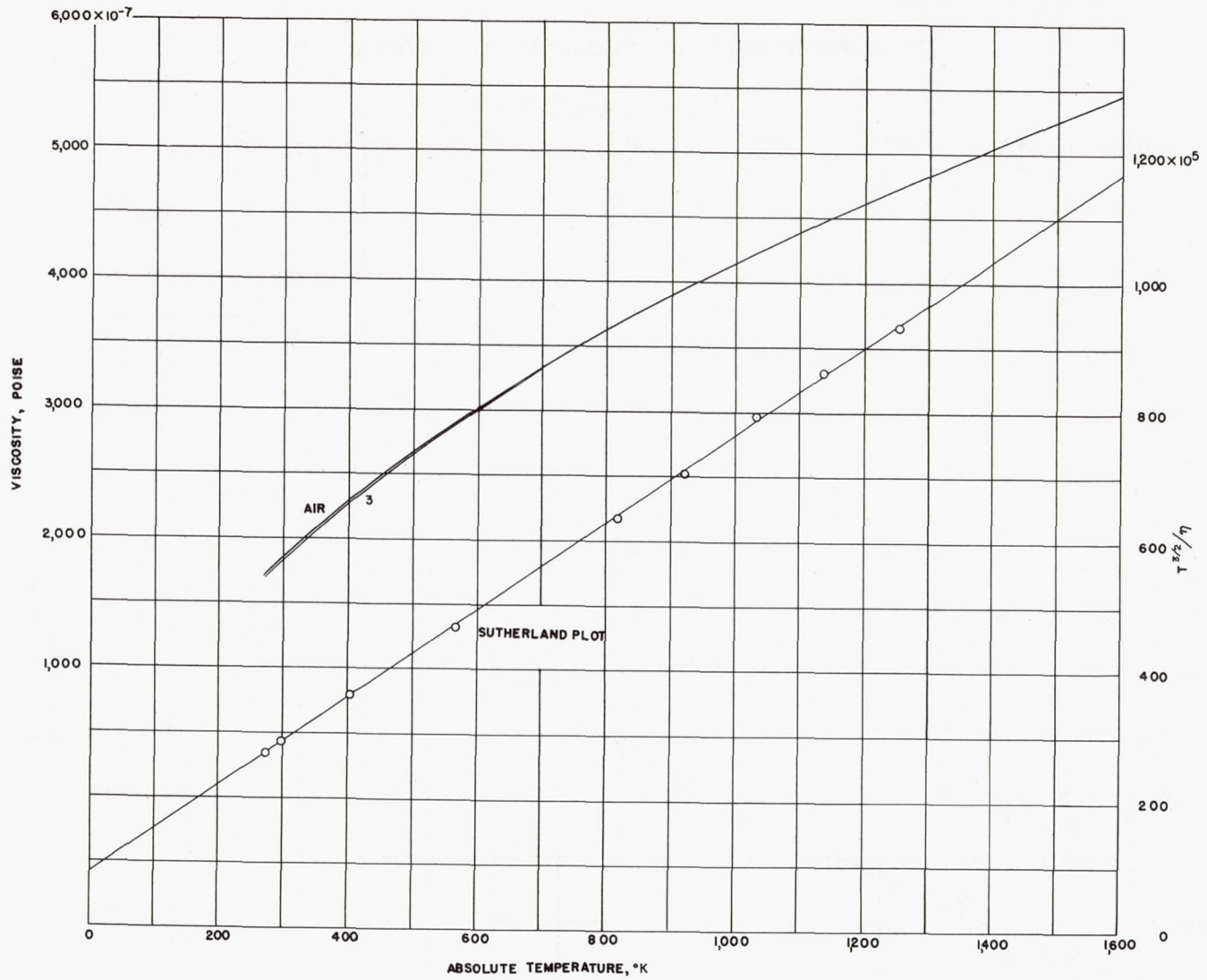


Figure 9.- Viscosity of exhaust gas 3.

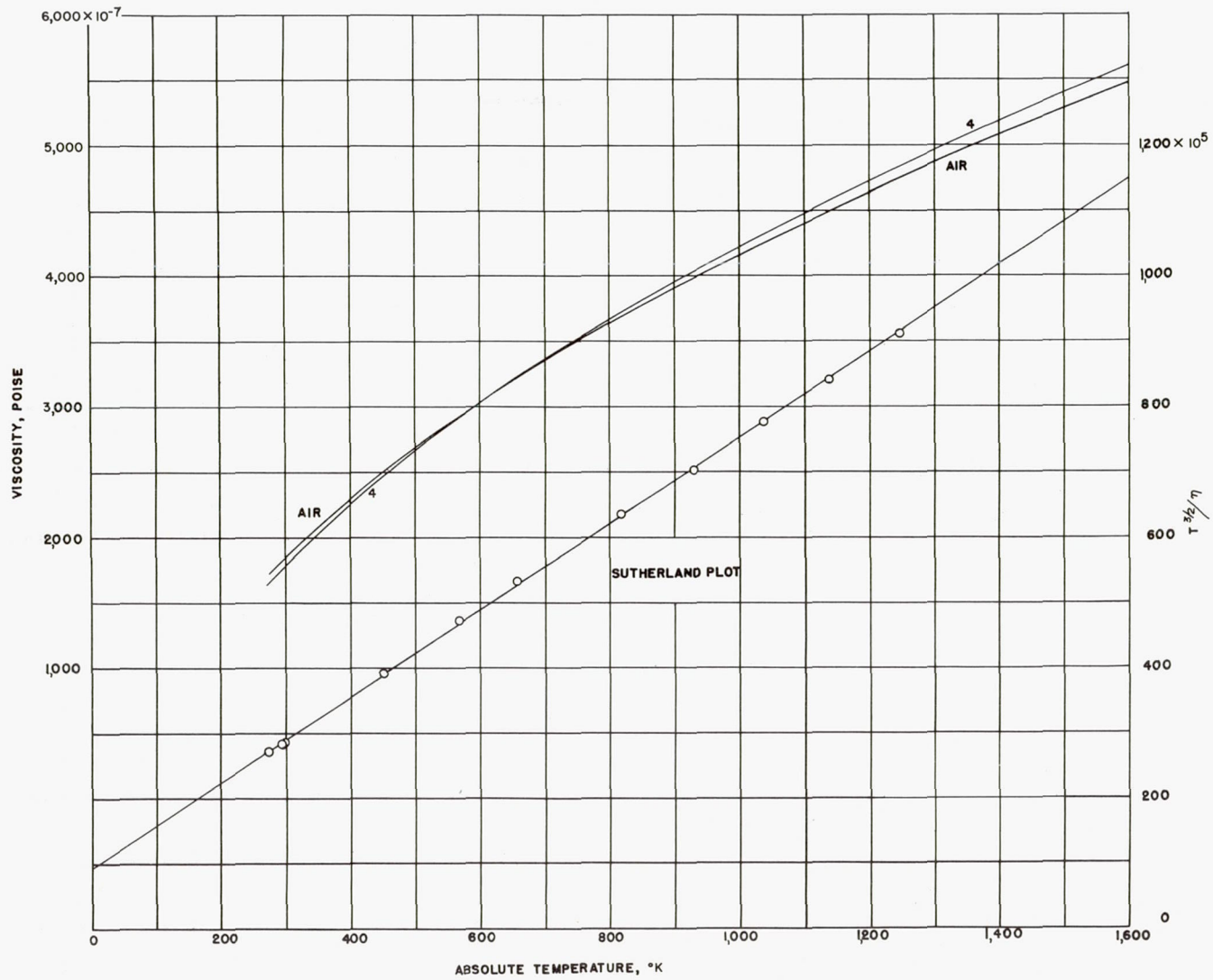


Figure 10.- Viscosity of exhaust gas 4.

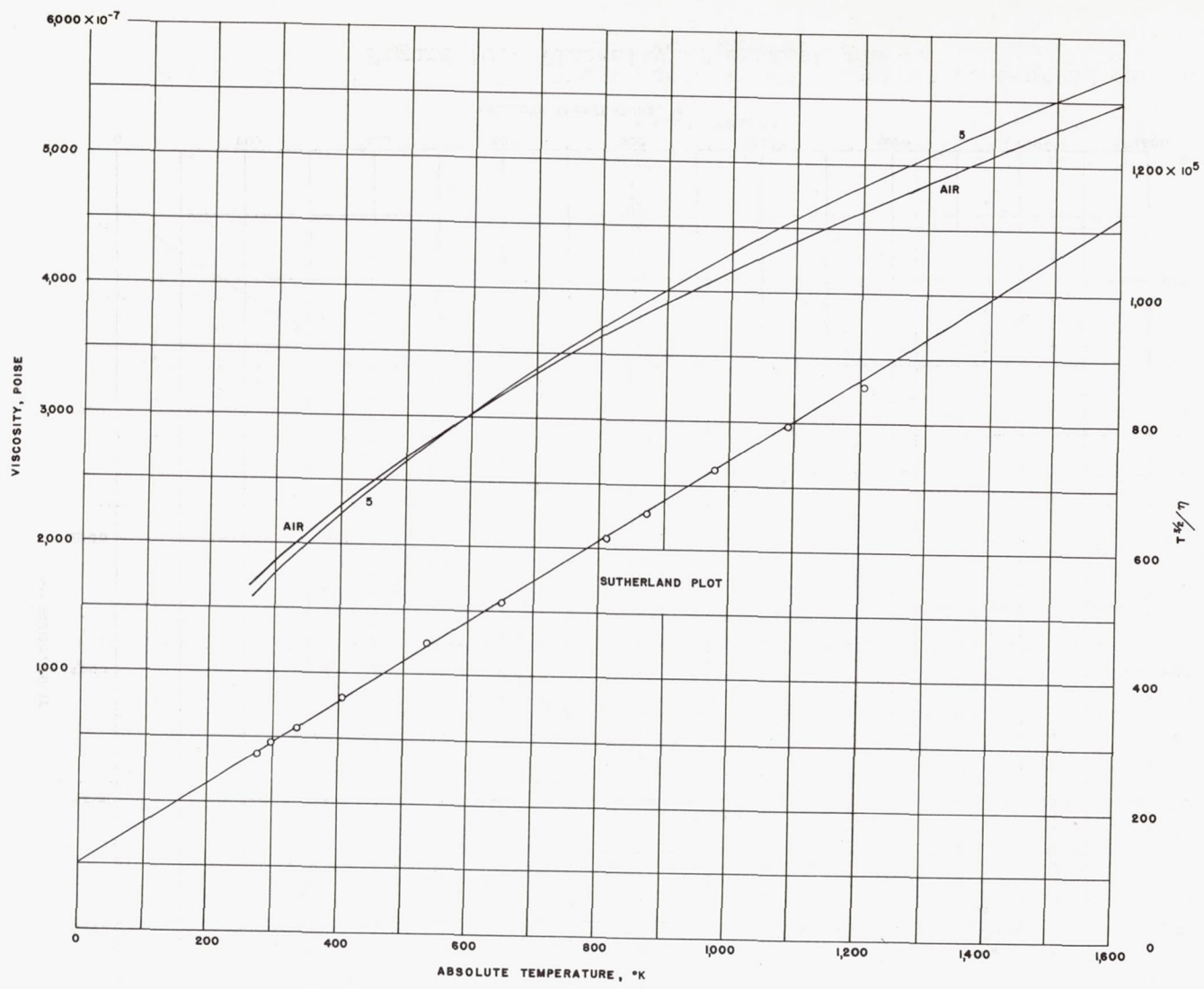


Figure 11.- Viscosity of exhaust gas 5.

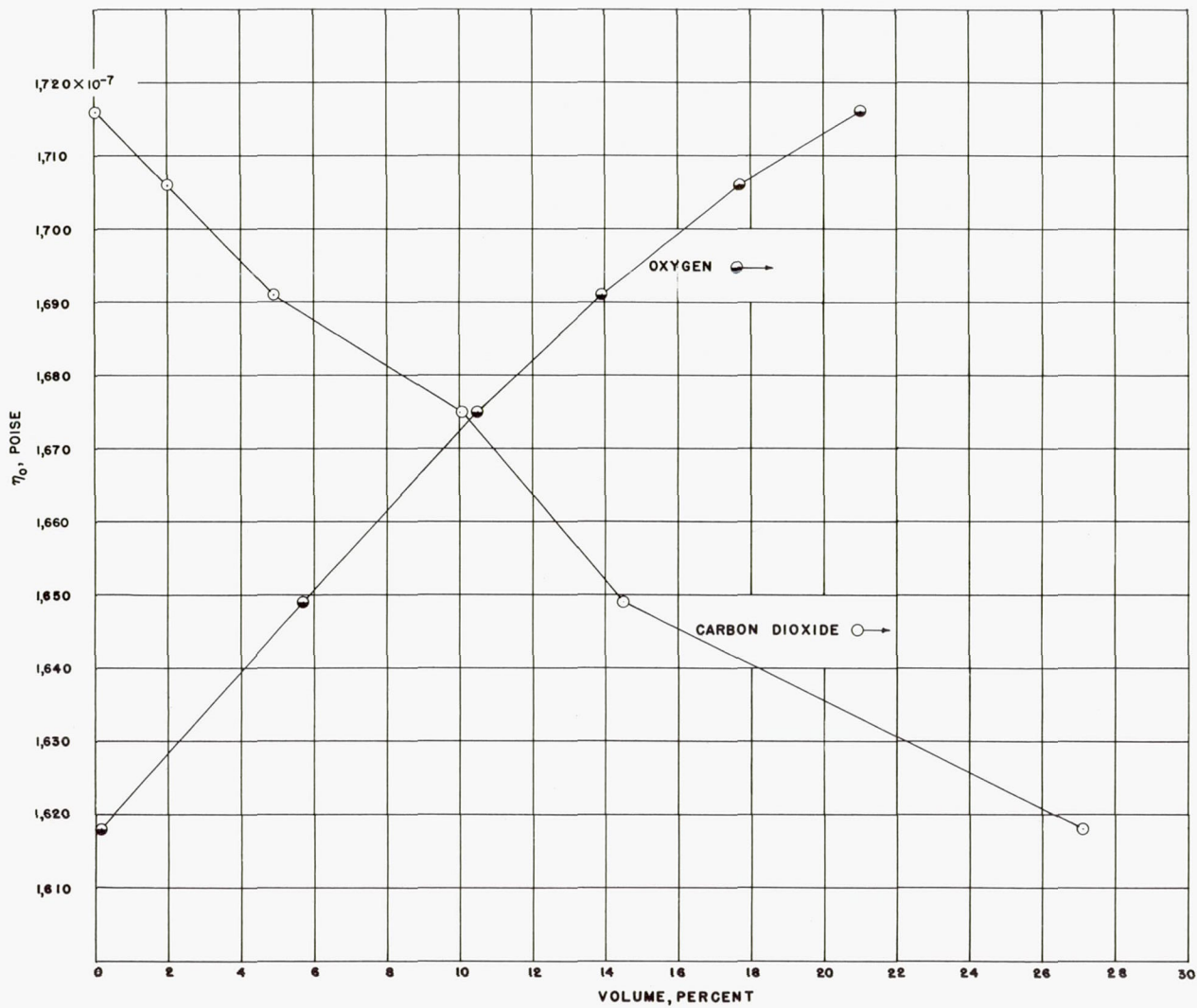


Figure 12.- Viscosity of exhaust gases at 0°C against content of carbon dioxide and oxygen.

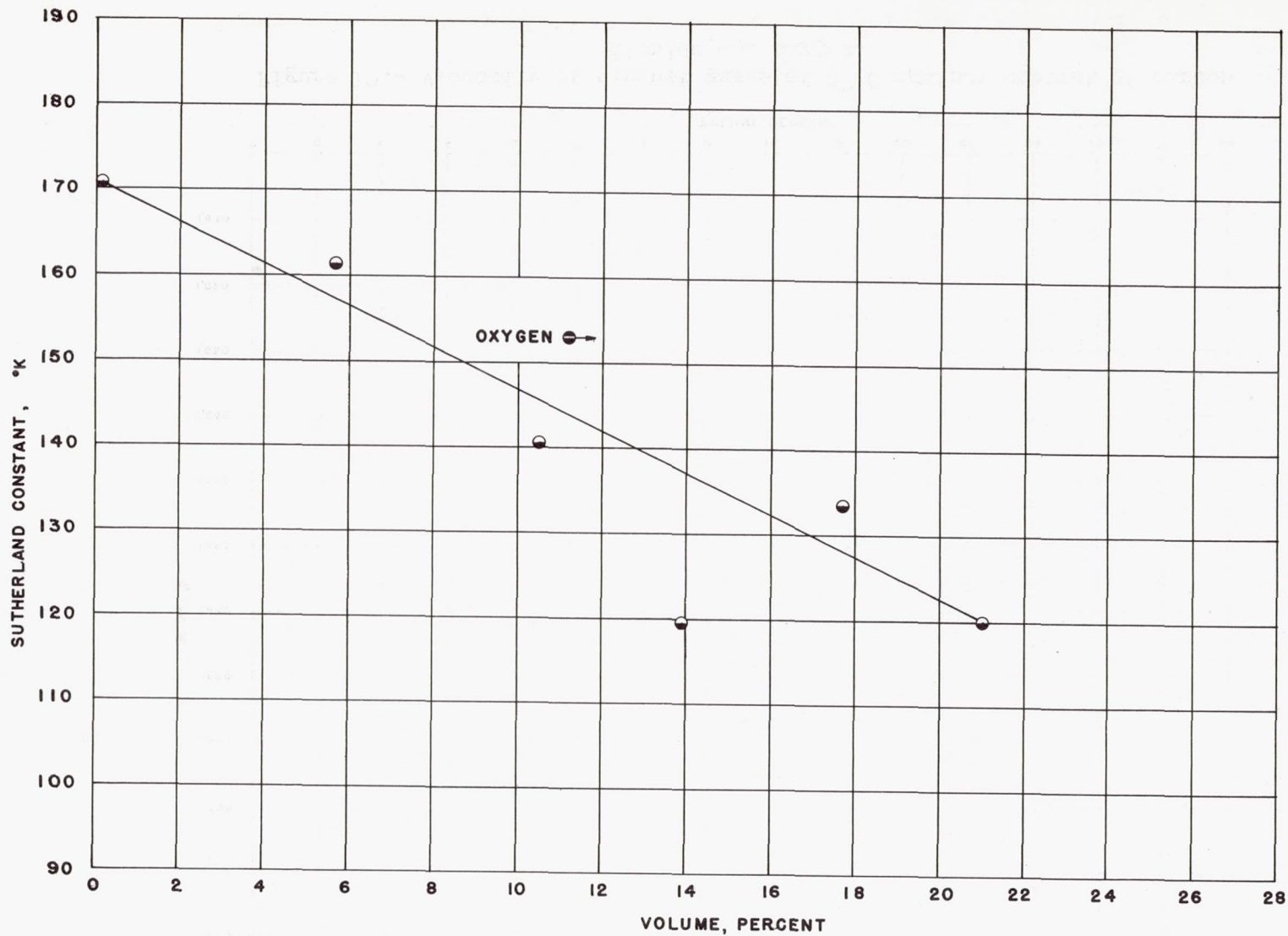


Figure 13.- Sutherland constant against oxygen content.

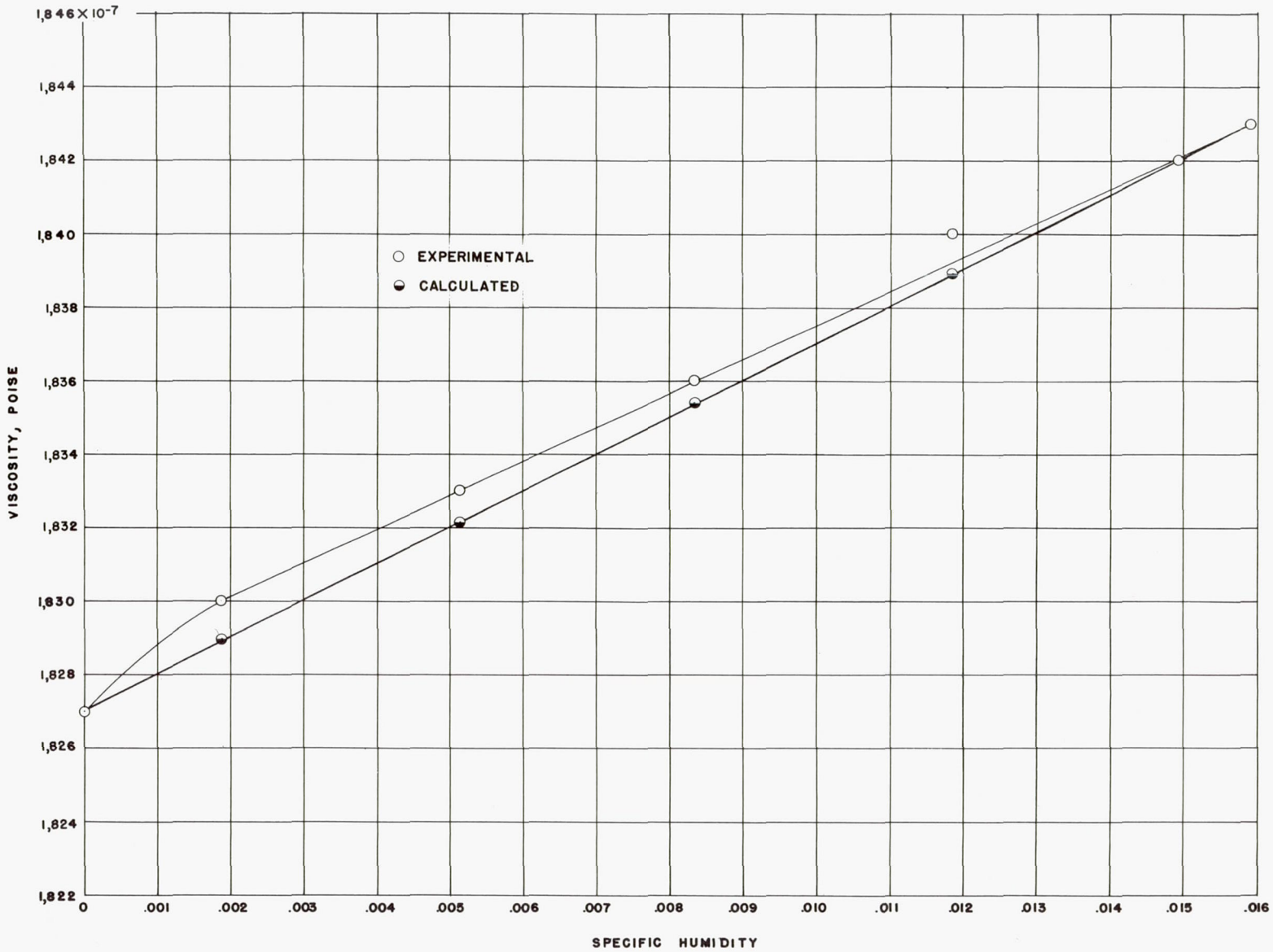


Figure 14.- Viscosity of moist air against specific humidity at 21.2° C.

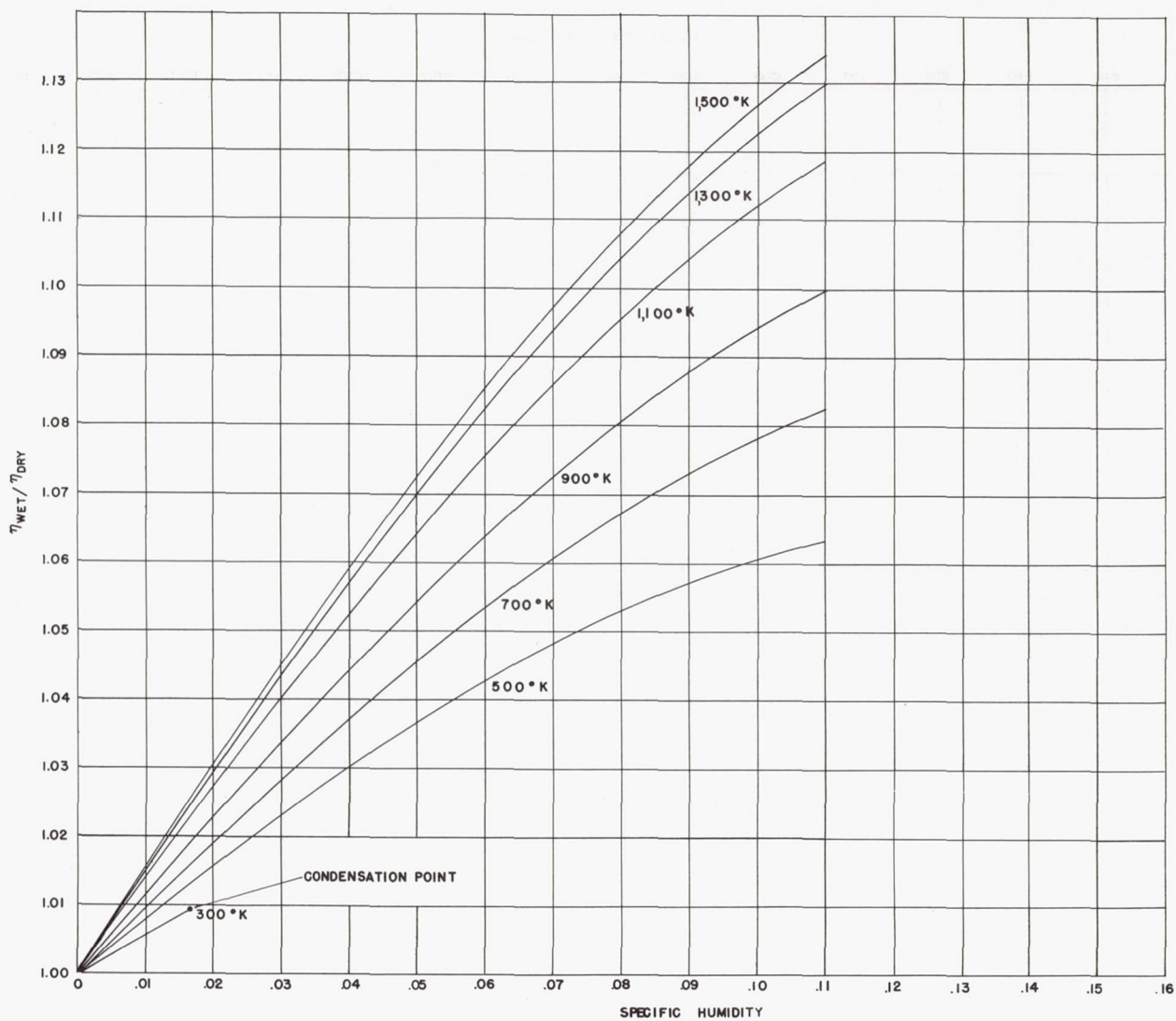


Figure 15.- Effect of water vapor on viscosity of exhaust gases.