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A COMPARISON OF THE AVAILABLE VISCOSITY DATA OF  
HIGH PRESSURE AND HIGH TEMPERATURE STEAM WITH  
A MODIFIED REINGANUM'S EQUATION FOR VISCOSITY

A THESIS

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## SUMMARY

A semi-empirical equation for calculating the viscosity of high-density steam is presented. Reinganum's equation for viscosity has been modified to include the high density regime.

Results of the present study were compared to the experimental findings of Timrot, Khlopkina, Schmidt, Mayinger, Whitelaw and Barnett. The average deviation of the equation from the experimental data is 2.3 percent, and the maximum deviation is approximately six percent.

## CHAPTER I

### INTRODUCTION

#### Definition of the Problem

Pressure and temperature limits of modern steam power plants are constantly increasing with the state of the art. Thermodynamic and transport properties are required in many engineering calculations concerning physical processes such as fluid flow and heat transfer. In calculating the Reynolds, Prandtl or the Grashof number, the values of viscosity are needed.

At the present time, very little viscosity data exist in the high density region recently made available for commercial exploitation by the increased state of the art. Design calculations for new high pressure power plants make it very desirable to have an equation which can estimate the viscosity in the high density region.

#### History

Steam viscosity above the critical point has been measured and reported by Hawkins, Solberg and Potter (1), Sigwart (2), Timrot (3), Timrot and Khlopkina (4), Schmidt and Mayinger (5), Thomas and Jackson (6), and Barnett (7). Because there are still discrepancies between the experimental results and empirical equations, it is desirable to obtain an equation with some theoretical significance.

Purpose of this Study

It was the purpose of this study to derive an equation defining the viscosity of steam in the supercritical region which could be applied to general engineering calculations.

## CHAPTER II

## THE CONCEPT OF VISCOSITY FOR DILUTE GASES

The classical view of the viscosity of gases is based on the Kinetic theory. The first analysis of viscosity from the point of view of the Kinetic theory was due to Maxwell in 1860 (8). It was his conclusion that the viscosity is proportional to the number of molecules per unit volume, the mean velocity of the molecules, the mass of the individual molecule, and the mean free path of the molecules. Mathematically stated Maxwell's solution is:

$$\mu = \frac{1}{3} NM\bar{C}L \quad (1)$$

where:  $\mu$  = viscosity  
 $N$  = number of molecules per unit volume  
 $M$  = Mass of the individual molecule  
 $\bar{C}$  = velocity of the molecules  
 $L$  = mean free path of the molecules

Equation (1) has a degree of uncertainty because of the averaging techniques used in determining the constant,  $1/3$ . Chapman's analysis of the mean collision frequency gave a constant in Equation (1) of 0.499.

In Maxwell's deduction for viscosity, he assumed no attractive forces existing between the molecules. The first one to consider the attractive forces in studying the mean free path, which affects the coefficient of viscosity, was Sutherland. His analysis of the mean free

path resulted in an equation as follows:

$$L = \frac{1}{\sqrt{2} \pi N \sigma_o^2 \left(1 + \frac{K}{T}\right)} \quad (2)$$

where:  $\pi = 3.1416$

$N =$  number of molecules per unit volume

$\sigma_o =$  diameter of molecule

$K =$  Sutherland's constant

$T =$  absolute temperature

Therefore, Sutherland's analysis with Chapman's constant gave the following equation for viscosity:

$$\mu = \frac{0.499 M \bar{C}}{\sqrt{2} \pi \sigma_o^2 \left(1 + \frac{K}{T}\right)} \quad (3)$$

since

$$C \propto \sqrt{T} .$$

Sutherland's equation expressed  $\mu$  as a function of temperature only if the diameter of the molecule remains a constant, or

$$\mu = \mu_o \sqrt{\frac{T}{T_o}} \left[ \frac{1 + \frac{K}{T_o}}{1 + \frac{K}{T}} \right] \quad (4)$$

where  $\mu$  is the coefficient at  $T$ , and  $\mu_o$  is the coefficient at  $T_o$ .

Reinganum considered attractive forces between the molecules on the basis of the concentration of the particles in a given region; his analysis lead to the following expression of the mean free path,

$$L = \frac{1}{\sqrt{2} \pi N_0 \sigma_0^2 e^{\frac{K}{T}}} \quad (5)$$

Reinganum's equation, therefore, can be stated,

$$\mu = \frac{0.499 \rho \bar{C}}{\sqrt{2} \pi N_0 \sigma_0^2 e^{\frac{K}{T}}} \quad (6)$$

where:  $\rho$  = density and

$$e = 2.71828. . . .$$

It can be shown that if the first two terms in the exponential series for  $e^{\frac{K}{T}}$  are substituted into Reinganum's equation, this equation will then reduce to Sutherland's equation.

## CHAPTER III

## DERIVATION OF SEMI-EMPIRICAL FORMULA

The modern theories on the behavior of the general fluid indicate that the coefficient of viscosity should be expressed as a sum of two contributions, one due to the motion of molecules between collisions and the second due to the action of intermolecular forces.

In the preceding chapter, viscosity equations for dilute gases were discussed. Actually neither Sutherland's nor Reinganum's equation is satisfactory for dense gases. As the density increases, more molecules would be expected to cross any given plane in the fluid per unit time, which would cause the momentum contribution to be increased. However, the increased molecular density would cause shielding of molecules, which would cause the momentum contribution to be decreased. These are somewhat compensating effects and their joint effect together with the assumption of a constant apparent molecular diameter and lack of information on intermolecular forces may be the reasons the equations are not applicable to dense gases.

The viscosity for high density gases can be written

$$\mu (\rho, T) = \mu_K (\rho, T) + \mu_{\phi A} (\rho, T) + \mu_{\phi R} (\rho, T) \quad (7)$$

where:

$\mu$  = total viscosity

$\mu_K$  = viscosity due to Kinetic contribution

$\mu_{\phi A}$  = viscosity due to the attractive part of intermolecular force contribution

$\mu_{\phi R}$  = viscosity due to the repulsive part of intermolecular force contribution

The success of the residual viscosity-density correlations indicates that the Kinetic contribution can be considered to be independent of density. Then the viscosity equation reduces to the form:

$$\mu(\rho, T) = \mu_K(T) + \mu_{\phi A}(\rho, T) + \mu_{\phi R}(\rho, T) \quad (8)$$

In dilute gases, viscosity due to the repulsive part of the intermolecular force contribution is negligible. Therefore, the viscosity of dilute gases may be represented by

$$\mu_o(\rho, T) = \mu_K(T) + \mu_{\phi A}(\rho, T) \quad (9)$$

where  $\mu_o$  is the total viscosity in dilute gases. Because Sutherland's equation has been successfully applied to dilute gases, it can further be assumed that the attractive part of the intermolecular force contribution is only a function of temperature, then equation (9) can be stated as

$$\mu_o(T) = \mu_K(T) + \mu_{\phi A}(T) \quad (10)$$

Furthermore, Enskog's study (9) of viscosity for dense gases suggested the form

$$\mu(\rho, T) = \mu_o(T) \sum_{j=0}^4 a_j (b \rho)^j \quad (11)$$

where:

$a_j$  = constants

$b$  = function of temperature and density

If it is assumed that the only interaction at contact between rigid spheres is repulsion, part of the Enskog relation, series sum from  $j=1$  to  $j-m$ , can be assumed to represent the repulsive part of the intermolecular force contribution. If the above assumption is valid, then the viscosity equation for a dense gas is

$$\mu(\rho, T) = \mu_0(T) \left[ 1 + \sum_{j=1}^n a_j (b, \rho)^j \right] \quad (12)$$

where  $\mu_0$  is defined by equation (10).

In the present study other assumptions were made as follows: (1) the series in the brackets can be replaced by an exponential function and (2)  $b$  is a function of temperature only. The resulting expression can be written in the form

$$\mu(\rho, T) = \mu_0(T) \exp \left[ G(\rho, T) \right] \quad (13)$$

For convenience in the analysis, the function  $G(\rho, T)$  was considered to be equal to

$$G(\rho, T) = G_1(T) G_2(\rho) \quad (14)$$

where

$G_1$  = function of temperature only

$G_2$  = function of density only

The resulting expression for viscosity is

$$\mu (\rho, T) = \mu_0 (T) \exp \left[ G_1 (T) G_2 (\rho) \right] \quad (15)$$

which can be written in the form

$$\ln \mu (\rho, T) = \ln \mu_0 (T) + G_1 (T) G_2 (\rho) \quad (16)$$

If enough experimental data can be obtained for  $\mu$  and  $\mu_0$  then functions  $G_1 (T)$  and  $G_2 (\rho)$  can be determined. Further if  $G_2 (\rho)$  is proportional to density, a plot of  $\ln \mu$  versus density should yield a family of straight lines with slopes  $G_1 (T)$  and intercepts  $\ln \mu_0 (T)$ . The results, shown in Figure 1, were obtained for supercritical steam when  $\ln \mu$  was plotted versus  $\rho$ . From Figure 1 it is apparent that  $G_1 (T)$  is proportional to  $\frac{1}{T}$ , therefore, equation (15) for steam becomes

$$\mu (\rho, T) = \mu_0 (T) \exp \left[ \frac{B \rho}{T} \right] \quad (17)$$

where B is a constant which can be determined as follows

$$B = \frac{T}{\rho} \ln \frac{\mu}{\mu_0} \quad (18)$$

In the present study  $\mu_0$  was taken as Reingnum's equation which can be stated

$$\mu_0 = \frac{A \sqrt{T}}{e^{\frac{K}{T}}} \quad (19)$$

where constants A and K must be determined from existing experimental data at low pressures. With  $\mu_0$  known, the equation for viscosity of steam at high density can be expressed as

$$\mu = \frac{A \sqrt{T}}{e^{\frac{K}{T}}} \exp \left[ \frac{B \rho}{T} \right] \quad (20)$$

or

$$\mu = A \sqrt{T} \exp \left[ \frac{B \rho - K}{T} \right] \quad (21)$$

## CHAPTER IV

## COMPARISON OF RESULTS WITH EXISTING VISCOSITY DATA

In the preceding chapter, it was shown that the viscosity of steam can be predicted by

$$\mu = A \sqrt{T} \exp \left[ \frac{B \rho - K}{T} \right]$$

where  $\mu$  = poise

$\rho$  = grams per cubic centimeter

$T$  = absolute temperature in degree Kelvin

$A$  = constant

$B$  = constant

$K$  = constant

Constants  $A$  and  $K$  are determined from existing viscosity data (3, 4, 5 and 10) for low densities, constant  $B$  is determined by using equation (18).

In the present study of steam viscosity, constants  $A$ ,  $B$ , and  $K$  were found to be  $16.3 \times 10^{-6}$ , 1200 and 365 respectively. Equation (21) can, therefore, be written as

$$\mu = 16.3 \times 10^{-6} \sqrt{T} \exp \left[ \frac{1200 \rho - 365}{T} \right] \quad (22)$$

Equation (22) is compared with the experimental results of Timrot and Khlopkina (4), Timrot (3), Schmidt and Mayinger (5) and Whitelaw (10) in Tables 1, 2, 3 and 4, respectively; the average deviation from predicted values to experimental findings is 2.3 percent. Generally,

using the constants mentioned above, equation (22) predicts values of viscosity lower than the results of Timrot, Timrot and Khlopkina, and Schmidt and Mayinger but agree well with Whitelaw's experimental findings.

A comparison with Barnett's data shows that they are somewhat lower than predictions from equation (22). The deviation is due to the higher viscosity data which was used to determine the constants A and K. If A and K are determined from Thomas' (11) viscosity data at atmospheric pressure, they are  $14.7 \times 10^{-6}$  and 365, respectively. Using these constants, equation (21) becomes

$$\mu = 14.7 \times 10^{-6} \sqrt{T} \exp \left[ \frac{1200}{T} - \frac{365}{T} \right] \quad (23)$$

Calculated results from equation (23) are compared with Barnett's data in Figure 2. It is apparent from the figure that equation (23) agrees fairly well with the experimental results.

## CHAPTER V

## CONCLUSIONS

In the preceding chapter, a semi-empirical formula has been tested and compared to the existing experimental data.

A constant pressure viscosity versus temperature curve from equation (22) is shown in Figure 3.\* Two sets of different constants were determined due to discrepancies between different sets of experimental results. Equations (22) and (23) both show good agreement with corresponding test data. Therefore, it may be concluded that the basic equation (21) will describe the behavior of viscosity of steam in the high density region.

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\* In calculating viscosities, reference densities were taken from reference (12).

## CHAPTER VI

## RECOMMENDATIONS

It is recommended that the following equation be used for determining viscosity values:

$$\mu = 16.3 \times 10^{-6} \sqrt{T} \exp \left[ \frac{1200}{T} - 365 \right]$$

where the various symbols have meanings as previously defined.

It is suggested that as more data become available for the viscosity of steam, constants A, B, and K be adjusted to conform to the best data available.

It is recommended that the semi-empirical formula developed be extended to gases other than steam.

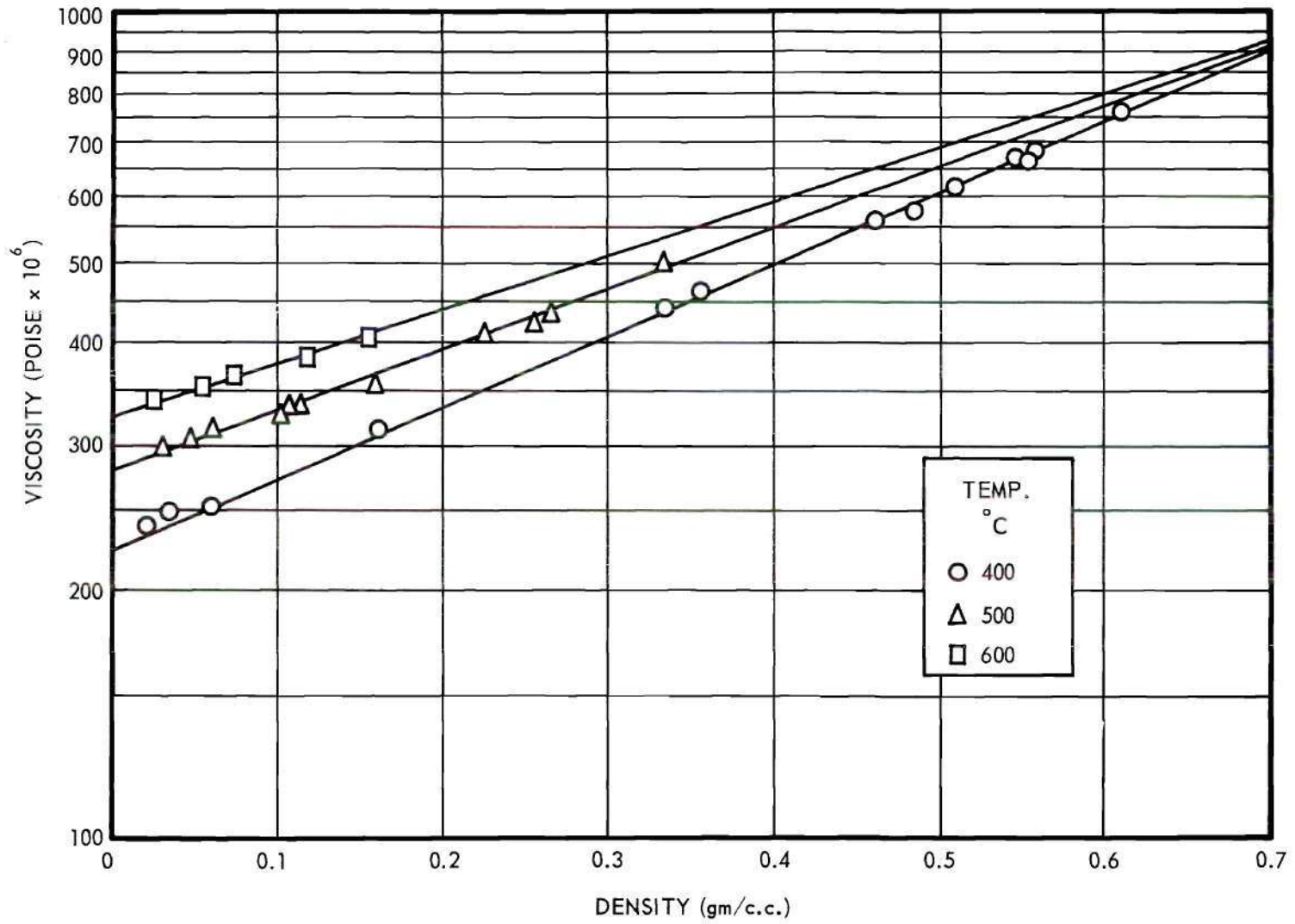


Figure 1. Experimental Steam Viscosity Versus Density (References 3, 4, 5 and 10).

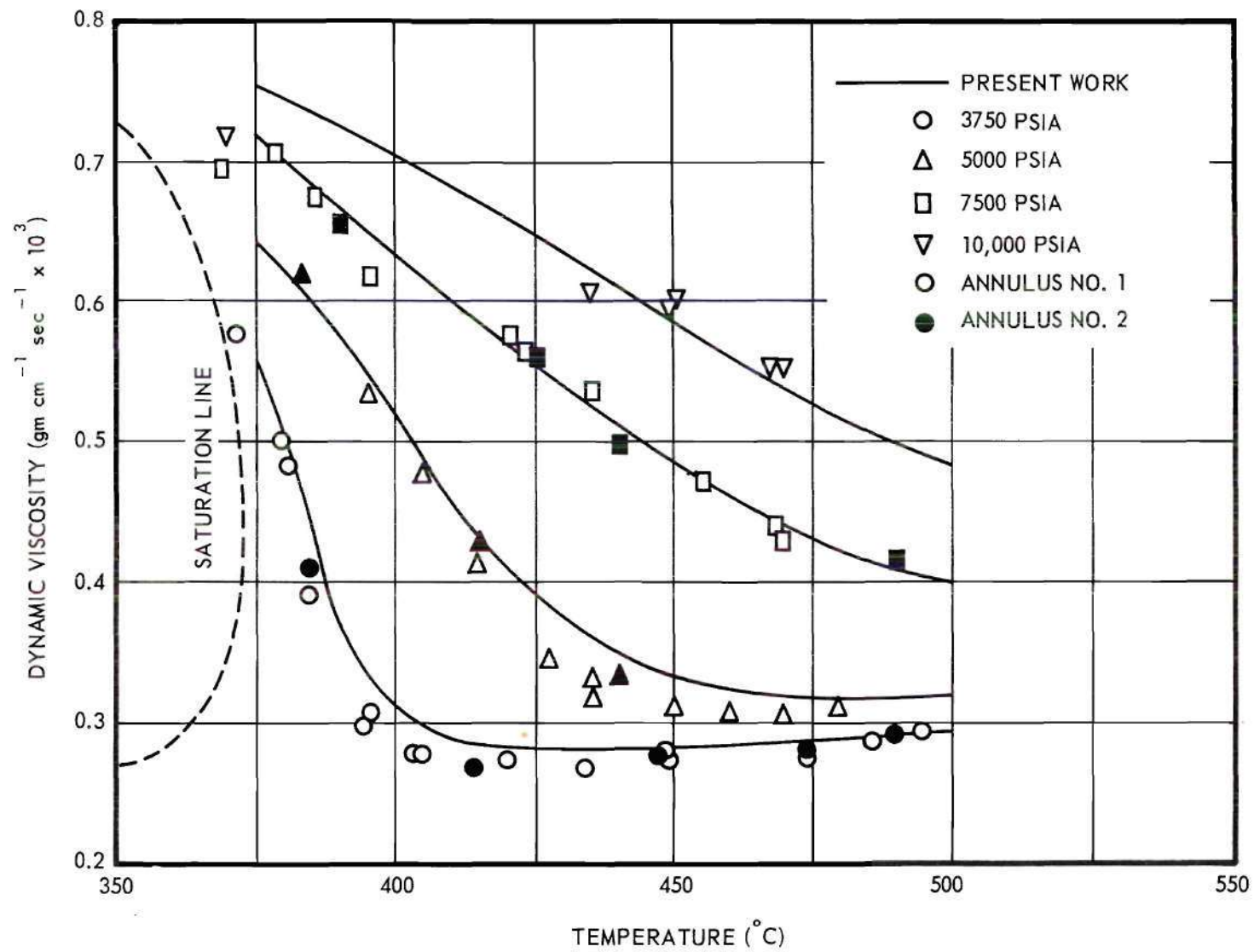


Figure 2. Comparison of Barnett's Experimental Results and Value of Viscosity Predicted by Present Study.

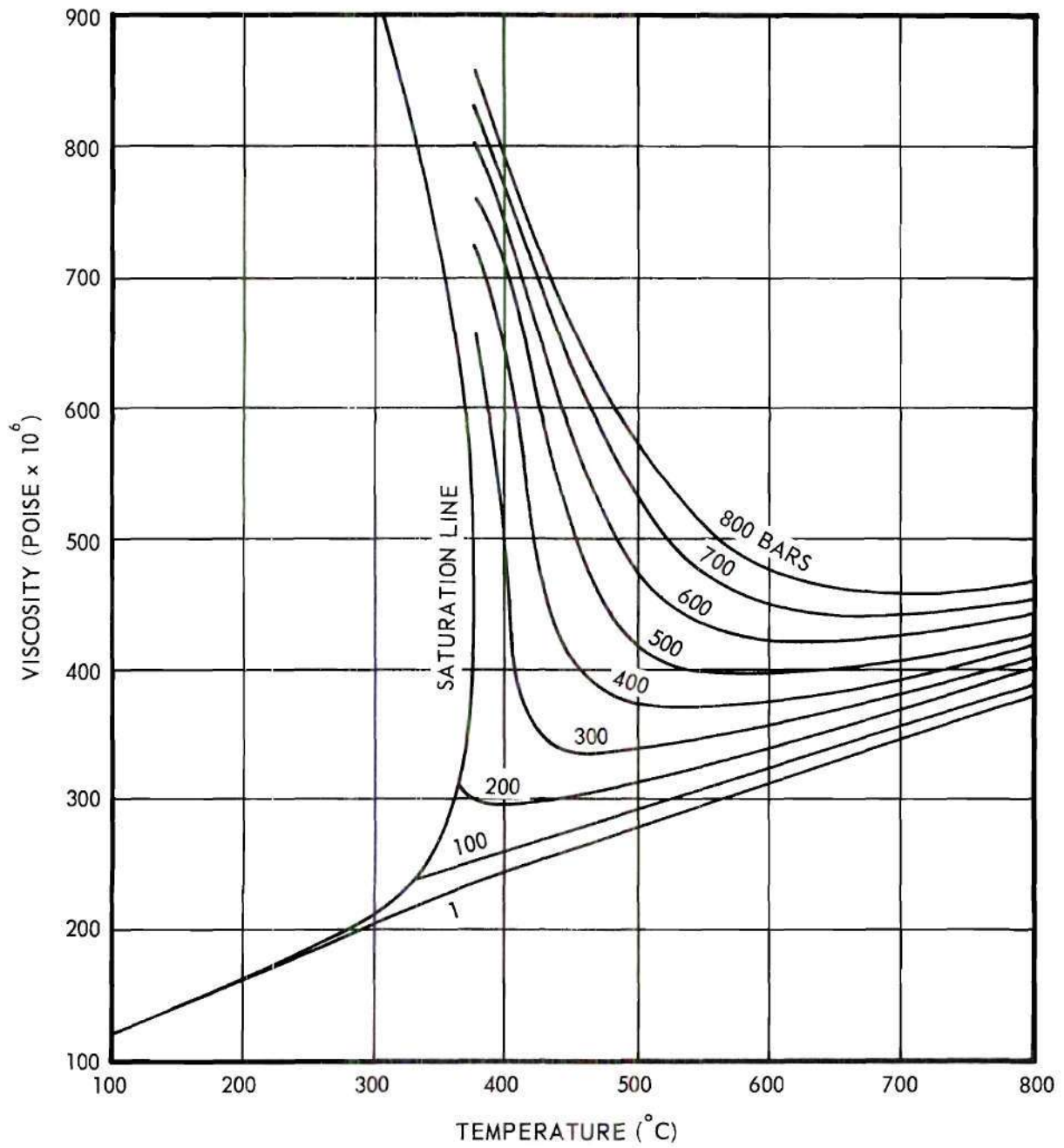


Figure 3. Coefficient of Viscosity of Steam Predicted by Present Study.

Table 1. A Comparison of Timrot and Khlopkina's Experimental Results and Value of Viscosity Predicted by Present Study

Pressure P/(Kp/cm <sup>2</sup> )	Temperature T°/C	Density ρ/(g/cm <sup>3</sup> )	Dynamic Viscosity (Measured) μ/micropoise	Dynamic Viscosity (Calculated from eq. 22) μ/micropoise
400	380	.5913	709.5	705.9
499	380	.6264	770.5	753.0
403	390	.5591	670.9	665.7
438	390	.5768	697.9	687.4
504	390	.6028	723.4	720.5
505	390	.6032	735.9	721.1
29	400	.00952	242.6	250.0
64	400	.02216	244.7	255.7
96	400	.03521	250.0	261.7
301	400	.3337	443.8	445.7
302	400	.3383	443.1	449.3
306	400	.3557	465.9	463.5
396	400	.5142	622.1	614.9
399	400	.5166	614.7	617.5
449	400	.5493	664.6	654.6
483	400	.5662	673.8	674.6
492	400	.5703	707.1	679.6
399	425	.3789	496.4	489.6

Table 1 (continued)

Pressure P/(Kp/cm <sup>2</sup> )	Temperature T°/C	Density ρ/(g/cm <sup>3</sup> )	Dynamic Viscosity (Measured) μ/micropoise	Dynamic Viscosity (Calculated from eq. 22) μ/micropoise
449	400	.5493	664.6	654.6
483	400	.5662	673.8	674.6
492	400	.5703	707.1	679.6
399	425	.3789	496.4	489.6
399	425	.3789	488.8	489.6
503	425	.4931	626.3	595.9
503	425	.4931	616.4	595.9
399	450	.2577	412.2	405.7
500	450	.3920	521.4	507.0
401	475	.2034	374.1	379.2
402	475	.2043	374.7	379.8
502	475	.3068	448.5	447.6
503	475	.3079	449.4	448.4
28.6	500	.00803	286.7	286.1
101.5	500	.03034	295.1	296.2
284	500	.1038	327.7	332.0
285	500	.1043	327.9	332.2
389	500	.1649	360.7	365.0
473	500	.2268	399.7	401.8
396	550	.1375	365.6	366.7
498	550	.1889	395.5	395.2

Table 1 (continued)

Pressure P/(Kp/cm <sup>2</sup> )	Temperature T°/C	Density $\rho$ /(g/cm <sup>3</sup> )	Dynamic Viscosity (Measured) $\mu$ /micropoise	Dynamic Viscosity (Calculated from eq. 22) $\mu$ /micropoise
498	550	.1889	400.4	395.2
22.2	600	.00546	340.5	319.4
102	600	.02608	339.0	328.6
275	600	.07717	361.9	352.5
283	600	.07978	357.4	353.7
398	600	.1199	384.8	373.8
486	600	.1539	401.7	391.7
486	600	.1539	410.9	391.7
27.2	650	.00633	358.5	363.2

Table 2. A Comparison of Timrot's Experimental Results and Value of Viscosity Predicted by Present Study

Pressure P/(Kp/cm <sup>2</sup> )	Temperature T°/C	Density $\rho$ /(g/cm <sup>3</sup> )	Dynamic Viscosity (Measured) $\mu$ /micropoise	Dynamic Viscosity (Calculated from eq. 22) $\mu$ /micropoise
102	397.5	.03811	245.4	262.1
204	399	.1012	272.3	294.0
300	398	.3572	485.8	464.2
249.5	398.5	.1601	312.2	326.5
146	400	.05983	255.5	273.5
304.5	446	.1516	338.0	338.8
249	449	.1056	299.9	314.8
198.7	453	.07512	287.7	300.7
151.2	453	.05296	281.8	289.9
92.7	453	.03000	273.0	279.1
301	500.3	.1124	331.5	336.6
248.5	498.5	.08724	315.8	323.0
199.5	501	.06568	311.3	313.3
151	501	.04724	310.8	304.4
101	504.5	.02994	298.5	297.6
296.5	525.5	.1012	334.1	339.5
249	526.2	.08091	329.3	329.5
201.3	526.5	.06252	319.5	320.6
303	528	.1034	340.0	341.4

Table 2 (continued)

Pressure P/(Kp/cm <sup>2</sup> )	Temperature T°/C	Density $\rho$ /(g/cm <sup>3</sup> )	Dynamic Viscosity (Measured) $\mu$ /micropoise	Dynamic Viscosity (Calculated from eq. 22) $\mu$ /micropoise
305	528.3	.1042	339.5	342.0
145.5	532	.04262	308.1	313.1
105	530.6	.02987	304.7	306.7
307.5	529	.1050	342.5	342.6
249	531	.07993	332.5	330.7
198.5	531	.06089	318.5	321.4
149.5	530	.04409	306.5	313.1
105	529	.02995	297.1	306.2
198.5	599	.05348	352.4	340.8
150.1	601.5	.03925	348.5	335.1
97	601.5	.02469	348.3	328.4

Table 3. A Comparison of Schmidt and Mayinger's Experimental Results and Value of Viscosity Predicted by Present Study

Pressure P/(Kp/cm <sup>2</sup> )	Temperature T°/C	Density $\rho$ /(g/cm <sup>3</sup> )	Dynamic Viscosity (Measured) $\mu$ /micropoise	Dynamic Viscosity (Calculated from eq. 22) $\mu$ /micropoise
235.5	386	.1695	311.1	327.4
235.5	387.3	.1644	306.8	324.8
308.3	391	.4635	568.7	560.1
315.5	391.5	.4722	533.1	569.1
401.3	389.2	.5611	666.0	668.0
403.8	390.3	.5585	682.5	665.0
402.9	390.3	.5580	669.0	664.0
516.5	392.2	.6014	725.9	718.6
517.5	395.3	.5936	730.7	708.5
518	395.3	.5938	733.9	708.8
586	396.5	.6128	753.8	733.3
595	396.5	.6142	718.0	735.1
596	396.8	.6151	740.5	736.3
304.8	500.5	.1143	335.4	337.6
311.5	501	.1176	339.9	339.5
313.6	501	.1188	333.4	340.2
415	492.5	.1912	377.1	377.7
401.5	494.3	.1790	360.9	371.2
381	498.6	.1607	348.5	362.2

Table 3 (continued)

Pressure P/(Kp/cm <sup>2</sup> )	Temperature T°/C	Density $\rho$ /(g/cm <sup>3</sup> )	Dynamic Viscosity (Measured) $\mu$ /micropoise	Dynamic Viscosity (Calculated from eq. 22) $\mu$ /micropoise
382.3	498.6	.1616	355.7	362.7
507	500.2	.2540	422.7	419.2
511.5	500.5	.2527	424.9	421.4
515.8	501	.2598	417.5	423.3
504.8	493.5	.2644	417.7	424.3
521.5	498.6	.2690	433.7	428.6
607	499.3	.3366	494.8	476.3
609.5	499.3	.3385	500.6	477.8
607	499.8	.3354	490.7	475.6
513	501	.2575	424.6	421.8
501.8	501.6	.2474	408.6	415.4
208.1	497.4	.06982	308.5	314.0
188	598.2	.05043	336.6	339.2
188	598.2	.05043	333.8	339.2
188	598.2	.05043	336.5	339.2
390.8	597	.1181	375.7	371.9
393.6	597	.1191	358.8	372.4
598	597.5	.2024	439.6	417.9
598	597	.2028	431.6	418.0
207	386	.1168	292.8	297.4
235	388.5	.1591	314.4	322.2

Table 3 (continued)

Pressure P/(Kp/cm <sup>2</sup> )	Temperature T°/C	Density $\rho$ /(g/cm <sup>3</sup> )	Dynamic Viscosity (Measured) $\mu$ /micropoise	Dynamic Viscosity (Calculated from eq. 22) $\mu$ /micropoise
210.5	497	.07090	314.0	314.4
223.5	497	.07645	313.5	317.1
416.5	593.5	.1290	379.3	376.4
463	595.8	.1465	387.8	386.4
508	597	.1643	393.3	396.4
319	594	.09300	363.6	358.3
319.5	594	.09317	363.2	358.3
222	594.5	.06108	345.1	342.9
212	594.5	.05800	336.6	341.5
343.5	700.5	.08312	402.4	387.2
415	701.5	.1084	409.6	396.8
424	703.5	.1045	419.0	398.5
509	703.5	.1284	431.1	410.4
540.5	706.5	.1367	445.5	415.5

Table 4. A Comparison of Whitelaw's Experimental Results and Value of Viscosity Predicted by Present Study

Pressure P/(Kp/cm <sup>2</sup> )	Temperature T°/C	Density ρ/(g/cm <sup>3</sup> )	Dynamic Viscosity (Measured) μ/micropoise	Dynamic Viscosity (Calculated from eq. 22) μ/micropoise
500	473.3	.3097	454.3	449.2
600	478	.3874	499.3	510.2
300	387	.4817	568.9	578.2
300	386.1	.4886	577.1	585.4
300	390.3	.4527	521.5	549.2
300	387.1	.4809	559.7	577.4
400	378	.5974	705.0	714.0
400	389	.5610	648.6	668.0
400	389.5	.5592	644.8	665.8
500	386	.6118	724.4	732.6
500	389.5	.6027	701.0	720.4
600	389	.6335	745.7	761.8
800	388.2	.6769	806.2	824.4
250	433	.1159	287.5	314.4
400	423	.3930	485.3	501.1
500	427.3	.4824	577.4	585.4
500	428	.4797	583.9	582.8
500	427.3	.4824	593.5	585.4
600	426.5	.5415	643.9	647.7

Table 4 (continued)

Pressure P/(Kp/cm <sup>2</sup> )	Temperature T°/C	Density ρ/(g/cm <sup>3</sup> )	Dynamic Viscosity (Measured) μ/micropoise	Dynamic Viscosity (Calculated from eq. 22) μ/micropoise
600	427.7	.5382	643.2	644.1
700	429	.5729	687.5	683.6
400	538	.1455	364.6	367.0
500	538	.2033	394.2	398.0
500	536.6	.2016	394.1	398.3
500	537	.2012	389.0	398.2
600	534.6	.2657	448.6	437.4
700	534.1	.3279	488.0	479.7
800	534.4	.3814	549.2	519.4
800	538.1	.3748	531.8	515.3
500	541	.1976	386.8	397.4
700	540.7	.3168	473.6	473.7
300	650	.0777	369.7	368.9
400	653.8	.1071	374.3	384.4
400	654.1	.1070	371.0	384.5
500	646.3	.1415	386.9	399.6
500	649.6	.1404	386.4	400.1
700	650	.2100	439.2	438.1
800	650	.2457	466.9	458.9

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