Measurement of Pressure Effect on Viscosity of Steam

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The viscosity of steam at subcritical pressures is measured by a capillary viscometer in the temperature range 250–600°C and at pressures up to 200 bar. In this region the gradient of isotherms in the viscosity–pressure diagram changes its sign from negative to positive. Results show that about 600°C is the lowest limit of the temperature range where the excess viscosity can be expressed as a function of density only. The measured viscosity agrees reasonably well with the correlation based on the authors' previous measurements at higher pressures.

A negative pressure effect on the viscosity of steam at subcritical temperatures was first discovered by Kestin and coworkers and recorded in several experimental reports (*1*). However, the highest temperature of these observations was limited to 450°C where the residual effect is still significant, and it is not clear at what temperature the effect dies out and becomes negligible.

The authors previously reported measurements of viscosity of water and steam up to 900°C and 1000 bar (*3*), but few measurements in the region of lower pressure were included in it. This paper describes some results at temperatures from 250° to 600°C and at pressures below 200 bar.

Method and Apparatus

Measurements were performed with a high-pressure capillary viscometer which is similar in principle to that used in the previous investigation (*3*) but different in detail. At subcritical pressures, liquid-gas interfaces in the flow system often cause trouble in flow rate measurement. The major differences compared with the previous apparatus were: addition of preheaters and coolers in order to fix the position of the interfaces in the flow circuit; and use of a shorter capillary for better temperature distribution.

Figure 1 shows a schematic outline of the experimental setup. The capillary is installed in the pressure vessel (4), which is heated by a main heater (6) through a thermostat cylinder (5) made of copper. The test fluid is circulated by a high-pressure injector system (13); it flows into the test section via the cooler (2) and subheater (3) and returns to the other end of the injector system. The flow rate is calculated from the record of an electric counter (14), while the pressure drop between both ends of the capillary is measured by a mercury manometer (12) and a traveling microscope. The capillary is made of Pt-Rh (5%) alloy and has the dimensions of 100 mm length and about 0.27 mm i.d.; it was calibrated with water and nitrogen (*2*). Because the inner surface of the metallic capillary was not perfectly smooth and also because the capillary was comparatively short, the critical Reynolds number was about 220, which was lower than the normal value of 2300 for a smooth circular tube. Variation of the capillary constant against the Reynolds number was checked with nitrogen. At low Reynolds numbers, the calibrated constant with respect to nitrogen agreed with those with respect to water (1.002 cP for water at 1 atm, 20°C).

Calculation

Viscosity values were calculated by use of the following modified Poiseuille equation (*3*):

$$\eta = \frac{\pi C}{8lQ}\frac{P_1^2 - P_2^2}{2P_1}(1 + 3\alpha\Delta t) - \frac{\rho Q}{8\pi l}\frac{(m + \ln P_1/P_2)}{1 + \alpha\Delta t} \quad (1)$$

where η is the viscosity in μP, C is a capillary constant in cm^4, l is the length of the capillary in cm, Q is the volumetric flow rate in cm^3/s, P_1 and P_2 are pressures at the inlet and exit of the capillary in dyne/cm^2, α is the expansion coefficient of platinum (1.02×10^{-5} C^{-1}), Δt is the temperature difference between experimental temperature and 20°C, ρ is the density of the fluid in g/cm^3, and m is the kinetic energy correction factor, 1.12. The density of steam was calculated with the aid of the equation of state approved by ICPS (1967) (*5*).

Estimated Error

The largest error in the viscosity comes from the measurement of the pressure difference owing to the small value of $P_1 - P_2$ (keeping the Reynolds number as low as possible). The flow rate Q, calculated from the injector speed, was measured with a possible maximum error of 0.5%. The pressure was measured to 0.1 bar by a Bourdon-type pressure gage calibrated against a standard dead-weight gage, and the temperature was measured with the aid of a platinum resistance thermometer. The error in viscosity owing to the temperature measurement, including fluctuations and imperfect distribution, was estimated to be less than 0.5%. The length of the capillary was measured to 0.02%. The error owing to the uncertainty in the factor m was estimated to be less than 0.1%. The estimated error of viscosity is thus about 1.5%.

Results and Conclusion

Experimental results are given in Table I. All data taken with a Reynolds number greater than 400 were disregarded. As seen in Figure 2, discrepancies between measured data and the ICPS equation (*4*) are quite large along the 375° and 400°C isotherms. The ICPS equation expresses the residual viscosity as a function of density only. The discrepancy of the ICPS equation and Equation 2 becomes smaller than experimental error above about 600°C. Measured data agree with the authors' equation in ref. *3*:

$$\eta = 80.4 + 0.407t + 276.667\rho + 866.667\rho^2 - \frac{2.39474 \times 10^5 \times (1-\rho)^4}{1 + t + 1.75439 \times 10^{-8} t^4} + \frac{5.44832 \times 10^8}{(t+90)^3 \times (1-\rho)^2 + 4.64786 \times 10^{-2}} \quad (2)$$

In ref. *3* a constant in the equation was misprinted as -2.39474×10^4, which should be corrected as above.

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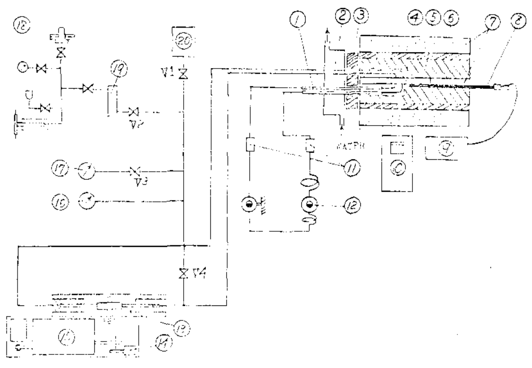

Figure 1. Experimental apparatus

1. Manometer tube
2. Cooler
3. Subheater
4. Pressure vessel
5. Thermostat (Cu)
6. Main heater
7. Insulator
8. Resistance thermometer
9. Double bridge
10. Temperature controller
11. Mercury trap
12. Manometer
13. Injector system
14. Counter
15. Regulator
16. Pressure gage (high)
17. Pressure gage (low)
18. Dead-weight gage
19. Water–oil separator
20. High-pressure pump

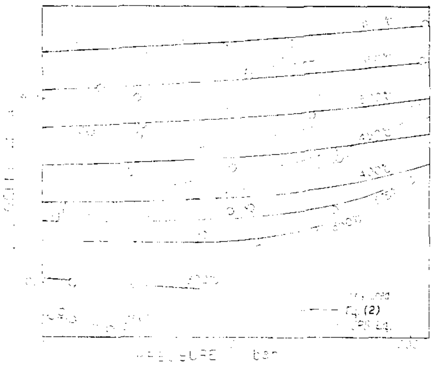

Figure 2. Measured results

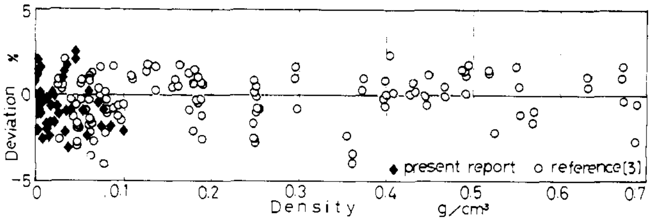

Figure 3. Deviation of measured points from Equation 2

The standard deviation between Equation 2 and the measured data is about 1.5%. The above expression describes the viscosity of water and steam up to 1000°C and 1000 bar with the aid of a single equation and agrees with Rivkin's data (*1*). Because of the trouble caused by water–steam interfaces in the connecting tubes, the reproducibility obtained during the present investigation was less satisfactory than that in the authors' previous investigation at higher pressures (*3*). A deviation plot of the results, as well as of those of ref. *3* with respect to Equation 2, is shown in Figure 3.

At temperatures higher than 600°C, the excess viscosity of steam may be treated as a function of density only. Below about 600°C, the residual effect of the negative pressure gradient should be taken into account as given by Equation 2.

Table I. Measured Data

t, °C	P, bar	ρ, g/cm³	η, μP	t, °C	P, bar	ρ, g/cm³	η, μP
		10^{-6}				10^{-6}	
250.7	4.9	2049	181.6	400.8	13.3	4367	240.6
250.2	10.2	4366	184.0	400.9	13.4	4400	238.4
251.1	15.8	6930	180.1	402.8	102.0	38497	239.6
251.0	37.0	18147	174.4	400.4	200.0	100210	256.0
250.8	37.1	18216	172.5				
250.9	37.9	18751	171.1	450.4	23.3	7162	263.1
				450.5	47.0	14782	259.9
301.2	16.0	6283	200.5	450.4	103.0	34737	262.5
301.2	16.2	6361	200.4	451.0	161.3	59161	267.6
302.9	25.7	10340	196.2				
301.2	50.4	22194	198.8	503.1	21.1	5998	283.5
301.2	50.5	22242	195.6	500.8	25.9	7399	282.2
				501.8	52.2	15241	280.0
350.7	29.3	10761	221.3	500.8	53.7	15714	286.1
350.4	50.1	19267	218.0	500.8	146.1	46580	291.1
350.3	83.4	35137	225.1				
350.5	87.3	37229	226.1	551.0	31.3	8384	306.2
349.7	115.7	55054	219.6	551.4	51.1	13857	300.8
349.9	115.7	55011	221.7	552.0	111.8	31566	313.0
350.8	150.0	86493	226.4	552.1	111.8	31561	314.9
				551.2	112.8	31906	317.4
377.3	6.7	2248	235.8	550.6	205.9	62410	320.6
377.5	7.0	2346	238.8				
377.5	7.1	2380	237.4	601.4	16.7	4164	329.8
376.7	22.9	7899	237.4	601.3	56.8	14463	322.5
377.2	57.2	21038	234.2	601.3	58.4	14897	321.1
378.3	111.8	46524	242.8	601.3	98.1	25536	328.5
377.9	112.8	47149	241.5	601.4	99.7	25926	327.3
377.0	158.8	78182	240.5	601.3	135.3	35905	330.5
				601.3	157.9	42382	332.6
				599.3	207.8	57533	340.1

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Nomenclature

C = capillary constant, cm⁴
l = length of the capillary, cm
m = kinetic energy correction factor
P_1, P_2 = pressures at inlet and outlet of the capillary, dyne/cm²
Q = volumetric flow rate, cm³/s
t = temperature, °C
Δt = temperature difference, $t - 20$, °C
α = thermal expansion coefficient of platinum, 1.02×10^{-5}, °C^{-1}
ρ = density, g/cm³
η = viscosity, μP

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