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Measurement of Xenon Viscosity as a Function of Low Temperature and Pressure

Stanley P. Grisnik
Lewis Research Center, Cleveland, Ohio

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MEASUREMENT OF XENON VISCOSITY AS A FUNCTION OF LOW TEMPERATURE AND PRESSURE

Stanley P. Grisnik
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Abstract

The measurement of xenon gas viscosity at low temperatures (175 to 298 K) and low pressures (350 to 760 torr) has been performed in support of Hall Thruster testing at NASA Lewis Research Center. The measurements were taken using the capillary flow technique. Viscosity measurements were repeatable to within 3 percent. The results in this paper are in agreement with data from Hanley and Childs and suggest that the data from Clarke and Smith is approximately 2 percent low. There are no noticeable pressure effects on xenon absolute viscosity for the pressure range from 350 to 760 torr.

Introduction

An interest in Russian electric propulsion technologies, specifically "Hall effect" thrusters, has increased due to their potential to increase the performance of Western spacecraft. Testing of these thrusters has been performed at NASA Lewis Research Center, to identify plume properties, performance limits, and component life limitations.[1] Of interest is the Russian "thermal throttle," a capillary tube that uses resistive heating to vary the viscosity and density of the gas flowing through it and therefore throttle the mass flowrate. The thermal throttle operates at propellant pressures of 200 to 400 torr, and temperatures as low as –90 °C during cold soak testing. Difficulties with thermal throttle operation at the low temperatures and pressures seen in the NASA Lewis testing has prompted the need for xenon viscosity data. During the course of this work, limited sources of xenon viscosity data were identified.[2,3] To remedy this situation, absolute viscosity measurements were made using a single capillary tube. The single capillary tube method introduces the possibility of additional errors in the viscosity values but due to the low pressure operation with no previous data available, an absolute viscosity value was needed. The dual capillary tube method eliminates the need for a mass flowrate measurement, and thus would have reduced the sources of error but would only furnish a relative viscosity value. In this paper all references to viscosity imply absolute viscosity.

Since the experimental apparatus was operated below atmospheric pressure, any leaks would change the gas composition and viscosity. The system was leak checked to 1×10^{-9} atm cc/sec of helium using a Helium mass spectrometer to eliminate this possibility.

Expermental Apparatus

A schematic diagram of the flow system is shown in Fig. 1. It consists of a 2 liter high pressure xenon gas storage bottle, two stage gas pressure regulator, inlet flowcontroller, inlet pressure transducer, capillary tube, outlet pressure transducer, outlet flow controller, and vacuum pump.

The capillary tube was constructed of nominally 0.41 mm i.d. stainless steel tubing, 152 cm in length, wrapped on a 5.1 cm dia helix. The pressure transducers were capacitance manometer type, with an accuracy of 0.5 percent FS for 0 to 101 kPa operation. The mass flow controllers were 0 to 20 sccm, with an accuracy of 1 percent FS. The mass flow controllers showed a 2 to 3 percent change in flowrate reading during subatmospheric pressure operation. This was attributed to the change in heat transfer associated with the flow sensing element, as the pressure was lowered.

The capillary tube was immersed in an ethyl-alcohol/ LN_2 bath. The bath was constructed of concentric cylinders with the annular space between the cylinders filled with glass beads and a heating element. The inner cylinder was filled with ethyl-alcohol and the cylinders were immersed in liquid nitrogen. The ethyl-alcohol was kept at the desired temperature, within ±1 °C, by on/off control of the heating element, using a PID (proportional, integral, derivative) controller with an RTD (resistance temperature detector) temperature sensor. The ethyl-alcohol was constantly stirred using an electric motor, to keep the temperature uniform.

The capillary tube's helical dimensions were chosen to reduce the "curved-pipe flow" pressure drop to a negligible value. This was accomplished by setting the Dean number to less than 7.0 as described by Dawe.[4] The Dean number is described as follows:

$$D = (2a\rho v / \mu)(a / R)^{1/2} \quad (1)$$

where a is the capillary tube radius, R is the helix radius, ρ is the gas density, μ is the viscosity, and v is the gas velocity.[5] The helical dimension was thus chosen to be 5.1 cm.

Procedure

Before taking data, the valve between the capacitance manometers was opened and the system pressure was varied. Pressure readings between the two gages were compared to minimize any offset errors.

At ambient temperatures, the desired flowrate was set on the inlet flow controller. After the system was brought to the desired operating pressure (with the outlet flow controller "wide open"), the outlet flow controller was adjusted until the differential pressure across the capillary tube remained constant with respect to time. Data was then taken and the viscosity at ambient conditions was determined and compared to literature. The data set was repeated several times to establish the repeatability of the experimental hardware.

Finally, the ethyl-alcohol bath temperature was varied from ambient to –100 °C. At each temperature, the differential pressure was recorded for four different flowrates and three different operating pressures. The operating pressures were taken as the arithmetic average of the inlet and outlet pressures for each test point.

Results and Discussion

The capillary flow technique uses the Poiseulle formula for gases under low Reynold's number flow, and equates the pressure drop across a section of tubing to the viscosity of the gas, as follows:

$$Q = \frac{\pi r^4 \rho \, \Delta p}{8 X \mu} \quad (2)$$

where Q is mass flowrate, r is the radius of the capillary tube, μ is viscosity, X is the length of the capillary tube, ρ is density of the gas, and Δp is the pressure drop in the capillary tube.[6] The capillary tube inner diameter and length were determined by estimating the viscosity change that would be seen when the temperature of the gas was reduced from 300 to 190 K. Then an acceptable gas flowrate was chosen, one that would give a measurable differential pressure at the two temperature extremes. The Reynolds number was checked to ensure laminar flow. This process was iterated until the proper capillary tube dimensions were obtained.

The capillary tube design was then checked to insured that the gas flowing inside the tube would reach equilibrium with the cold bath temperature. Hausen's equation for convective heat transfer in horizontal circular tubes was used (for Graetz numbers <100).

$$Nu = 3.66 + \left\{0.085Gz / \left(1 + 0.047Gz^{2/3}\right)\left(\mu_b / \mu_w\right)^{0.14}\right\} \quad (3)$$

where Nu is the Nusselt number, Gz is the Graetz number, μ_b and μ_w is the viscosity evaluated at the bulk fluid temperature and wall temperature, respectively.[7] The outlet temperature was estimated, a bulk viscosity was estimated, then a convective heat transfer coefficient was calculated. This value was used in a heat balance equation for the system:

$$MCp(To - Ti) = hA(Tb - Ts) \quad (4)$$

where M is mass flowrate, Cp is specific heat of xenon, h is convective heat transfer coefficient, A is surface area of tube, To is outlet temperature, Ti is inlet temperature, Ts is surface temperature , and Tb is bulk fluid temperature {(To + Ti)/2}. Simultaneously solving the heat balance and Hausen's equation for To and iterating until To estimated equals To calculated gives the outlet temperature expected for the capillary tube design. If the outlet temperature is not close enough to the desired outlet temperature, the capillary tube dimensions and/or mass flowrate needs to be changed and the entire process is repeated.

Corrections for the capillary tube dimensional changes with temperature were included. The equation used was:

$$a = a_0(1 + \alpha \Delta T) \quad (5)$$

where a_0 is capillary radius at ambient conditions, α is the coefficient of thermal expansion for the capillary material,

ΔT is the temperature difference between ambient and the operating temperature. This correction was <0.2 percent.

Corrections for slip flow were examined. The correction is based on the equation:

$$f_S = (1 + 4\beta\lambda / a) \quad (6)$$

where β is equal to 1.147 as described by Dean,[8] a is the radius of the capillary tube in cm, λ is the mean free path in cm. Corrections for slip flow were examined and found to contribute less than 0.01 percent to the viscosity values and were therefore ignored.

Table I shows the data taken during testing along with the calculated viscosity values using Eq. (1). Figure 2 shows the viscosity vs. temperature data for atmospheric pressure measurements. The viscosity values vary from 152 μP at 190K to 229 μP at 294 K. A linear trend line through the data fits the equation:

$$V = (0.719)T + 17.2 \quad (7)$$

where V is viscosity in μPoise, and T is temperature in Kelvin. Included on the graph is previously published data from Dawe/Smith[9] and Hanley/Childs[10]and Clarke/ Smith.[11]

The Data from Dawe, and Smith is for the 300 to 400 K temperature range. Extrapolating this data down to 190 K gives a viscosity valve of 151 μP, which is 0.6 percent lower than this papers measured value. The data from Clarke and Smith is for the 175 to 298 K temperature range. At 190 K Clarke and Smith measured a viscosity value of 149 μP, which is 2 percent lower than this papers measured value, and 1.3 percent lower than the values from Dawe and Smith. The data from Hanley and Childs is for the 100 to 180 K temperature range. Extrapolating this data to 190 K gives a viscosity value of 153 μP, which is 0.7 percent higher than this papers measured value.

Conclusion

The measurement of xenon gas viscosity at low temperatures (175 to 298 K) and low pressures (350 to 760 torr) has been performed in support of the Hall Thruster testing at NASA Lewis Research Center. The measurements were taken using the capillary flow technique. Viscosity measurements were repeatable to within 3 percent. The results in this paper are in agreement with data from Hanley and Childs and suggest that the data from Clarke and Smith is approximately 2 percent low. There are no noticeable pressure effects on xenon absolute viscosity for the pressure range from 350 to 760 torr.

References

1. Sankovic, J.M., Hamley, J.A., and Haag, T.W. "Performance Evaluation of the Russian SPT-100 Thruster at NASA LeRC," IEPC-93-094.
2. Clarke, A.G. and Smith, E.B., "Low-Temperature Viscosities of Argon, Krypton, and Xenon," The Journal of Chemical Physics, vol. 48 no. 9, May 1967.
3. Hanley, H.J.M., and Childs, G.E., "The Viscosity and Thermal Conductivity Coefficients of Dilute Neon, Krypton, and Xenon," NBS Technical Note 352, March 1967.
4. Dawe, R.A., Smith, E.B., "Viscosities of the Inert Gases at High Temperatures," The Journal of Chemical Physics, vol. 52, no. 2, Jan. 1970.
5. Dean, R.W., Phil. Mag. vol. 4, p. 208, 1927.
6. Rabinovich, V.A., Vasserman, A.A., Nedostup, V.I., Veksler, L.S., "Thermophysical Properties of Neon, Argon, Krypton, and Xenon," Hemisphere Publishing Corp. copyright 1988, p. 187.
7. Perry, R.H., Chilton, C.H., "Chemical Engineers' Handbook" Fifth Edition, McGraw-Hill Book Co. pp. 10-12 and 10-13.
8. Guevara, F.A., Mcinteer, B.B., Wageman, W.E., "High Temperature Viscosity Ratios for Hydrogen, Helium Argon and Nitrogen," The Physics of Fluids, vol. 12, no. 12, Dec. 1969.
9. Dawe, R.A., Smith, E.B., "Viscosities of the Inert Gases at High Temperatures," The Journal of Chemical Physics, vol. 52, no. 2, Jan. 1970.
10. Hanley, H.J.M., and Childs, G.E., "The Viscosity and Thermal Conductivity Coefficients of Dilute Neon, Krypton, and Xenon," NBS Technical Note 352, March 1967.
11. Clarke, A.G. and Smith, E.B., "Low-Temperature Viscosities of Argon, Krypton, and Xenon," The Journal of Chemical Physics, vol. 48 no. 9, May 1967.

TABLE I.—EXPERIMENTAL DATA

Flowrate, sccm	Upstream press, torr	Downstream press, torr	Operating press, torr	Density, lb/ft^3	Gas vel. ft/sec	ΔP, act	Viscometer, temperature	Tube diameter, in.	Tube area, ft^2	Act. visc., μP	dp, ref
5.9	775.7	753.2	764.5	0.48365	1.87526	22.5	210	0.01548	1.3071×10^{-6}	166	22.5
4.94	773.7	754.9	764.3	0.48356	1.57044	18.8	210	0.01548	1.3071×10^{-6}	166	18.8
7.94	778	748.1	763.1	0.48277	2.52829	29.9	210	0.01548	1.3071×10^{-6}	164	29.9
6.94	771.6	745.1	758.4	0.47980	2.22356	26.5	210	0.01548	1.3071×10^{-6}	165	26.5
7.94	772.9	742.6	757.8	0.47942	2.54597	30.3	210	0.01548	1.3071×10^{-6}	165	30.3
4.94	767.3	748	757.7	0.47935	1.58423	19.3	210	0.01548	1.3071×10^{-6}	169	19.3
8	753.4	692.4	722.9	0.32603	3.76271	61	295	0.01550	1.3104×10^{-6}	225	61
7.82	730.3	703.6	717.0	0.50135	2.39883	26.7	190	0.01548	1.3065×10^{-6}	154	26.7
4.8	721.4	704.9	713.2	0.49869	1.48027	16.5	190	0.01548	1.3065×10^{-6}	155	16.5
6.84	724.5	701.1	712.8	0.49845	2.11042	23.4	190	0.01548	1.3065×10^{-6}	154	23.4
5.8	722.5	702.6	712.6	0.49827	1.79017	19.9	190	0.01548	1.3065×10^{-6}	154	19.9
6.84	724	700.8	712.4	0.49817	2.11161	23.2	190	0.01548	1.3065×10^{-6}	152	23.2
7.8	725.7	699	712.4	0.49813	2.40814	26.7	190	0.01548	1.3065×10^{-6}	154	26.7
4.8	719.3	702.6	711.0	0.49715	1.48485	16.7	190	0.01548	1.3065×10^{-6}	156	16.7
5.8	720.6	700.6	710.6	0.49691	1.79508	20	190	0.01548	1.3065×10^{-6}	154	20
8	728.8	690.1	709.5	0.41342	2.97335	38.7	228	0.01548	1.3077×10^{-6}	181	38.7
7	725.3	691.6	708.5	0.41284	2.60535	33.7	228	0.01548	1.3077×10^{-6}	180	33.7
6	721.3	691.3	706.3	0.41159	2.23996	30	228	0.01548	1.3077×10^{-6}	186	30
6	726.8	678.6	702.7	0.31691	2.90315	48.2	295	0.01550	1.3104×10^{-6}	231	48.2
7	730.6	674.7	702.7	0.31689	3.38725	55.9	295	0.01550	1.3104×10^{-6}	229	55.9
4.98	714	689	701.5	0.40879	1.87189	25	228	0.01548	1.3077×10^{-6}	185	25
7.14	729.4	672.3	700.9	0.31247	3.50385	57.1	298	0.01550	1.3104×10^{-6}	227	57.1
5.12	721.5	679.4	700.5	0.31230	2.51400	42.1	298	0.01550	1.3104×10^{-6}	233	42.1
8.06	733.2	667.4	700.3	0.31223	3.95843	65.8	298	0.01550	1.3104×10^{-6}	231	65.8
6.1	724.2	674.9	699.6	0.31189	2.99905	49.3	298	0.01550	1.3104×10^{-6}	229	49.3
6	713.8	684	698.9	0.40727	2.26367	29.8	228	0.01548	1.3077×10^{-6}	183	29.8
7	716.1	681.6	698.9	0.40724	2.64114	34.5	228	0.01548	1.3077×10^{-6}	181	34.5
5	711.2	686	698.6	0.40710	1.88721	25.2	228	0.01548	1.3077×10^{-6}	185	25.2
8	718.3	678.6	698.5	0.40701	3.02018	39.7	228	0.01548	1.3077×10^{-6}	182	39.7
5	716.4	675.8	696.1	0.31394	2.44223	40.6	295	0.01550	1.3104×10^{-6}	231	40.6
5.04	716.3	674.1	695.2	0.30996	2.49341	42.2	298	0.01550	1.3104×10^{-6}	235	42.2

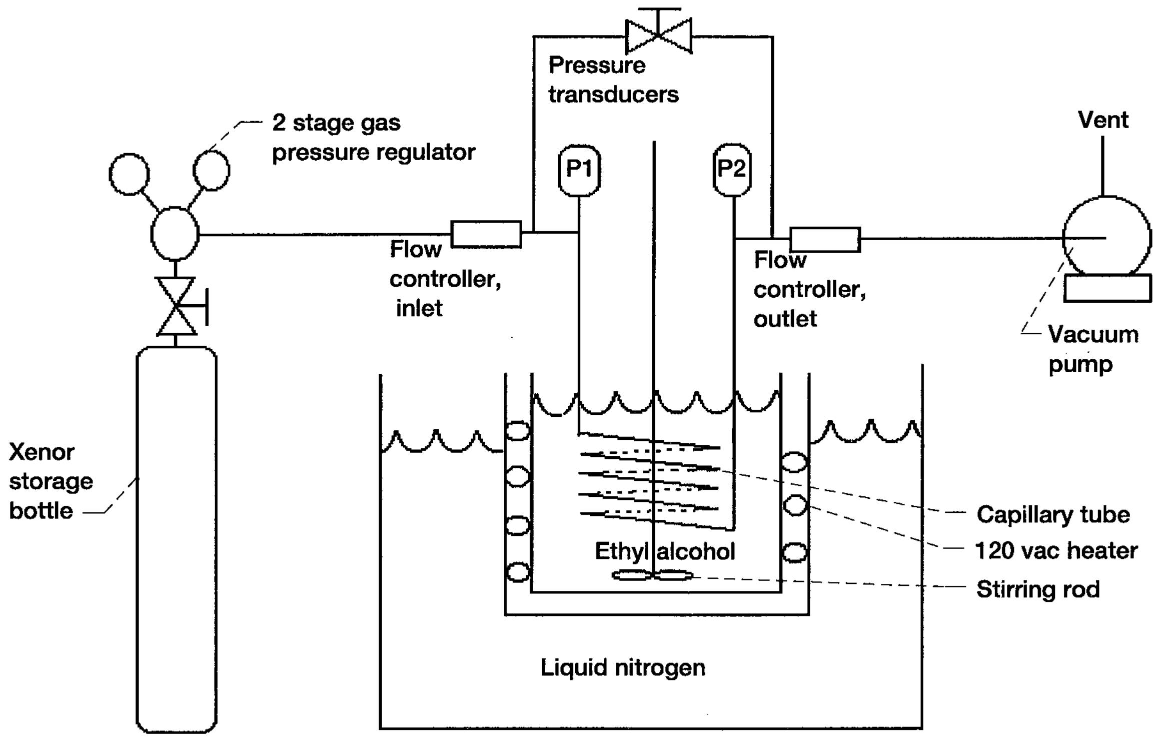

Figure 1.—Schematic diagram of experimental apparatus.

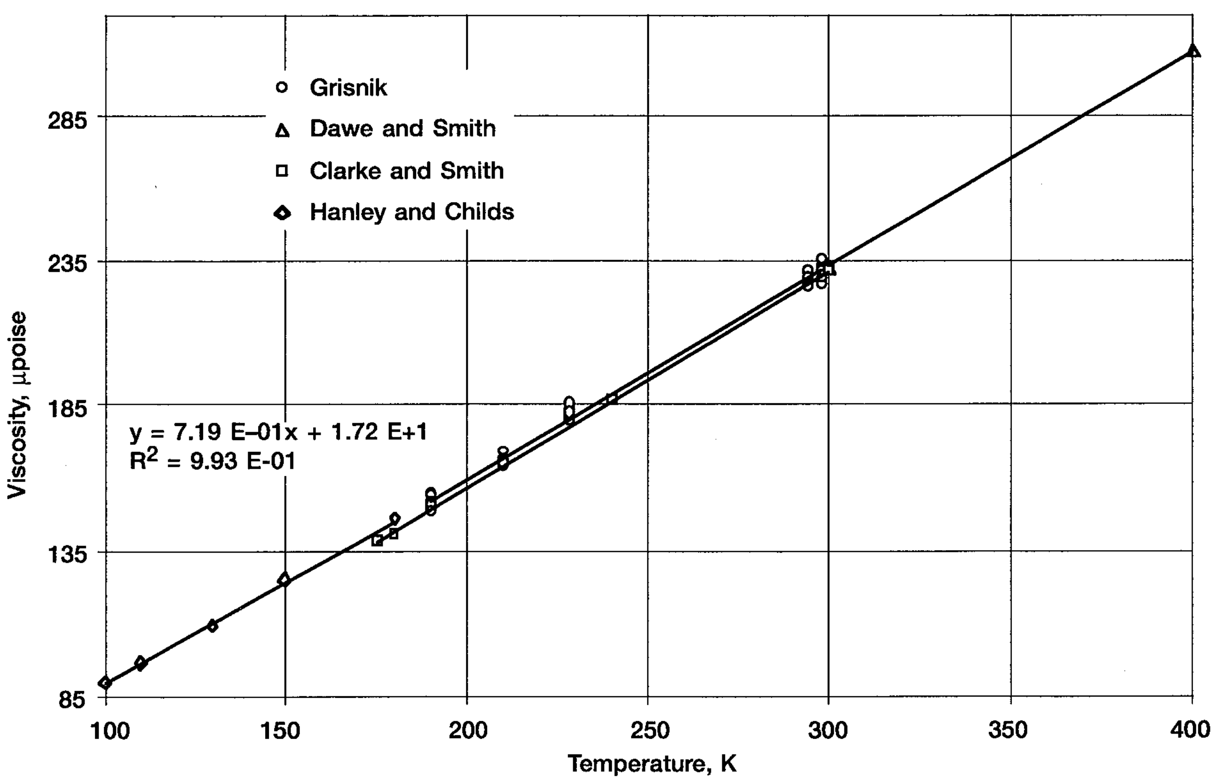

Figure 2.—Viscosity of gasous xenon vs temperature, 700-760 Torr.

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The measurement of xenon gas viscosity at low temperatures (175–298K) and low pressures (350 torr–760 torr) has been performed in support of Hall Thruster testing at NASA Lewis Research Center. The measurements were taken using the capillary flow technique. Viscosity measurements were repeatable to within 3%. The results in this paper are in agreement with data from Hanley and Childs and suggest that the data from Clarke and Smith is approximately 2% low. There are no noticeable pressure effects on xenon absolute viscosity for the pressure range from 350 torr to 760 torr.

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