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U.S. DEPARTMENT OF COMMERCE/National Bureau of Standards **Interpolation Formulas for Viscosity of Six Gases:** Air, Nitrogen, Carbon Dioxide, Helium, Argon, and Oxygen QC-100 .115753

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### Interpolation Formulas for Viscosity of Six Gases: Air, Nitrogen, Carbon Dioxide, Helium, Argon, and Oxygen

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#### INTERPOLATION FORMULAS FOR VISCOSITY OF SIX GASES: AIR, NITROGEN, CARBON DIOXIDE, HELIUM, ARGON, AND OXYGEN

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Equations for the calculation of viscosity for dry air, nitrogen, carbon dioxide, helium, argon, and oxygen have been developed as interpolation formulas fitted to experimental data. The approximate ranges of strict application of the equations are the ranges of temperature  $(20^{\circ}C \le t \le 50^{\circ}C)$  and pressure  $(0.04 \le p \le 4$  MPa;  $0.4 \le p \le 40$  atm) for the experimental data. The estimates of relative residual standard deviation for the fits (0.05% for air, 0.03% for nitrogen, 0.02% for carbon dioxide, 0.02% for helium, 0.03% for argon, and 0.03% for oxygen) are in close agreement with estimates of precision for the experimental data.

Key words: Air; argon; calculation; carbon dioxide; helium; nitrogen; oxygen; viscosity.

#### 1. INTRODUCTION

In the calibration and use of flow metering devices the precise, accurate value of the viscosity of the gas being metered is often required. The availability of simple equations relating viscosity,  $\mu$ , to temperature, t, and pressure, p, would be a convenience to the engineer in calculating  $\mu$ . In the present work, simple interpolation formulas have been developed which enable the engineer to conveniently make precise, accurate calculations of  $\mu$  for dry air, nitrogen, carbon dioxide, helium, argon, and oxygen using small readily available hand-held calculators. The formulas are fitted to experimental data. The data were selected from the literature on the basis of claimed accuracy and precision, and of internal consistency. The last of these criteria is particularly important for the development of empirical equations for volume flow with a dominant term of the Poiseuille form, the subject of a later paper. The sets of data published by Kestin and

1

his collaborators [1-10] meet these criteria and have been used to develop the formulas.

#### 2. EXPERIMENTAL DATA

The ranges of temperature and pressure of interest in the present work are  $0^{\circ}C < t < 50^{\circ}C$  and 0 MPa (<math>0 atm). Theexperimental data used in developing the equations for  $\mu$  are listed in Tables 1-6. In Table'l for dry air, the data in the first and third groups are taken from Table III of [1]; the second and fourth groups are taken from Table II of [2]; and the 50.00°C point is inferred from the data in [2]. In Table 2 for nitrogen, the first and third groups are taken from Table XI of [1]; the second, fifth, and sixth groups are taken from Table VIII of [2]; the fourth group is taken from Table III of [3]; the 20.58°C point is taken from Table XI of [1]; and the 24.920°C point is taken from Table III of [3]. In Table 3 for carbon dioxide, the 20.00°C data are taken from Table V of [1]; the second group is taken from Table IV of [2]; and the 25.00°C point is taken from Table III of [4]. In Table 4 for helium, the first group is taken from Table VII of [1]; the 25.00°C point is taken from Table IV of [5]; and the third group is taken from Table V of [2]. In Table 5 for argon, the first and second groups are taken from Table IV of [1]; the third group is taken from Table IV of [3]; and the fourth group is taken from Table III of [2]. In Table 6 for oxygen, the first and second groups are adjusted values from Table XII of [1]; the third group is taken from Table V of [10].

2

#### 3. DEVELOPMENT OF EQUATIONS

The equations for  $\mu$  (t,p) were developed using a procedure [6] in which  $\mu$ (t,p) is expressed as

$$\mu(t,p) = \mu_{0}(t,0) + \Delta \mu(p).$$
 (1)

where  $\mu_0$  (t,0) is the viscosity at "zero pressure" and  $\Delta\mu(p)$  is the experimental value of viscosity,  $\mu_{meas.}$ , minus  $\mu_0$  (t,0). The procedure will be outlined below.

#### Air

The data pairs,  $(20.00^{\circ}\text{C}, 181.94 \ \mu\text{g/cm}\cdot\text{s})$ ,  $(23.44^{\circ}\text{C}, 183.75 \ \mu\text{g/cm}\cdot\text{s})$ ,  $(23.90^{\circ}\text{C}, 184.21 \ \mu\text{g/cm}\cdot\text{s})$ ,  $(25.00^{\circ}\text{C}, 184.62 \ \mu\text{g/cm}\cdot\text{s})$ , and  $(50.00^{\circ}\text{C}, 197.31 \ \mu\text{g/cm}\cdot\text{s})$ , taken from Table 1, were fitted by least squares to an equation quadratic in t to enable calculation of  $\mu$  at 0.101325 MPa,  $\mu_{1}$ . The small departures of p from this value of pressure for these pairs are not significant. The resulting equation is

$$\mu_1 = 170.368 + 0.605434 t - 1.33200 \times 10^{-3} t^2$$
, (2)

where  $\mu_{1}$  is in  $\mu$ g/cm·s and t is in °C. To reduce  $\mu_{1}$  to "zero pressure,"  $\mu_{0}$ , the value of the increase in  $\mu$  per 0.10325 MPa, 0.11  $\mu$ g/cm·s, estimated from the tabulated data was subtracted from  $\mu_{1}$  resulting in

 $\mu_0 = 170.258 + 0.605434 t - 1.33200 \times 10^{-3} t^2.$  (3)

Calculated values of  $\mu_0$  are listed in Table 1.

The difference,  $\Delta\mu$ , between the experimental values of  $\mu$  and calculated values of  $\mu_0$  is also listed in Table 1. The values of  $\Delta\mu$  were fitted by least squares to an equation quadratic in p. The resulting equation is

$$\Delta \mu = -2.44358 \times 10^{-3} + 1.17237 \text{ p} + 0.125541 \text{ p}^2.$$
 (4)

Equations (3) and (4) were added together to synthesize the final equation for calculating  $\mu$ :

<sup>$$\mu$$</sup>calc. =  $\mu_0 + \Delta \mu$  = 170.256 + 0.605434 t - 1.33200 x 10<sup>-3</sup> t<sup>2</sup>

+ 1.17237 p + 0.125639 
$$p^2$$
, (5)

where  $\mu_{calc.}$  is in  $\mu g/cm \cdot s$ , t is in  $\underline{^{\circ}C}$ , and p is in <u>MPa</u>. Values of  $\mu_{calc.}$  and differences between  $\mu_{calc.}$  and experimental values,  $\mu_{meas.}$ , are listed in Table 1.

The estimate of residual standard deviation (RSD), that is, the estimate of the standard deviation of  $\mu_{calc}$ .  $^{-\mu}_{meas}$ , is 0.10 µg/cm·s for the 19 differences (n=19). The estimate of the relative residual standard deviation (RRSD), that is, the ratio of RSD to the mean  $\mu_{meas}$ , is 0.05%. Kestin and Leidenfrost [1] estimated that for their measurements "a precision ranging from ±0.01% to ±0.07%, depending on the gas, has been achieved. The final accuracy of the measurements is estimated to be of the order of ±0.05%." DiPippo and Kestin [2] estimated the precision of their data to be ±0.05%; they reached the conclusion that "no meaningful assessment of the <u>accuracy</u> of the present data can be given if by accuracy we mean the <u>irreducible</u> discrepancy between the best measurements available at any particular time."

4

For  $\mu$  in  $\mu$ Pa·s, t in <u>°C</u>, and p in <u>MPa</u>, equation (5) becomes

$$^{\mu}$$
calc. = 17.0256 + 6.05434 x 10<sup>-2</sup> t -1.33200 x 10<sup>-4</sup> t<sup>2</sup>  
+ 0.117237 p + 1.25639 x 10<sup>-2</sup> p<sup>2</sup>. (6)

For  $\mu$  in <u>10<sup>-6</sup> lb ft<sup>-1</sup> sec<sup>-1</sup></u>, t in <u>°C</u>, and p in <u>PSI</u>, equation (5) becomes

$$^{\mu}$$
calc. = 11.4407 + 4.06833 x 10<sup>-2</sup> t -8.95063 x 10<sup>-5</sup> t<sup>2</sup>

+ 5.43165 x 
$$10^{-4}$$
 p + 4.01338 x  $10^{-7}$  p<sup>2</sup>. (7)

#### Nitrogen

The data pairs,  $(20.58^{\circ}C, 175.93 \ \mu g/cm \cdot s)$ ,  $(21.98^{\circ}C, 176.56 \ \mu g/cm \cdot s)$ ,  $(23.15^{\circ}C, 177.05 \ \mu g/cm \cdot s)$ ,  $(24.920^{\circ}C, 177.94 \ \mu g/cm \cdot s)$ ,  $(29.75^{\circ}C, 180.08 \ \mu g/cm \cdot s)$ , and  $(49.37^{\circ}C, 189.71 \ \mu g/cm \cdot s)$ , taken from Table 2, were fitted by least squares to an equation quadratic in t to enable calculation of  $\mu_1$ . The resulting equation is

$$\mu_1 = 167.335 + 0.392728 t + 1.22474 x 10^{-3} t^2$$
. (8)

To reduce  $\mu_1$  to  $\mu_0$ , 0.11  $\mu$ g/cm·s estimated from the tabulated data was subtracted from  $\mu_1$  resulting in

$$\mu_{o} = 167.225 + 0.392728 t + 1.22474 x 10^{-3} t^{2}$$
. (9)

The values of  $\Delta\mu$  were fitted by least squares to an equation quadratic in p. The resulting equation is

$$\Delta \mu$$
 = -1.12860 x 10<sup>-2</sup> + 1.24165 p + 9.87206 x 10<sup>-2</sup> p<sup>2</sup>. (10)

Equations (9) and (10) were added together to synthesize the final equation for calculating  $\mu$ :

$$^{\mu}$$
 calc. = 167.214 + 0.392728 t + 1.22474 x 10<sup>-3</sup> t<sup>2</sup>

+ 1.24165 p + 9.87206 x 
$$10^{-2}$$
 p<sup>2</sup>, (11)

where  $\mu_{calc.}$  is in  $\underline{\mu g/cm \cdot s}$ , t is in  $\underline{\circ C}$ , and p is in <u>MPa</u>.

The RSD is 0.05  $\mu$ g/cm·s for n = 50; the RRSD is 0.03%. Kestin et. al. [3] estimated the accuracy of their experimental measurements to be of the order of <u>+0.2%</u> and the relative precision to be 0.03%. The accuracy and precision estimates quoted above for air from [1] and [2] apply also to nitrogen.

For  $\mu$  in  $\mu$ Pa·s, t in <u>°C</u>, and p in <u>MPa</u>, equation (11) becomes

 $\mu_{calc.} = 16.7214 + 3.92728 \times 10^{-2} t + 1.22474 \times 10^{-4} t^{2}$ 

+ 0.124165 p + 9.87206 x  $10^{-3}$  p<sup>2</sup>. (12)

For  $\mu$  in <u>10<sup>-6</sup> lb ft<sup>-1</sup> sec<sup>-1</sup></u>, t in <u>°C</u>, and p in <u>PSI</u>, equation (11) becomes

 $\mu_{calc.}$  = 11.2363 + 2.63901 x 10<sup>-2</sup> t + 8.22987 x 10<sup>-5</sup> t<sup>2</sup>

+ 5.75263 x 
$$10^{-4}$$
 p + 3.15351 x  $10^{-7}$  p<sup>2</sup>. (13)

#### Carbon Dioxide

The data pairs, (20.00°C, 146.63  $\mu$ g/cm·s), (25.00°C, 149.09  $\mu$ g/cm·s), (30.40°C, 151.81  $\mu$ g/cm·s), and (49.12°C, 161.75  $\mu$ g/cm·s), taken from Table 3, were fitted by least squares to an equation quadratic in t to enable calculation of  $\mu_1$ . The resulting equation is

$$\mu_1 = 137.335 + 0.441133 t + 1.12987 \times 10^{-3} t^2$$
. (14)

To reduce  $\mu_1$  to  $\mu_0$ , 0.13  $\mu$ g/cm·s estimated from the tabulated data was subtracted from  $\mu_1$  resulting in

$$\mu_0 = 137.205 + 0.441133 t + 1.12987 \times 10^{-3} t^2$$
. (15)

The values of  ${\scriptstyle\Delta}_{\mu}$  were fitted by least squares to an equation quadratic in p. The resulting equation is

$$\Delta \mu = 0.133827 + 6.28105 \times 10^{-2} p + 0.562974 p^2.$$
 (16)

Equations (15) and (16) were added together to synthesize the final equation for calculating  $\mu$ :

$$^{\mu}$$
calc. = 137.339 + 0.441133 t + 1.12987 x 10<sup>-3</sup> t<sup>2</sup>  
+ 6.28105 x 10<sup>-2</sup> p + 0.562974 p<sup>2</sup>, (17)

where  $\mu_{calc.}$  is in  $\mu g/cm \cdot s$ , t is in  $\underline{\circ}C$ , and p is in <u>MPa</u>.

The RSD is 0.04  $\mu$ g/cm·s for n = 11; the RRSD is 0.02%. Kestin et. al. [4] estimated the accuracy of the 25.00°C point, "expressed as the maximum estimated uncertainty in the quoted values," to be  $\pm 0.1\%$ . The accuracy and precision estimates quoted above for air from [1] and [2] apply also to carbon dioxide.

For  $\mu$  in  $\mu$ Pa·s, t in °C, and p in MPa, equation (17) becomes

$$^{\mu}calc. = 13.7339 + 4.41133 \times 10^{-2} t + 1.12987 \times 10^{-4} t^{2}$$
$$+ 6.28105 \times 10^{-3} p + 5.62974 \times 10^{-2} p^{2}.$$
(18)

For  $\mu$  in <u>10<sup>-6</sup> 1b ft<sup>-1</sup> sec<sup>-1</sup></u>, t in <u>°C</u>, and p in <u>PSI</u>, equation (17) becomes

$$^{\mu}$$
calc. = 9.22876 + 2.96428 x 10<sup>-2</sup> t + 7.59238 x 10<sup>-5</sup> t<sup>2</sup>

+ 2.91005 x 
$$10^{-5}$$
 p + 1.79836 x  $10^{-6}$  p<sup>2</sup>. (19)

#### Helium

The data pairs, (20.00°C, 196.14  $\mu$ g/cm·s), (24.28°C, 198.19  $\mu$ g/cm·s), (25.00°C, 198.59  $\mu$ g/cm·s), (30.56°C, 201.18  $\mu$ g/cm·s), and (52.79°C, 211.04  $\mu$ g/cm·s), were fitted by least squares to an equation quadratic in t to enable calculation of  $\mu_{1}$ . The effect of pressure on  $\mu$  for helium is so small that no correction is made to reduce  $\mu_{1}$  to  $\mu_{0}$ . The resulting equation is

$$\mu_1 = \mu_0 = 185.946 + 0.530773 t - 1.04982 \times 10^{-3} t^2$$
. (20)

The values of  $\Delta\mu$  were fitted by least squares to an equation linear in p. The resulting equation is

$$\Delta \mu = 2.91664 \times 10^{-2} - 6.99813 \times 10^{-2} p.$$
 (21)

Equations (20) and (21) were added together to synthesize the final equation for calculating  $\mu$ :

calc. = 
$$185.975 + 0.530773 t - 1.04982 \times 10^{-3} t^2$$
  
-  $6.99813 \times 10^{-2} p$ , (22)

where  $\mu_{calc.}$  is in  $\mu g/cm \cdot s$ , t is in  $\underline{\circ}C$ , and p is in MPa.

μ

The RSD is 0.04  $\mu$ g/cm·s for n = 15; the RRSD is 0.02%. The accuracy and precision estimates quoted above for air from [1] and [2] apply also to helium. The 25.00°C °C value is estimated to be accurate within <u>+</u> 0.1% [5].

For  $\mu$  in  $\mu$ Pa·s, t in <u>°C</u>, and p in <u>MPa</u>, equation (22) becomes

$$^{\mu}$$
calc. = 18.5975 + 5.30773 x 10<sup>-2</sup> t - 1.04982 x 10<sup>-4</sup> t<sup>2</sup>

$$- 6.99813 \times 10^{-3} \text{ p.}$$
(23)

For  $\mu$  in <u>10<sup>-6</sup> lb ft<sup>-1</sup> sec<sup>-1</sup></u>, t in <u>°C</u>, and p in <u>PSI</u>, equation (22) becomes

$$^{\mu}$$
calc. = 12.4969 + 3.56663 x 10<sup>-2</sup> t - 7.05446 x 10<sup>-5</sup> t<sup>2</sup>

$$-3.24228 \times 10^{-5}$$
 p. (24)

#### Argon

The data pairs, (20.00°C, 222.86  $\mu$ g/cm·s), (24.39°C, 225.79  $\mu$ g/cm·s), (25.00°C, 226.36  $\mu$ g/cm·s), and (50.31°C, 243.43  $\mu$ g/cm·s), taken from Table 5, were fitted by least squares to an equation quadratic in t to enable calculation of  $\mu_1$ . The resulting equation is

$$\mu_1 = 208.940 \div 0.702190 t - 3.30712 \times 10^{-4} t^2$$
. (25)

To reduce  $\mu_1$  to  $\mu_0$ , 0.21  $\mu$ g/cm·s estimated from the tabulated data was subtracted from  $\mu_1$  resulting in

$$\mu_0 = 208.730 + 0.702190 t - 3.30712 \times 10^{-4} t^2$$
. (26)

The values of  $\Delta\mu$  were fitted by least squares to an equation quadratic in p. The resulting equation is

$$\Delta \mu = 3.17420 \times 10^{-2} + 1.73987 \text{ p} + 0.152358 \text{ p}^2.$$
 (27)

Equations (26) and (27) were added together to synthesize the final equation for calculating  $\mu$ :

$$\mu_{calc.} = 208.762 + 0.702190 t - 3.30712 \times 10^{-4} t^2$$
  
+ 1.73987 p + 0.152358 p<sup>2</sup>, (28)

where  $\mu_{calc.}$  is in  $\mu g/cm \cdot s$ , t is in  $\underline{\circ}C$ , and p is in <u>MPa</u>.

The RSD is 0.07  $\mu$ g/cm·s for n = 38; the RRSD is 0.03%. The estimates of accuracy and precision of the experimental data for argon are those quoted above from [1], [2], and [3].

For  $\mu$  in  $\mu$ Pa·s, t in °C, and p in MPa, equation (28) becomes

$$^{\mu}$$
 calc. = 20.8762 + 7.02190 x 10<sup>-2</sup> t - 3.30712 x 10<sup>-5</sup> t<sup>2</sup>

+ 0.173987 p + 1.52358 x 
$$10^{-2}$$
 p<sup>2</sup>. (29)

$$^{\mu}$$
calc. = 14.0282 + 4.71850 x 10<sup>-2</sup> t - 2.22228 x 10<sup>-5</sup> t<sup>2</sup>

+ 8.06091 x 
$$10^{-4}$$
 p + 4.86689 x  $10^{-7}$  p<sup>2</sup>. (30)

#### Oxygen

The data pairs,  $(20.00^{\circ}C, 203.17 \ \mu g/cm \cdot s)$ ,  $(25.00^{\circ}C, 206.25 \ \mu g/cm \cdot s)$ ,  $(35.00^{\circ}C, 212.18 \ \mu g/cm \cdot s)$ , and  $(50.00^{\circ}C, 220.80 \ \mu g/cm \cdot s)$ , taken from Table 6, were fitted by least squares to an equation quadratic in t to enable calculation of  $\mu_1$ . The resulting equation is

$$\mu_1 = 190.539 + 0.650043 t - 8.97542 \times 10^{-4} t^2.$$
 (31)

To reduce  $\mu_1$  to  $\mu_0$ , 0.12  $\mu$ g/cm·s estimated from the tabulated data was subtracted from  $\mu_1$  resulting in

$$\mu_0 = 190.419 + 0.650043 t - 8.97542 \times 10^{-4} t^2.$$
 (32)

The values of  $\Delta\mu$  were fitted by least squares to an equation quadratic in p. The resulting equation is

$$\Delta \mu = -0.0239595 + 0.130897 \text{ p} + 1.323418 \times 10^{-3} \text{ p}^2. \tag{33}$$

Equations (32) and (33) were added together to synthesize the final equation for calculating  $\mu$ :

$$^{\mu}$$
calc. = 190.395 + 0.650043 t - 8.97542 x 10<sup>-4</sup> t<sup>2</sup>  
+ 0.130897 p + 1.32418 x 10<sup>-3</sup> p<sup>2</sup> (34)

where  $\mu_{calc}$  is in  $\mu g/cm \cdot s$ , t is in °C, and p is in atm.

The RSD is 0.06 g/cm s for n = 16; the RRSD is 0.03%. The estimates of accuracy and precision of the experimental data for oxygen are those quoted above from [1], [2], and [3].

For  $\mu$  in  $\mu$ Pa·s, t in °C, and p in MPa, equation (34) becomes

$$^{\mu}calc. = 19.0395 + 6.50043 \times 10^{-2} t - 8.97542 \times 10^{-5} t^{2} + 0.129185 p + 1.28975 \times 10^{-2} p^{2}.$$
 (35)

For  $\mu$  in <u>10<sup>-6</sup> lb ft<sup>-1</sup> sec<sup>-1</sup></u>, t in <u>°C</u>, and p in <u>PSI</u>, equation (34) becomes

calc. = 
$$12.7940 + 4.36809 \times 10^{-2} t - 6.03121 \times 10^{-5} t^{2}$$
  
+  $5.98525 \times 10^{-4} p + 4.11587 \times 10^{-7} p^{2}$ . (36)

#### 4. RANGES OF APPLICATION OF THE EQUATIONS

The equations developed in this paper are <u>interpolation</u> formulas fitted to experimental data. The range of strict application is indicated by the range of t and p of the experimental data listed in Tables 1-5. In the absence of measurements of  $\mu$  for temperatures below 20°C of comparable quality to that of the data in the tables, there are two options in extending calculations <u>below</u> 20°C (0 < t < 20°C): 1) apply the extended law of corresponding states [3,7-10]; 2) <u>extrapolate</u> using the equations developed here, with probable loss in accuracy. Either option might be followed until suitable experimental data at temperatures below 20°C became available. Hanley et al. [11] have developed a functional form to represent critically evaluated viscosity and thermal conductivity coefficient data, and have generated tables. The gases treated by Hanley et al. include nitrogen and argon. Values of  $\mu$  calculated using the formulas in the present work have been compared with interpolated values from the tables in [11] at 0°C, 5°C, 10°C, 15°C, 20°C, and 25°C, and 0.1 MPa, for nitrogen and argon. The deviation of the values in the present work from the values from reference [11], expressed in percent are: for nitrogen, +0.26% at 0°C, +0.02% at 5°C, -0.12% at 10°C, -0.28% at 15°C, -0.32% at 20°C, and -0.38% at 25°C; for argon, -1.16% at 0°C, -1.10% at 5°C, -0.99% at 10°C, -0.86% at 15°C, -0.78% at 20°C, and -0.66% at 25°C. These deviations are all well within the uncertainty, + 2%, estimated by Hanley et al. for their tables.

#### 5. CONCLUSIONS

Equations (interpolation formulas fitted to experimental data) for the calculation of  $\mu$  for dry air, nitrogen, carbon dioxide, helium, argon, and oxygen have been developed. The estimates of relative residual standard deviation for the fits are in close agreement with the estimates of precision for the experimental data in the above stated ranges.

#### 6. ACKNOWLEDGMENTS

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13

#### Nomenclature

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p = pressure
RRSD = estimate of relative residual standard deviation
RSD = estimate of residual standard deviation
t = temperature in °C
\Delta \mu = \mu_{meas}.^{-\mu}o
\mu = viscosity
\mu_{calc.} = calculated value of viscosity
\mu_{meas.} = experimental value of viscosity
\mu_{0} = viscosity at "zero pressure"
<math>\mu_{1} = viscosity at 0.101325 MPa
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Temp., t, (C)	Press., P, (atm)	µmeas. (µg/cm∙s)	μ <sub>0</sub> (μg/cm·s)	<sup>∆μ</sup> (µg/cm⋅s)	<sup>μ</sup> calc. (μg/cm.s)	<sup>μ</sup> calc <sup>μ</sup> meas (μg/cm.s)
20.00 20.00	1.00 4.39	181.94 182.38	181.83 181.83	0.11 0.55	181.95 182.37	+0.01
20.00	11.22	182.84 183.32	181.83 181.83	1.49	182.83 183.32	0.00
20.00 20.00	14.61 18.03	183.88 184.40	181.83 181.83	2.05 2.67	183.84 184 39	-0.04 -0.01
20.00	21.40	184.98	181.83	3.15	184.96	-0.02
20.00	34.97	187.70	181.83	5.87	187.56	-0.14
23.44	1.07	183.75	183.72	0.03	183.85	+0.10
24.68	0.69	184.45	184.39	0.06	184.47	+0.02
24.00	1.71	184.33	184.02	0.31	184.22	-0.11
23.90	1.04	184.21	183.97	0.24	184.09	-0.12
23.89	0.83	184.13	183.96	0.17	184.06	-0.07
23.97	0.42	184.08	184.00	0.08	184.05	-0.03
25.00	1.00	184.62	184.56	0.06	184.68	+0.06
24.99	18.01	186.98	184.56	2.42	187.12	+0.14
24.99	35.12	190.18	184.56	5.62	190.32	+0.14
49.91	1.70	197.25	197.16	0.09	197.36	+0.11
49.39	1.08	196.99	196.91	0.08	197.04	+0.05
<sup>a</sup> 50.00	1.00	197.31				

Table l Viscosity of Dry Air

<sup>a</sup>Used for calculating  $\mu_1$  only.

<sup>μ</sup> calc <sup>μ</sup> meas. (μg/cm.s)	-0.07 -0.08 +0.02 +0.03 +0.07 +0.07 +0.03 +0.03 +0.03	+0.02 +0.01 -0.03 +0.04 +0.03 +0.03 +0.03 +0.03	+0.05 +0.04 -0.04 +0.01
<sup>μ</sup> calc. (μg/cm.s)	181.17 178.56 178.56 178.16 177.61 177.09 177.09 176.13 176.13 175.65 175.65	176.54 176.57 177.77 177.79 177.90 177.99 177.99 177.13 177.08	184.84 182.16 179.85 178.84 177.92
<sup>Δμ</sup> (µg/cm⋅s)	5.67 3.07 2.57 1.39 0.93 0.12 0.05 0.05	0.17 0.11 0.25 0.18 0.18 0.12 0.16 0.16 0.18 0.18	6.98 4.31 2.08 1.02 0.15
μ <sub>0</sub> (μg/cm.s)	175.57 175.57 175.57 175.57 175.57 175.57 175.57 175.57 175.57	176.35 176.45 177.55 177.61 177.68 177.84 177.88 177.88 177.00 176.97	177.81 177.81 177.81 177.81 177.81
<sup>μ</sup> meas. (µg/cm•s)	181.24 178.64 178.14 177.58 176.96 176.06 175.69 175.69 175.57	176.52 176.56 177.80 177.84 177.86 177.86 177.99 177.05	184.79 182.12 179.89 178.83 177.96
Press., P, (atm)	34.82 20.48 18.04 14.59 7.79 4.38 1.00 0.687 0.385	1.57 1.06 1.53 1.53 1.15 1.10 1.04	41.86 28.21 14.60 7.80 0.991
Temp., t, (C)	20.00 20.00 20.00 20.00 20.00 20.00 20.00	21.75 21.75 21.98 24.56 24.72 24.72 24.72 24.72 23.15 23.15 23.15	25.00 25.00 25.00 25.00 25.00

Viscosity of Nitrogen

Table 2

<sup>μ</sup> calc <sup>μ</sup> meas. (μg/cm.s)	-0.05 -0.04 -0.04	0.00-0.04	-0.04 +0.01	-0.06 -0.05	-0.04	-0.03	-0.02	-0.05	+0.02	+0.07	-0.03	-0.04	+0.01	+0.03+0.08	+0.04 -0.03 +0.01	
<sup>μ</sup> calc. (μg/cm.s)	177.93 178.02 178.09	178.19 178.28	178.37 178.45	178.53 178.68	178.77	179.01	179.15	179.54	179.90	181.52	182.46	183.41	184.44	180.11 180.20	190.02 189.98 189.72	
<sup>∆μ</sup> (µg/cm⋅s)	0.17 0.25 0.32	0.38 0.51	0.60 0.63	0.78 0.92	1.00	1.23	1.36	1.78	2.07	3.64	4.68	5.64	6.62	0.09 0.04	0.16 0.23 0.11	
μ <mark>υ</mark> (μg/cm.s)	177.81 177.81 177.81	177.81 177.81	177.81 177.81	177.81 177.81	177.81	177.81	177.81	177.81	177.81	177.81	177.81	177.81	177.81	179.99 180.08	189.82 189.78 189.60	
μg/cm•s)	177.98 178.06 178.13	178.19 178.32	178.41 178.44	178.59 178-73	178.81	179.04	179.17	179.59	179.88	160.00 181.45	182.49	183.45	184.43	180.08 180.12	189.98 190.01 189.71	175.93 177.94
Press., P, (atm)	1.000 1.714 2.300	3.009 3.715	4.341 4.979	5.579 6 613	7.307	8.029 8.954	9.931	12.567	14.830	24,644	29.838	34.816	39.919	1.06 1.06	1.64 1.64 1.06	1.00
Temp., t, (C)	25.00 25.00 25.00	25.00 25.00	25.00 25.00	25.00 25.00	25.00	25.00 25.00	25.00	25.00	25.00 25.00	25.00	25.00	25.00	25.00	29.75 29.93	49.80 49.73 49.37	a20.58 a24.920

Table 2 (continued)

Nitrogen

<sup>a</sup>Used for calculating  $\mu_1$  only.

<sup>µ</sup> calc <sup>µ</sup> meas (µg/cm•s)	-0.01 +0.01 +0.02 -0.03 -0.03 +0.06	-0.04 0.00 0.00	0.00
<sup>μ</sup> calc. (μg/cm•s)	148.61 147.94 147.41 147.01 146.75 146.63 146.62	151.79 151.81 161.75	149.09
∆µ (µg/cm•s)	2.14 1.45 0.91 0.15 0.15 0.08	0.20 0.15 0.15	0.15
μ <sub>o</sub> (µg/cm•s)	146.48 146.48 146.48 146.48 146.48 146.48 146.48	151.63 151.66 161.60	148.94
<sup>μ</sup> meas. (µg/cm•s)	148.62 147.93 147.39 147.01 146.78 146.63 146.56	151.83 151.81 161.75	149.09
Press., P, (atm)	18.02 14.63 7.78 4.38 0.976 0.640	1.69 1.06 1.08	1.00
Temp., t, (C)	20.00 20.00 20.00 20.00 20.00 20.00	30.34 30.40 49.12	25.00

Viscosity of Carbon Dioxide

Table 3

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Viscosity of Helium

Temp., t, (C)	Press., P, (atm)	μmeas. (µg/cm•s)	µ₀ (µg/cm•s)	(µg/cm∙s)	<sup>μ</sup> calc. (μg/cm.s)	<sup>µ</sup> calc <sup>µ</sup> meas. ( <sub>µ</sub> g/cm.s)
20.00	34.85	195.94	196.14	-0.20	195.92	-0.02
20.00	21.40	195.99	196.14	-0.15	196.02	+0.03
20.00	18.00	196.02	196.14	-0.12	196.04	+0.02
20.00	14.61	196.09	196.14	-0.05	196.07	-0.02
20.00	11.19	196.03	196.14	-0.11	196.09	+0.06
20.00	7.80	196.17	196.14	+0.03	196.11	-0.06
20.00	4.39	196.19	196.14	+0.05	196.14	-0.05
20.00	1.01	196.14	196.14	0.00	196.16	+0.02
25.00	1.0	198.59	198.56	+0.03	198.58	-0.01
24.01	1.57	198.12	198.08	+0.04	198.10	-0.02
24.28	1.06	198.19	198.21	-0.02	198.23	+0.04
30.49	1.71	201.20	201.15	+0.05	201.17	-0.03
30.56	1.07	201.18	201.19	-0.01	201.21	+0.03
53.00	1.61	211.16	211.13	+0.03	211.15	-0.01
52.79	1.07	211.04	211.04	0.00	211.06	+0.02

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# Viscosity of Argon

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227.29
8 227.4
6 227.7
9 228.1
3 228.5
8 229.1
6 230.3
7 230.9
2 231.3
5 232.8
5 234.21
1 230.1

			Argon			
Temp., t, (C)	Press., P, (atm)	μmeas. (μg/cm•s)	μ <sub>0</sub> (μg/cm·s)	∆µ (µg/cm·s)	μcalc. (μg/cm•s)	<sup>μ</sup> calc <sup>μ</sup> meas (μg/cm•s)
24.33	1.56	225.83	225.62	+0.21	225.93	+0.10
24.39	1.07	225.79	225.66	+0.13	225.88	+0.09
49.37	1.73	242.68	242.59	+0.09	242.93	-0.25
49.43	1.46	243.05	242.63	+0.42	242.92	-0.13
49.83	1.22	243.17	242.90	+0.27	243.15	-0.02
50.31	1.08	243.43	243.22	+0.21	243.44	+0.01

Table 5 (continued)

<pre> µcalcµmeas (μg/cm.s)</pre>	-0.13 -0.04 -0.03 +0.01 +0.01 -0.03	+0.01 +0.04 +0.03 +0.13 -0.03	-0.03 0 -0.01
<sup>μ</sup> calc. (μg/cm·s)	206.44 205.42 205.23 204.67 204.13 203.17 203.17 203.12	213.88 210.83 208.28 207.19 206.22	206.22 212.18 220.79
∆µ (µg/cm·s)	3.51 2.80 2.13 1.64 1.64 0.55 0.55 0.07	7.76 4.68 2.14 0.95 0.14	0.14 0.11 0.12
μ <sub>0</sub> (μg/cm・s)	203.06 203.06 203.06 203.06 203.06 203.06 203.06 203.06 203.06	206.11 206.11 206.11 206.11 206.11	206.11 212.07 220.68
μmeas. (μg/cm°s)	206.57 205.86 205.19 204.70 204.12 203.17 203.13 203.13	213.87 210.79 208.25 207.06 206.25	206.25 212.18 220.80
Press., P, (atm)	21.40 18.02 14.58 11.19 7.77 4.39 0.981 0.634	41.83 28.22 14.61 7.80 0.998	
emp., t, (C)	20.00 20.00 20.00 20.00 20.00 20.00 20.00	25.00 25.00 25.00 25.00 25.00	25.00 35.00 50.00

Table 6 Viscosity of Oxygen

NBS-114A (REV. 2-80)						
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Equations for the helium, argon, ar experimental data are the ranges of $0.4 \le p \le 40$ atm) standard deviation carbon dioxide, (close agreement with the standard deviation dioxide) are the the standard deviation dioxide, the standard deviation dioxide devia	e calculation of visco nd oxygen have been de a. The approximate ra f temperature (20°C <u>&lt;</u> ) for the experimental on for the fits (0.05% 0.02% for helium, 0.03 with estimates of prec	sity for dry air, nitr veloped as interpolati nges of strict applica t < 50°C) and pressure data. The estimates for air, 0.03% for ni % for argon, and 0.03% ision for the experime	ogen, carbon dioxide, on formulas fitted to tion of the equations $(0.04 \le p \le 4 \text{ MPa};$ of relative residual trogen, 0.02% for for oxygen) are in ntal data.			
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