Dynamic Viscosity of Gas Mixtures

G. J. GURURAJA, M. A. TIRUNARAYANAN, and A. RAMACHANDRAN
Department of Mechanical Engineering, Indian Institute of Science, Bangalore-12, India

The viscosity of five binary gas mixtures—namely, oxygen-hydrogen, oxygen-nitrogen, oxygen–carbon dioxide, carbon dioxide–nitrogen, carbon dioxide–hydrogen—and two ternary mixtures—oxygen-nitrogen-carbon dioxide and oxygen–hydrogen–carbon dioxide—were determined at ambient temperature and pressure using an oscillating disk viscometer. The theoretical expressions of several investigators were in good agreement with the experimental results obtained with this viscometer. In the case of the ternary gas mixture oxygen–carbon dioxide–nitrogen, as long as the volumetric ratio of oxygen to carbon dioxide in the mixture was maintained at 11 to 8, the viscosity of the ternary mixture at ambient temperature and pressure remained constant irrespective of the percentage of nitrogen present in the mixture.

IN MANY engineering processes, particularly in transport phenomena, knowledge of the viscosity of gases and gas mixtures is necessary. Although viscosity data of pure gases are readily available, data for gas mixtures are lacking. An investigation was undertaken to determine the viscosity of binary and ternary gas mixtures resulting from the combination of hydrogen, oxygen, nitrogen, and carbon dioxide. Five binary mixtures, O_2–N_2, O_2–H_2, O_2–CO_2, CO_2–N_2, and CO_2–H_2, and two ternary mixtures, CO_2–O_2–N_2 and CO_2–O_2–H_2, were studied at ambient temperature and pressure.

There are several methods available for the determination of viscosity of gases. Kestin *et al.* (*4, 6, 9-12*) have recently established that the oscillating disk viscometer is suitable for the determination of viscosity of gases at high pressures and ambient temperature. An oscillating disk viscometer was designed and developed for the present investigation. The design and operation of the viscometer is similar to that used by Kestin and Pilarczyk (*9*). The following equations derived according to Newell's theory (*13*) were used for evaluating the viscosity of gas mixtures.

$$C_N = \left[\frac{2I}{\pi\rho\, bR^4}\left(\frac{\Delta}{\theta} - \Delta_0\right) + a\,\frac{\Delta}{\theta}\right]\beta^2 + \left[f\,\frac{3\Delta^2 - 1}{\theta^2}\right]\beta^4 + \left[h\,\frac{\Delta(\Delta^2 - 1)}{\theta}\right]\beta^6 \qquad (1)$$

$$\mu = \frac{2\pi\rho b^2}{\beta^2\, T_0} \qquad (2)$$

EXPERIMENTAL

Methods and Equipment. The oscillating disk viscometer employed in this investigation is shown in Figure 1. The main component parts are an oscillating disk, a fine suspension wire, two fixed plates, a stem with a mirror, and the container.

The oscillating disk, 1, is a lapped glass disk of about 70-mm. diameter having a hole of 3-mm. diameter at the center. A miniature, specially made, two-jaw chuck, 2, is fitted to the hole in the glass disk. Platinum-rhodium wire, 3, having a diameter of 0.002 inch, is used as the suspension wire. The wire is gripped at one end by the two-jaw chuck of the glass disk, the other end being held in four-jaw chuck, 4. The lower portion of the two-jaw chuck carries a brass stem, 5, of diameter 2-mm. and length 155-mm. A mirror 4 × 4 mm. is fixed at its lower end. This end of the brass stem is shaped to engage in an iron pole piece, 6, for starting the oscillations by an external magnet.

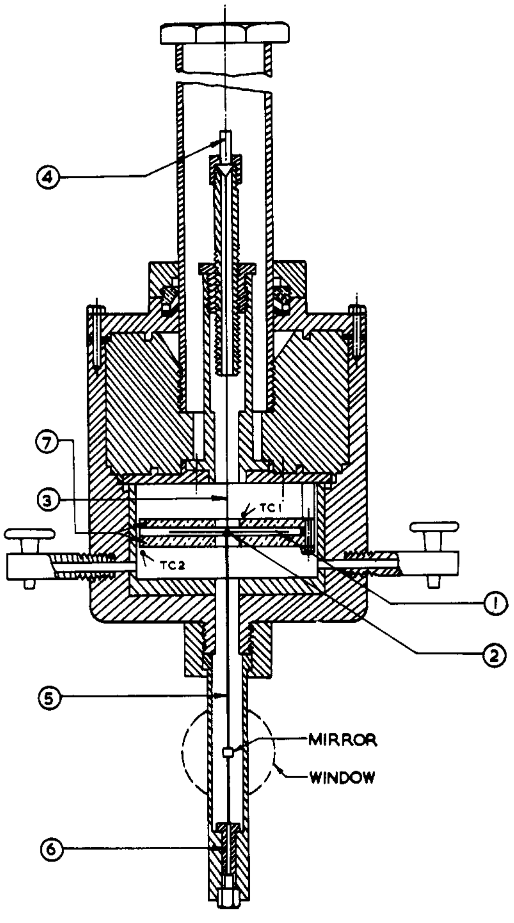

Figure 1. Oscillating disk viscometer

1. OSCILLATING DISK. (GLASS DISK)
2. TWO-JAW CHUCK.
3. Pt-Rh SUSPENSION WIRE.
4. FOUR-JAW CHUCK.
5. BRASS STEM.
6. POLE PIECE.
7. FIXED PLATES (LAPPED ALUMINIUM-DISKS)

TC 1, TC 2-THERMOCOUPLES.

The glass disk oscillates between the two lapped aluminium disks (fixed plates), 7. The gap between the oscillating disk and fixed aluminium disks is about 1 mm. Two calibrated copper-constantan thermocouples, TC_1, TC_2, located close to the fixed plates, are used to determine the temperature of the gas. The oscillations are observed with

Table I. Characteristics of the Suspension System

Radius of the disk	3.487 cm.
Moment of inertia of the suspension system	57.06 g. sq. cm.
Total gap, D	0.2997 cm.
Upper separation, b_1	0.0980 cm.
Lower separation, b_2	0.1019 cm.
Thickness of the disk, d	0.0998 cm.
Damping decrement in vacuum, Δ_0	0.0001
Period of oscillation in vacuum, T_0	34.28 sec.
Distance of the scale from the mirror	200.8 cm.

the help of a standard lamp and scale arrangement. The characteristics of the suspension system are given in Table I.

The gas mixtures for investigation were mixed outside the viscometer in a separate mixing chamber fitted with a needle valve and a combined vacuum and pressure gage. The residual gases were evacuated before filling the chamber with the test gas mixture. This mixture was allowed to remain thus for two days to ensure thorough mixing by diffusion. The gas mixture was periodically analyzed during this period using an Orsat apparatus to assure a homogeneous composition of the mixture. At the end of two days, experiments were conducted for the determination of viscosity.

The diameter of the glass disk was determined within 0.01% with a toolmaker's microscope and slip gages. The

Table II. Viscosity Data of Binary Gas Mixtures[a]

x_1, %	x_2, %	Period, T_1 Sec.	Damping Decrement, Δ	Temperature, °C.	Density, G./Cc.	Experimental Viscosity, $\mu \times 10^6$ Poise	Viscosity by Wilke's (17) Equation $\mu \times 10^6$ Poise	Viscosity by Saxena and Gambhir's (14) Equation, $\mu \times 10^6$ Poise
O_2–N_2 Mixture x_1 = % volume O_2 x_2 = % volume N_2								
0	100	...	...	25.02	...	177.96	...	...
13.2	86.8	34.49	0.0602	24.45	0.00117	178.50	181.20	...
25.6	74.4	34.50	0.0612	25.20	0.00114	184.50	185.50	...
41.0	59.0	34.50	0.0626	25.30	0.00117	188.55	190.18	...
51.0	49.0	34.51	0.0636	25.02	0.00118	191.00	192.70	...
66.0	34.0	34.51	0.0649	25.02	0.00120	196.50	197.95	...
76.0	24.0	34.51	0.0655	25.02	0.00122	197.50	199.80	...
100	0	34.54	0.0692	29.45	0.00125	208.00	...	...
O_2–CO_2 Mixture x_1 = % volume O_2 x_2 = % volume CO_2								
0	100	34.49	0.0500	27.55	0.00162	149.90	...	...
8.3	91.7	34.49	0.0520	24.40	0.00158	154.20	152.40	153.15
20.0	80.0	34.49	0.0534	24.40	0.00164	159.50	157.70	159.30
29.0	71.0	34.50	0.0557	25.00	0.00161	166.00	162.20	165.70
44.0	56.0	34.50	0.0574	25.00	0.00153	177.10	169.90	174.32
66.1	33.9	34.50	0.0614	25.00	0.00142	184.50	182.40	187.37
69.4	30.6	34.50	0.0619	25.00	0.00141	186.00	184.70	189.04
80.5	19.5	34.50	0.0634	24.20	0.00136	189.50	191.90	195.16
100	0	34.54	0.0692	29.45	0.00125	208.00	...	
N_2–CO_2 Mixture x_1 = % volume N_2 x_2 = % volume CO_2								
0	100	34.49	0.0500	27.55	0.00162	149.90	...	...
20.0	80.0	34.50	0.0521	23.80	0.00162	152.70	153.60	159.48
25.0	75.0	34.50	0.0524	24.78	0.00158	156.90	155.10	163.60
42.0	58.0	34.57	0.0542	24.00	0.00185	161.00	159.40	168.45
67.4	32.6	34.50	0.0562	23.45	0.00131	167.20	167.50	176.90
72.3	27.7	34.51	0.0567	24.00	0.00128	169.20	168.60	178.20
77.4	22.6	34.52	0.0566	23.80	0.00126	170.10	169.80	177.70
100	0	...	...	25.02	...	177.96	...	...
H_2–CO_2 Mixture x_1 = % volume H_2 x_2 = % volume CO_2								
0	100	34.49	0.0500	27.55	0.00162	149.90	...	...
10.0	90.0	34.50	0.0493	23.80	0.00158	148.52	150.80	...
22.0	78.0	34.50	0.0507	24.00	0.00138	150.42	150.50	...
44.0	56.0	34.50	0.0515	23.80	0.00101	150.70	151.90	...
61.6	38.4	34.50	0.0508	24.30	0.00072	150.00	149.10	...
63.0	37.0	34.50	0.0504	24.25	0.00070	149.00	148.80	...
O_2–H_2 Mixture x_1 = % volume O_2 x_2 = % volume H_2								
25.0	75.0	34.49	0.0520	24.00	0.00038	156.00	170.00	158.25
36.7	63.3	34.49	0.0567	24.20	0.00052	170.00	184.20	174.30
57.5	42.5	34.49	0.0619	24.20	0.00077	186.00	197.40	191.05
65.0	35.0	34.49	0.0638	24.00	0.00086	192.20	199.82	195.35
74.5	25.5	34.49	0.0642	24.20	0.00096	195.30	202.74	199.75
81.7	18.3	34.50	0.0652	24.20	0.00105	196.00	203.81	201.73
100	0	34.54	0.0692	29.45	0.00125	208.00	...	...

[a] All data at 14.2 p.s.i.a.

mass of the glass disk, the two-jaw chuck, and the brass stem with mirror was determined with a precision balance within 0.001%, and the moment of inertia of the oscillating system was known with an uncertainty of 0.01%. The harmonic mean separation, *b*, was known with an uncertainty better than 0.6% from careful measurements of upper separation, total gap between the two lapped aluminium disks, and thickness of the glass disk.

The period of oscillation in vacuum, T_0, was determined by an indirect method suggested by Kestin and Moszynski (*7*). The period of oscillation in the gas mixture, *T*, was measured with a precision stop watch, and two sets of readings for five complete oscillations were taken and averaged. The uncertainty in the measured time for five complete oscillations in any experiment was better than 0.06%.

The damping decrement in vacuum, Δ_0, for platinum-rhodium wire (*8*) is 0.0001. The damping decrement, Δ, in gas was calculated from the equation

$$\Delta = \frac{1}{2\pi m} \ln \frac{(\alpha_{n+m}) + (\beta_{n+m})}{\alpha_n + \beta_n} \tag{3}$$

where α_n, β_n are the angular amplitudes to the right and to the left, respectively, at the commencement of measurement for Δ and α_{n+m}, β_{n+m} are the corresponding angular amplitudes to the right and to the left after the completion of *m* oscillations. The angular amplitudes were evaluated from linear amplitudes to the right and to the left measured from the zero postion on the scale situated at a distance, *L*, from the mirror. The number of oscillations, *m*, was so chosen that the ratio $(\alpha_{n+m} + \beta_{n+m}/\alpha_n + \beta_n)$ was as near to the Napierian base *e* as possible. This improves the precision of the determination of Δ. Depending on the rate of damping, four or five values of Δ were obtained during each run and averaged. The average value of 18 to 20 decrements was taken as the final value of the decrement for the calculation of the viscosity.

The temperature of the gas mixture was measured with the two calibrated copper-constantan thermocouples; the e.m.f. developed was measured with a precision L and N potentiometer of accuracy 0.01 mv. The pressure of the gas mixture in the viscometer was kept slightly above atmospheric and was measured by a manometer. The absolute pressure of the gas was determined within 0.07%. The density of the gas mixture was estimated from the known values of pressure, temperature, and percentage composition. The uncertainties in the density estimates varied in extreme cases from 0.2 to 0.8% for the gas mixtures O_2-N_2, O_2-CO_2, CO_2-N_2, and CO_2-O_2-N_2. The uncertainties in the density estimates of the remaining gas mixtures O_2-H_2, CO_2-H_2, and CO_2-O_2-H_2 were larger owing to the presence of hydrogen and varied in extreme cases from 3 to 7%.

Calibration of the Viscometer. The apparatus was calibrated using nitrogen. The viscosity of nitrogen was taken from the published data indicated below:

Kestin and Pilarczyk (*9*), 175.55 × 10^{-6} poise at 21° C.

Temperature correction factor taken from (*9*), 0.455 × 10^{-6} poise per ° C.

Viscosity of N_2 corrected to 30.56° C. is 179.99 × 10^{-6} poise (average)

Temperature inside viscometer = 30.56° C.

Pressure in the viscometer = 14.20 p.s.i.a.

Period of oscillation in gas, T_1 = 34.35 seconds

Damping decrement in gas

$$\Delta = 0.0595$$

$$a = 0.66690$$

$$f = 0.02227$$

$$h = 0.00851$$

Substituting the relevant quantities in Equation 1 and neglecting Δ^3, the calibrated instrument constant was obtained as $C_N = 1.489$.

TEST RESULTS AND DISCUSSION

The viscosities of air, oxygen, and carbon dioxide were determined at ambient temperature and pressure to check the accuracy of the viscometer. The viscosity thus determined is compared with the data from other sources.

Viscosity of air: μ = 185.6 × 10^{-6} poise at 30.56° C. (present investigation). This value of the viscosity of air is compared with data of other investigators. All values are corrected to a temperature of 30.56° C.: μ = 186.47 × 10^{-6} poise, Bearden (*1*); μ = 186.80 × 10^{-6} poise, Hirschfelder, Bird, and Spotz (*3*); μ = 187.28 × 10^{-6} poise, Kestin and Leidenfrost (*6*); μ = 186.56 × 10^{-6} poise, Kestin and Wang (*10*).

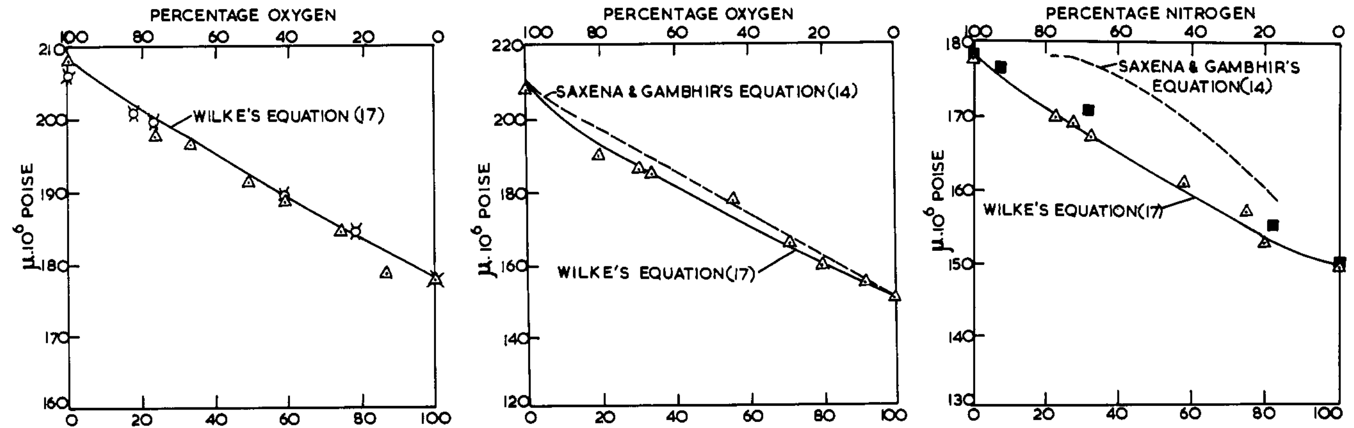

Figure 2. Viscosity data of O_2–N_2 (left), O_2–CO_2 (center), and N_2–CO_2 (right) mixtures

△ I.I.Sc DATA.

x BUDDENBERG & WILKE 25 °C (2)

o TRAUTZ & MELSTER 26·9 °C (15)

■ KESTIN, KOBAYASHI & WOOD 24·55 °C (5)

Viscosity of oxygen: $\mu = 208.00 \times 10^{-6}$ poise at 29.18° C. (present investigation). This value of the viscosity of oxygen is compared with the results of the following investigators. All values are corrected to a temperature of 29.18° C.: $\mu = 208.50 \times 10^{-6}$ poise, Hirschfelder, Bird, and Spotz (*3*); $\mu = 208.97 \times 10^{-6}$ poise, Kestin and Leidenfrost (*6*).

Viscosity of carbon dioxide: $\mu = 149.90 \times 10^{-6}$ poise at 27.55° C. (present investigation). The present results are compared with the data of Kestin and Leidenfrost (*6*) and Hirschfelder, Bird, and Spotz (*3*), the values being corrected to 27.55° C.: $\mu = 150.70 \times 10^{-6}$ poise, Kestin and Leidenfrost (*6*); $\mu = 149.80 \times 10^{-6}$ poise, Hirschfelder, Bird, and Spotz (*3*).

Data obtained in the present investigation agreed within ±1% of the data of earlier investigators (*1, 3, 6, 10*). This indicated the suitability of the apparatus for determining the viscosity of gas mixtures at ambient temperature and pressure.

Viscosity of Binary Gas Mixtures. The viscosity of binary gas mixtures investigated are given in Table II.

OXYGEN-NITROGEN. The data for the oxygen-nitrogen mixture are shown in Figure 2 and in Table II. Most of the experimental values agree within 1% of the equation given by Wilke (*17*). Also shown in the figure are the data of Buddenberg and Wilke (2) at 25° C., and Trautz and Melster (*15*) at 26.9° C. The present authors' results are in close agreement with the earlier data.

OXYGEN-CARBON DIOXIDE. The present experimental results are compared with the equations of Wilke (*17*) and Saxena and Gambhir (*14*) (Figure 2 and Table II). At lower percentages of oxygen, the Sexena and Gambhir's equation gives results which are in close agreement with the experimental results. Their equation, however, predicts slightly higher viscosity for percentages of oxygen between 30 and 90%, whereas Wilke's equation (*17*) is closer to the experimental data.

NITROGEN-CARBON DIOXIDE. The results of this gas mixture are shown in Figure 2 and Table II. Wilke's equation (*17*) is within about ±1% of the experimental results. The Saxena and Gambhir's equation (*14*) predicts viscosities which are higher than the experimental values. Also shown in Figure 2 are the experimental data of Kestin, Kobayashi, and Wood (*5*) at 24.55° C.

HYDROGEN-CARBON DIOXIDE. The results are presented in Table II and Figure 3. The small increase in viscosity with the addition of moderate amounts of hydrogen to carbon dioxide was followed by the instrument. The present experimental data are in good agreement with the equation of Wilke (*17*) and the results of Hirschfelder, Bird, and Spotz (*3*).

OXYGEN-HYDROGEN. The experimental results are shown in Figure 3 and Table II. The experimental results of Trautz and Melster (*15*) at 26.9° C., and Van Itterbeek, Van Paemel, and Vanlierde (*16*) at 20.6° C. are also shown on the same figure. Wilke's equation (*17*) gives values of viscosity which are higher than the experimental values, whereas those of Saxena and Gambhir (*14*) are in good agreement with the present results.

Viscosity of Ternary Gas Mixtures. OXYGEN-HYDROGEN-CARBON DIOXIDE. The experimental results are given in Table III. The data calculated from Wilke's (*17*) equation are shown for comparison. In general, the agreement is good. No experimental data are available in the literature for this combination.

OXYGEN-NITROGEN-CARBON DIOXIDE. The results of this ternary mixture are shown in Table III and compared with Wilke's equation. The agreement between experimental and theoretically predicted data is good. An interesting observation was made during this experimentation.

Wilke's (*17*) equation for a ternary mixture is:

$$\mu_m = \frac{\mu_1}{1 + (x_2/x_1)\,\phi_{12} + (x_3/x_1)\,\phi_{13}} + \frac{\mu_2}{1 + (x_3/x_2)\,\phi_{23} + (x_1/x_2)\,\phi_{21}} + \frac{\mu_3}{1 + (x_1/x_3)\,\phi_{31} + (x_2/x_3)\,\phi_{32}} \qquad (4)$$

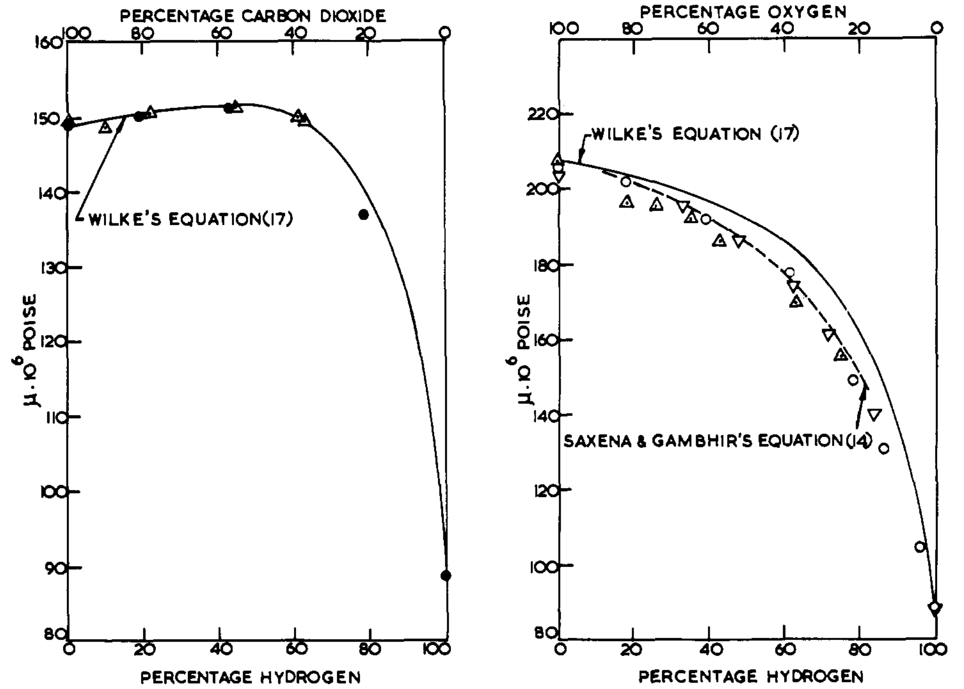

Figure 3. Viscosity data of H_2–CO_2 (left) and O_2–H_2 (right) mixtures

▲ I.I.Sc. DATA
● HIRSCHFELDER etal (3)
○ TRAUTZ & MELSTER 26·9 °C (15)
▽ VAN ITTERBEEK 20·6 °C (16)

Table III. Viscosity Data of Ternary Gas Mixtures[a]

x_1 %	x_2, %	x_3, %	Period, T_1 Sec.	Damping Decrement, Δ	Temperature, ° C.	Density, G./Cc.	Experimental Viscosity, $\mu \times 10^6$ Poise	Viscosity by Wilke's (17) Equation, $\mu \times 10^6$ Poise
				O_2-H_2-CO_2 Mixture				
		x_1 = % volume O_2		x_2 = % volume H_2		x_3 = % volume CO_2		
12.3	74.9	12.8	34.50	0.0541	25.30	0.00044	158.5	155.50
15.3	14.7	70.0	34.50	0.0530	25.80	0.00142	157.8	157.65
16.0	6.0	78.0	34.50	0.0534	26.10	0.00156	158.0	156.20
21.7	69.1	9.2	34.48	0.0557	24.80	0.00049	166.1	167.30
23.7	58.9	17.4	34.50	0.0562	24.95	0.00065	167.2	168.95
26.7	14.3	59.0	34.51	0.0558	24.78	0.00142	166.7	163.58
30.6	50.0	19.4	34.50	0.0577	23.80	0.00077	171.2	174.60
39.2	18.8	42.0	34.50	0.0575	24.50	0.00124	171.0	171.46
44.2	22.0	33.8	34.50	0.0598	23.80	0.00117	178.6	176.07
44.7	22.0	33.3	34.50	0.0587	23.10	0.00116	168.5	177.16
48.3	40.3	11.4	34.51	0.0608	23.80	0.00090	181.9	186.90
49.3	36.0	14.7	34.51	0.0610	23.68	0.00091	181.8	176.60
				O_2-N_2-CO_2 Mixture				
		x_1 = % volume O_2		x_2 = % volume N_2		x_3 = % volume CO_2		
3.3	88.3	8.4	34.50	0.0587	24.30	0.00117	174.5	175.28
9.0	81.2	9.8	34.50	0.0592	24.68	0.00118	175.5	176.00
11.4	79.6	9.0	34.50	0.0590	22.78	0.00118	179.0	180.28
11.8	73.6	14.6	34.50	0.0592	25.30	0.00114	176.0	176.44
20.3	50.0	29.7	34.50	0.0583	24.65	0.00134	174.0	171.38
21.3	28.0	50.7	34.50	0.0568	24.65	0.00146	168.0	164.60
23.0	68.0	9.0	34.50	0.0610	23.79	0.00120	180.5	179.10
				O_2-N_2-CO_2 Mixture				
		x_1 = % volume O_2		x_2 = % volume N_2		x_3 = % volume CO_2		
8.0	85.8	6.2	34.50	0.0585	24.30	0.00128	177.8	177.89
16.9	70.3	12.8	34.50	0.0597	24.70	0.00122	176.5	179.90
26.8	52.0	21.2	34.50	0.0602	24.30	0.00128	176.5	177.40
33.4	40.0	26.6	34.50	0.0594	24.15	0.00133	176.5	176.80

[a] All data at 14.2 p.s.i.a.

where subscript 1 refers to oxygen, 2 refers to nitrogen, and 3 refers to carbon dioxide.

Let:

$$\left.\begin{aligned} F_1 &= 1 + (x_2/x_1)\,\phi_{12} + (x_3/x_1)\,\phi_{13} \\ F_2 &= 1 + (x_1/x_3)\,\phi_{31} + (x_2/x_3)\,\phi_{32} \end{aligned}\right\} \qquad (5)$$

Now, if the percentage of nitrogen, x_2, is held fixed at a certain value—e.g., 90%—then, because $x_1 + x_2 + x_3 = 100$, $x_1 + x_3 = 10$. Hence, x_1 and x_3 can take various values such that $x_1 + x_3 = 10$.

Thus,

$x_1 = 1,\quad x_3 = 9,\quad x_1/x_3 = 1/9$

$x_1 = 2,\quad x_3 = 8,\quad x_1/x_3 = 1/4$

$x_1 = 3,\quad x_3 = 7,\quad x_1/x_3 = 3/7$

$x_1 = 9,\quad x_3 = 1,\quad x_1/x_3 = 9$

In all cases, $x_1 + x_2 + x_3 = 100$ with x_2 fixed at 90.

If F_1 is calculated for all the various values of x_1/x_3 as parameter with a fixed value of x_2, a set of values for F_1 is obtained. If these values of F_1 are now plotted against x_1/x_3 on semilog paper as shown in Figure 4, curve A_1 is obtained. If this procedure is repeated for F_2 for the same values of x_2, a set of values for F_2 is obtained. If these values of F_2 are plotted on the same graph against x_1/x_3, the curve A_2 is obtained. These two curves, A_1 and A_2, intersect at some point.

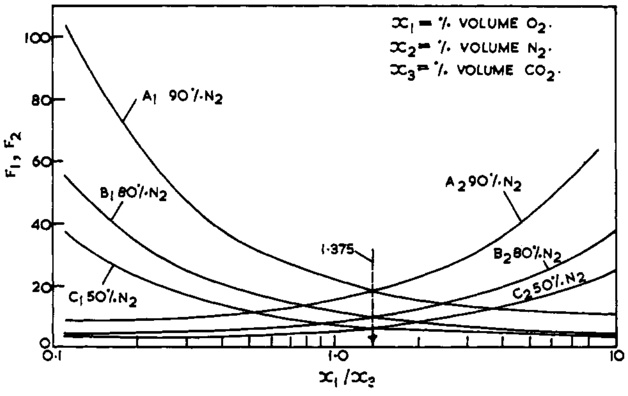

Figure 4. Variation of F_1 and F_2 with x_1/x_3 for constant values of x_2 for the gas mixture O_2–N_2–CO_2

If now x_2 is held fixed at 80% then $x_1 + x_3 = 20$ and if F_1 and F_2 are calculated as indicated above and plotted on the graph, two curves B_1 and B_2 are obtained. The intersection of B_1 and B_2 is at the same value of x_1/x_3 as that of A_1 and A_2. This is true for all percentages of nitrogen—say, 70, 50%, etc.—as long as the above procedure is followed. The graph shows that all such curves intersect at the value of $x_1/x_3 = 1.375 = 1\frac{3}{8}$. This ratio is in the inverse ratio of the molecular weights of the individual gases, oxygen and carbon dioxide.

The viscosity of the mixture is now calculated with x_1/x_3 (oxygen to carbon dioxide) held fixed at $1\frac{3}{8}$ and varying x_2 such that $x_1 + x_2 + x_3 = 100$. The viscosity of all mixtures which had x_1/x_3 in the ratio $^{11}/_{8}$ was the same irrespective of the percentage of nitrogen present in the mixture. The experimental data, with x_1/x_3 ranging from 1.25 to 1.33 and nitrogen percentage varying widely (Table III), indicate that the viscosity was practically constant at ambient temperature and pressure as mentioned above.

CONCLUSIONS

The viscosity values obtained from Wilke's equation for the binary gas mixtures oxygen-nitrogen, oxygen-carbon dioxide, nitrogen-carbon dioxide, and hydrogen-carbon dioxide agree within 1% with the experimental data obtained in this investigation. However, for oxygen-hydrogen mixture, Wilke's equation predicts values of viscosity which are higher by as much as 9%.

In the case of oxygen-carbon dioxide and oxygen-hydrogen gas mixtures, Saxena and Gambhir's equations predict viscosities which agree closely with the present experimental results. However, in the case of nitrogen-carbon dioxide mixture, the equations of Saxena and Gambhir predict viscosities which are about 6% higher than those of the present investigation.

For the ternary gas mixtures oxygen-nitrogen-carbon dioxide and oxygen-hydrogen-carbon dioxide, the viscosity values predicted by Wilke's equation agree well with the present experimental results. This equation can be used for the prediction of viscosity of ternary gas mixtures.

When the volumetric ratio of oxygen to carbon dioxide is about 11 to 8 in a ternary mixture of oxygen-nitrogen-carbon dioxide, the viscosity of this mixture at ambient temperature and pressure remains constant irrespective of the percentage of nitrogen in the mixture.

NOMENCLATURE

a = constant in Equation 1
A_1, A_2 = curves in Figure 3, plots of F_1 and F_2 against x_1/x_3 for the same percentage of N_2 ($x_2 = 90\%$)
b_1 = upper separation
b_2 = lower separation
b = harmonic mean separation, $2b_1b_2/(b_1 + b_2)$
B_1, B_2 = curves in Figure 3, plots of F_1 and F_2 against x_1/x_3 for the same percentage of $N_2(x_2 = 80\%)$
C_1, C_2 = curves in Figure 3, plots of F_1 and F_2 against x_1/x_3 for the same percentage of $N_2(x_2 = 50\%)$
C_N = calibrated instrument constant
f = constant in Equation 1
F_1, F_2 = functions given by Equation 5
h = constant in Equation 1
I = moment of inertia of the suspension system
L = distance of the scale from the mirror
R = radius of the disk
T_0 = period of oscillation of the disk in vacuum
T_1 = period of oscillation of the disk in the gas
x_1, x_2, x_3 = molar fractions of gases in the mixture
α_n, α_{n+m} = angular amplitudes to the right
β_n, β_{n+m} = angular amplitudes to the left
β = dimensionless harmonic mean separation, b/δ
δ = boundary layer thickness
Δ_0 = damping decrement in vacuum
Δ = damping decrement in the gas
$\mu, \mu_1, \mu_2, \mu_3, \mu_m$ = dynamic viscosity
ρ = density of the fluid
θ = ratio of periods of oscillation in the gas and in vacuum, T_1/T_0
$\phi_{12}, \phi_{13}, \phi_{21}, \phi_{23}, \phi_{31}, \phi_{32}$ = constants in Equation 4

LITERATURE CITED

(1) Bearden, J.A., *Phys. Rev.* **56**, 1023 (1939).
(2) Buddenberg, J.W., Wilke, C.R., *Ind. Eng. Chem.* **41**, 1345 (1949).
(3) Hirschfelder, J.O., Bird, R.B., Spotz, E.L., *Trans. A.S.M.E.* **71**, 921 (1949).
(4) Iwasaki, H., Kestin, J., *Physica* **29**, 1345 (1963).
(5) Kestin, J., Kobayashi, Y., Wood, R.T., *Ibid.*, **32**, 1065 (1966).
(6) Kestin, J., Leidenfrost, W., *Ibid.*, **25**, 1033 (1959).
(7) Kestin, J., Moszynski, J.H., *Trans. A.S.M.E.* **80**, 1009 (1958).
(8) Kestin, J., Moszynski, J.H., Brown Univ. Rept. A.F. 891/12, ASTIA, Doc. No. 201516, July 1958.
(9) Kestin, J., Pilarczyk, K., *Trans. A.S.M.E.* **76**, 987 (1954).
(10) Kestin, J., Wang, H.E., *Ibid.*, **80**, 11 (1958).
(11) Kestin, J., Whitelaw, J.H., *Physica* **29**, 335 (1963).
(12) Kestin, J., Whitelaw, J.H., Zien, T.F., *Ibid.*, **30**, 161 (1964).
(13) Newell, G.F., *Z. Angew. Math. Phys.* **10**, 160 (1959).
(14) Saxena, S.C., Gambhir, R.S., *Indian J. Pure Appl. Phys.* **1**, No. 6, 208 (1963).
(15) Trautz, M., Melster, A., *Ann. Physik* **7**, 409 (1930).
(16) Van Itterbeek, A., Van Paemel, O., Vanlierde, J., *Physica* **13**, 88 (1947).
(17) Wilke, C.R., *J. Chem. Phys.* **18**, 517 (1950).

RECEIVED for review February 15, 1966. Accepted May 25, 1967.