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VISCOSITY OF GAS MIXTURES

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SUMMARY

An approximate method is developed for predicting the viscosities of mixtures involving both nonpolar and polar gases. For nonpolar mixtures, only the viscosities and molecular weights of the constituents are required, in addition to the mixture composition. With polar gases, dipole moments, boiling points, and boiling-point densities are also needed. The method is tested by comparison with experimental data on 25 gas pairs comprising 280 mixtures. The average error is 0.7 percent; the maximum error is 3.7 percent. (Errors may be much larger if this method is used for gas mixtures involving ions, free radicals, or valence-unsaturated atoms.)

INTRODUCTION

The transport properties of dilute monatomic gases at low to moderate temperatures are now well understood; the rigorous Chapman-Enskog theory appears to provide an entirely adequate description for these gases. The theory applies to molecules with spherically symmetrical force fields and without internal energy. Hence, the theory does not apply, strictly, to polyatomic gases. In practice, however, it turns out that theory gives a good account of the viscosities (and diffusion coefficients) of polyatomic gases and gas mixtures. Consequently, if one wants to do a "best job" of calculating viscosity of gas mixtures at moderate pressures, the theoretical tools are already at hand.

However, the rigorous expression for mixture viscosity is algebraically complex - it requires, first of all, the reduction of a ratio of determinants of order $(\nu + 1)/\nu$, where ν is the number of components in the gas mixture. And the elements of the determinants are complicated, involving not only the viscosities and molecular weights of the constituent gases, but also cross sections characteristic of all pairwise interactions between unlike molecules. These unlike cross sections are often not known, and so must be estimated by using empirical rules of thumb. Hence, to apply the rigorous theory successfully, one needs some familiarity with kinetic theory of gases and also some

knowledge of the nature of intermolecular forces.

Thus, it is desirable to have a simpler method, useful to engineers, which does not require an understanding of theory and which is easy to use. This report develops such a technique. The method is derived from a more complicated approximation obtained heretofore (ref. 1, which reproduced rigorous calculations for the viscosity of helium-neon-argon mixtures within 3 parts in 10 000). Combination rules for the unlike cross sections are built into the mixture formula. For mixtures of nonpolar gases, only the gas composition and viscosities and molecular weights of the constituents are required. When polar gases are present, additional input is needed - dipole moments, boiling points, and liquid densities.

The method should be applicable to quite high pressures - perhaps even above the critical pressure provided the temperature is well above the critical point. It can be applied at any temperature, as long as there are not large concentrations of free radicals, valence-unsaturated atoms, or ions.

The accuracy of the method developed here compares favorably with rigorous theory when unlike cross sections are estimated from empirical combination rules. The largest errors are under 4 percent.

DERIVATION OF APPROXIMATE MIXTURE VISCOSITY FORMULA

An approximate formula for the viscosity of gas mixtures was derived by Sutherland (ref. 2) more than 70 years ago. His derivation, based on simple mean-free-path arguments, leads to the expression

$$\eta_{mix} = \sum_{i=1}^{\nu} \frac{x_i \eta_i}{x_i + \sum_{\substack{j=1 \\ j \neq i}}^{\nu} \varphi_{ij} x_j} \tag{1}$$

Here η_{mix} is the mixture viscosity while η_i is the viscosity of component i; x_i and x_j are mole fractions that specify the composition. The φ_{ij} are parameters presumed independent of composition.

Equation (1) has intrigued a number of investigators over the years because of its simple analytic form and because it represents experimental data extremely well, pro-

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vided the φ_{ij} are suitably chosen. (Often an extensive range of pairs of φ_{ij} and φ_{ji} give satisfactory agreement for binary mixtures.)

In reference 1 the rigorous expression for the viscosity of <u>binary</u> mixtures was cast in the form of equation (1); when this is done, the φ_{ij} turn out to be weakly dependent on composition. It was found, however, that if the φ_{ij} were fixed to correspond to the rigorous expression at one intermediate composition they served for very accurate calculations for all compositions. This expression is

$$\varphi_{ij} = \alpha_{ij}\left[1 + \frac{M_i - M_j\left(\dfrac{\alpha_{ji}}{\alpha_{ij}}\right)^{1/2}}{\dfrac{3A_{ij}^*(M_i + M_j)}{5 - 3A_{ij}^*} + \dfrac{(\alpha_{ij})^{1/2} + (\alpha_{ji})^{1/2}}{1 + (\alpha_{ij}\alpha_{ji})^{1/2}}M_j(\alpha_{ji})^{1/2}}\right] \tag{2}$$

where M_i and M_j are the molecular weights of components i and j and A_{ij}^* (defined in ref. 3, p. 528, eq. (8.2-15)) is a number close to 1 whose exact value depends on the nature of the intermolecular potential and the temperature. Also,

$$\alpha_{ij} \equiv \frac{\eta_i}{\eta_{ij}}\left(\frac{2M_j}{M_i + M_j}\right) \tag{3}$$

The quantity η_{ij} characterizes the interaction between unlike molecules.

The viscosity of component i in micropoises ($\times 10^{-7}$ (N)(sec)/m^2) is given by

$$\eta_i = 26.693\frac{\sqrt{M_iT}}{\sigma_i^2} \tag{4}$$

(ref. 3, p. 528, eq. (8.2-18)), where σ_i is the viscosity collision diameter of component i. Similarly,

$$\eta_{ij} = 26.693\frac{\sqrt{\dfrac{2M_iM_jT}{M_i + M_j}}}{\sigma_{ij}^2} \tag{5}$$

(ref. 3, p. 529, eq. (8.2-21)), with σ_{ij} a diameter for collisions between unlike molecules.

With the aid of equations (4) and (5), equation (3) can be cast in the form

$$\alpha_{ij} = \left(\frac{2M_j}{M_i + M_j}\right)^{1/2} \left(\frac{\sigma_{ij}^2}{\sigma_i \sigma_j}\right) \frac{\sigma_j}{\sigma_i} = S_{ij} \left(\frac{M_j}{M_i}\right)^{1/2} \left(\frac{\eta_i}{\eta_j}\right)^{1/2} m_{ij} \tag{6}$$

where $S_{ij} \equiv \sigma_{ij}^2 / \sigma_i \sigma_j$ and $m_{ij} \equiv \left[4M_i M_j \big/ (M_i + M_j)^2\right]^{1/4}$

For realistic intermolecular potentials A_{ij}^* is often approximately 10/9. This, together with equations (2) and (6), leads to

$$\varphi_{ij} = S_{ij} m_{ij} \left(\frac{M_j}{M_i}\right)^{1/2} \left(\frac{\eta_i}{\eta_j}\right)^{1/2} \left[1 + \frac{\frac{M_i}{M_j} - \left(\frac{M_i}{M_j}\right)^{1/2} \left(\frac{\eta_j}{\eta_i}\right)^{1/2}}{2\left(1 + \frac{M_i}{M_j}\right) + \frac{1 + \left(\frac{M_i}{M_j}\right)^{1/2} \left(\frac{\eta_j}{\eta_i}\right)^{1/2}}{1 + S_{ij} m_{ij}} S_{ij} m_{ij}}\right] \tag{7}$$

The second term in brackets in equation (7) is less than 1 and hence in the nature of a correction term, so that further approximations can be made. First, we can set S_{ij} equal to 1. Next, the ratios $(\eta_j / \eta_i)^{1/2}$ can be approximated by $(M_j / M_i)^{0.05}$. This can be justified by observing that at any given temperature the viscosities of all gases are very much of the same order of magnitude. (For example, among the common gases tabulated by Svehla (ref. 4) extremes at $300^{\rm O}$ K are neon, 315 micropoise ($3.15{\times}10^{-5}$ (N)(sec)/m^2) and normal hexane, 66 micropoise ($6.6{\times}10^{-6}$ (N)(sec)/m^2), differing by less than a factor of 5.) If the data of reference 4 at a fixed temperature are plotted as a function of molecular weight, a slight trend of increasing viscosity with increasing molecular weight is decernable; viscosity is roughly proportional to the 0.1 power of molecular weight. With these approximations, equation (7) becomes

$$\varphi_{ij} = S_{ij} A_{ij} \left(\frac{\eta_i}{\eta_j}\right)^{1/2} \tag{8}$$

where

$$A_{ij} \equiv m_{ij}\left(\frac{M_j}{M_i}\right)^{1/2}\left[1 + \frac{\left(\frac{M_i}{M_j}\right) - \left(\frac{M_i}{M_j}\right)^{0.45}}{2\left(1 + \frac{M_i}{M_j}\right) + \frac{1 + \left(\frac{M_i}{M_j}\right)^{0.45}}{1 + m_{ij}}\, m_{ij}}\right] \qquad (9)$$

The quantity A_{ij} is a function of molecular weight ratio (M_i/M_j) only which can be calculated once and for all; a scale giving A_{ij} and A_{ji} in terms of M_i/M_j is shown as figure 1.

The final equation for mixture viscosity is obtained by combining equations (1) and (9):

$$\eta_{mix} = \sum_{i=1}^{\nu} \frac{x_i \sqrt{\eta_i}}{\dfrac{x_i}{\sqrt{\eta_i}} + \displaystyle\sum_{\substack{j=1 \\ j \neq i}}^{\nu} \frac{S_{ij}A_{ij}}{\sqrt{\eta_j}}\, x_j} \qquad (10)$$
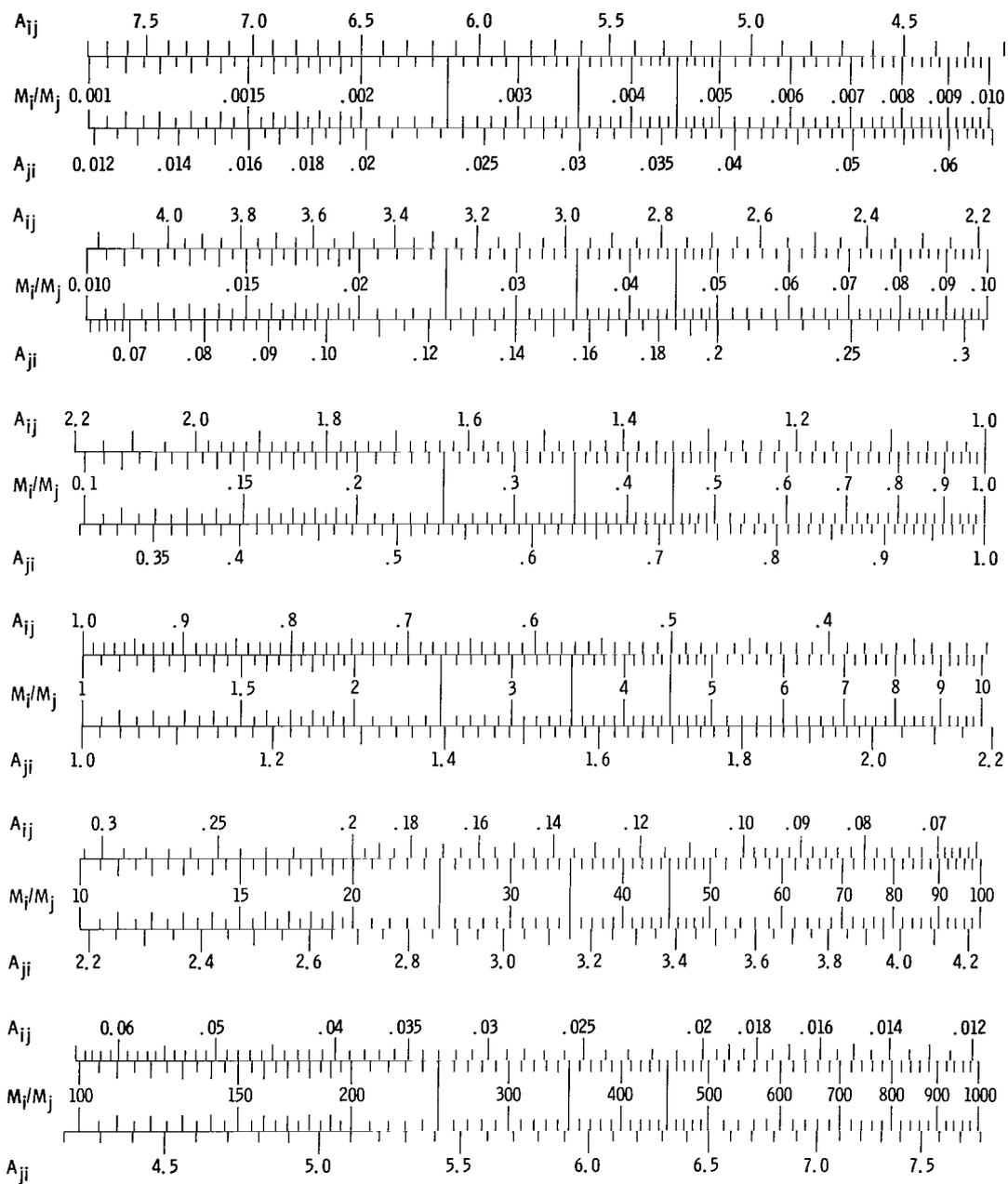
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Figure 1. - A_{ij} and A_{ji} as function of molecular weight ratio M_i/M_j.

APPLICATION FOR MIXTURES OF NONPOLAR GASES

For mixtures of nonpolar gases, we can take S_{ij} to be 1. This is equivalent to assuming the cross sections for unlike interactions to be the geometric mean of the cross sections for self-collisions. Experimental viscosities for a number of nonpolar binary gas mixtures are compared with approximate computations in table I. The most precise experimental measurements seem to be those of Kestin and coworkers (refs. 5 to 8); other data of lower precision are taken from references 9 to 12. For several of the mixtures results of rigorous calculations (refs. 9 and 13) are also shown.

The agreement between experiment and the approximate calculations seems very good indeed, especially for the mixtures among the noble gases. The average error is 0.6 percent while the largest error is 2.5 percent (one of the helium-hydrogen mixtures). Where comparisons are possible the accuracy of the approximate calculations is comparable with that of the rigorous results.[1]

APPLICATION FOR MIXTURES INVOLVING POLAR GASES

In mixtures of polar and nonpolar gases the polar-nonpolar interactions are essentially of a nonpolar nature; hence, the unlike cross sections are smaller than might be inferred from a simple averaging of the cross sections of the pure components. In other words, the $S_{ij} = \sigma_{ij}^2 / \sigma_i \sigma_j$ are less than 1.

Monchick and Mason (ref. 14) have carried out theoretical calculations which can be used to obtain viscosity cross sections for both polar and nonpolar gases. Their result can be written

$$\sigma^2 = \sigma_0^2 \left\langle \Omega^{(2,2)^*} \right\rangle \tag{11}$$

where σ_0 is a length characteristic of the particular molecule and $\left\langle \Omega^{(2,2)^*} \right\rangle$ is a function of reduced temperature $T^* \equiv kT/\epsilon$ and a parameter $\delta = \frac{1}{2} \mu^2 / \epsilon \sigma_0^3$ which characterizes the polarity of the molecule. Here μ is the dipole moment, k is the Boltzmann constant, and ϵ an energy characteristic of the molecule.

Monchick and Mason (ref. 14) present numerical values of $\left\langle \Omega^{(2,2)^*}(\delta, T^*) \right\rangle$ and have used them to fit experimental viscosity data for a number of polar gases, for which

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[1]The rigorous calculations used empirical combination rules to estimate the interactions between unlike species; the rigorous calculations may be improved by using accurate diffusion coefficient data to estimate unlike interactions (see ref. 13).

δ lies in the range 0 to 1. In the temperature range where the dipole forces are important, $T^* \sim 0.5$ to 5, and $\delta = 0$ to 1, the approximation

$$\left\langle \Omega^{(2,2)*} \right\rangle \cong \frac{4}{5} \left(1 + \frac{1}{T^*} + \frac{\delta^2}{4T^*} \right) \tag{12}$$

reproduces their tabulations within 5 percent.

By combining equations (11) and (12), we obtain (after adding indices corresponding to interactions between like (i, j) and unlike (ij) molecules)

$$S_{ij} = \frac{\sigma_{ij}^2}{\sigma_i \sigma_j} = \frac{1 + T_{ij}^{*-1} + \delta_{ij}^2 \left(4T_{ij}^*\right)^{-1}}{\left[1 + T_i^{*-1} + \delta_i^2 \left(4T_i^*\right)^{-1}\right]^{1/2} \left[1 + T_j^{*-1} + \delta_j^2 \left(4T_j^*\right)^{-1}\right]^{1/2}} \frac{\sigma_{oij}^2}{\sigma_{oi} \sigma_{oj}} \tag{13}$$

Let us now approximate $\sigma_{oij}^2 = \sigma_{oi}\sigma_{oj}$ (it is more usual to take the arithmetic mean); also, let $\epsilon_{ij} = (\epsilon_i \epsilon_j)^{1/2}$ so that $T_{ij}^* = \left(T_i^* T_j^*\right)^{1/2}$, $\delta_{ij}^2 = \delta_i \delta_j$, and

$$S_{ij} = S_{ji} \cong \frac{1 + \left(T_i^* T_j^*\right)^{1/2} + \dfrac{\delta_i \delta_j}{4}}{\left(1 + T_i^* + \dfrac{\delta_i^2}{4}\right)^{1/2} \left(1 + T_j^* + \dfrac{\delta_j^2}{4}\right)^{1/2}} \tag{14}$$

Thus, to calculate S_{ij}, δ and ϵ/k are required; values for some 22 polar gases are presented in reference 14.

It would also be desirable to estimate δ and ϵ/k from other properties. For nonpolar gases σ_o and ϵ/k may be estimated from boiling-point properties (ref. 3, eqs. (4.1-19) and (4.1-21):

$$\frac{\epsilon}{k} = 1.15 \, T_b \tag{15}$$

$$\left(\frac{2}{3\pi}\right) N\sigma_o^3 = 2V_b (=b_o) \tag{16}$$

where T_b is the boiling point, N is Avagadro's number, and V_b is the molar volume at the boiling point.

Equations (15) and (16) do not work at all well for polar molecules. Nonetheless, it is an empirical fact that the combination $\epsilon\sigma_o^3$ is approximated by the product of equations (15) and (16). Thus,

$$\delta \equiv \frac{1}{2}\frac{\mu^2}{\epsilon\sigma_o^2} \cong 2\times10^3 \frac{\mu^2}{V_b T_b} \tag{17}$$

where the dipole moment is in Debyes (10^{-18} esu-cm), the molar boiling point volume is in cubic centimeters and the boiling point is in $^\circ$K. Equation (17) works quite well, as is shown in figure 2, where values of δ obtained by Monchick and Mason (ref. 14) are compared with values estimated from boiling points and boiling point densities.
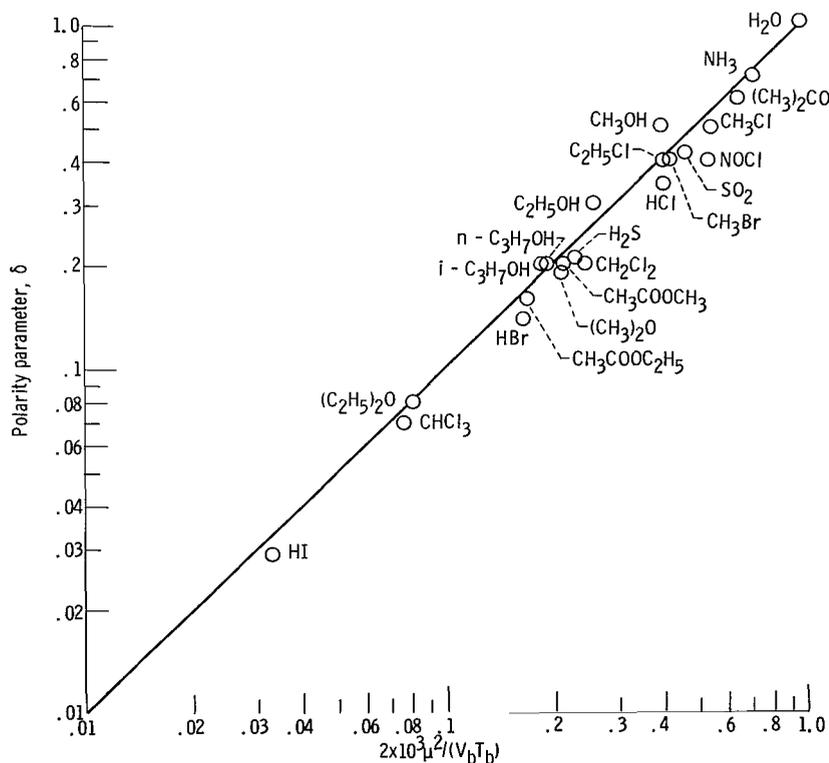
Figure 2. - Comparison of polarity parameter with estimates based on boiling points and boiling-point molar volumes.
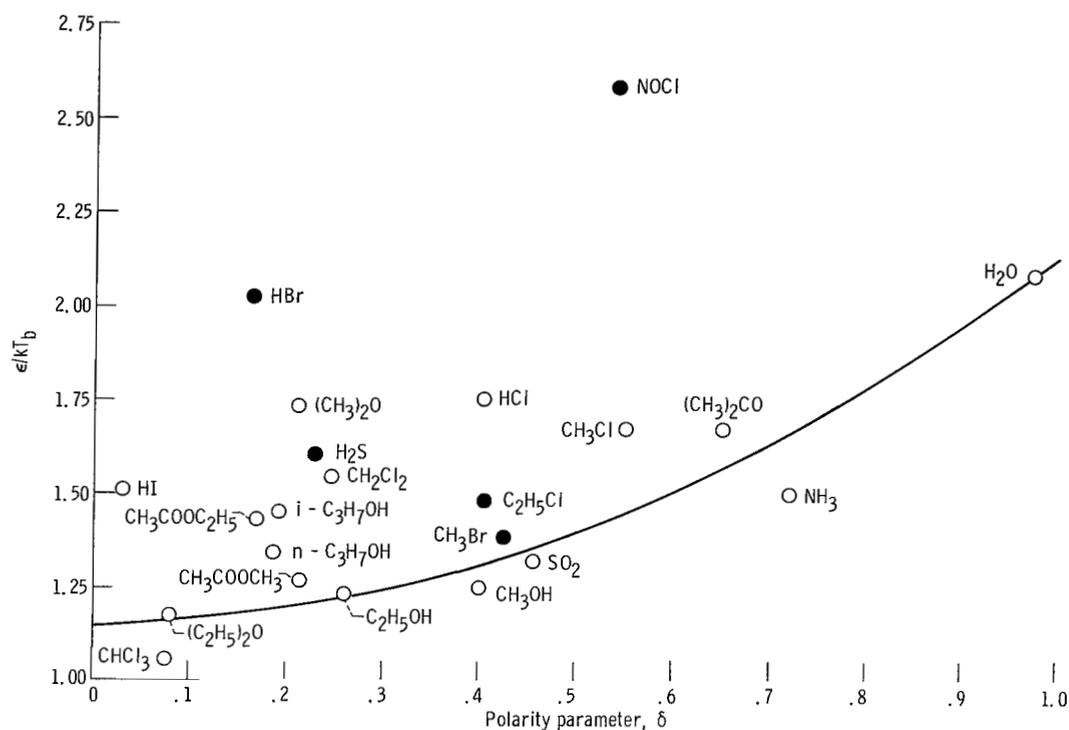
Figure 3. - Correlation of ϵ/kT_b with polarity parameter.

Next we must estimate ϵ/k. In figure 3, ϵ/kT_b for a number of polar molecules is plotted against δ. The solid symbols represent molecules for which the experimental viscosity data are scanty or uncertain. Although there is considerable scatter, there is a definite increase of ϵ/kT_b with increasing δ. The correlating line shown is

$$\frac{\epsilon}{kT_b} = 1.15(1 + 0.85\ \delta^2) \tag{18}$$

This equation was chosen to give a reasonable fit for the most strongly polar gases - water, ammonia, acetone, and methyl chloride - and also to reduce to equation (15) for nonpolar gases ($\delta = 0$).

Experimental viscosities for binary mixtures of polar and nonpolar gases are compared with approximate calculations in table II. The calculations have been made by using equations (9), (10), (14), (16), and (17) (except for hydrogen, where ϵ/k was taken to be 38° K (ref. 3, p. 1110)). The experimental data are largely those of Trautz and co-workers (refs. 15 to 17), with additional results of Iwasaki, Kestin, and Nagashima

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(ref. 18) and Mueller and Ignatowski (ref. 19); the rigorous theoretical calculations are from references 13 and 20.

Again, there is good agreement between experiment and the approximate calculations; the average error is 0.8 percent, with a maximum error of 3.5 percent. The accuracy of the approximate calculations compares favorably with rigorous results.

Results for mixtures of polar gases are presented in table III. The data on the alcohol-steam mixtures are those of Silgardo and Storrow (ref. 21) while the data and rigorous calculations for the methyl chloride - sulfur dioxide - dimethylether mixtures were taken from Chakraborti and Gray (ref. 22). The approximate calculations have an average deviation from experiment of slightly more than 0.7 percent. The maximum deviation of 3.7 percent for one of the water-ethanol mixtures very likely reflects experimental errors. The agreement between approximate and rigorous calculations is satisfactory.

One further point should be mentioned. Equation (14) does not reduce to 1 in the nonpolar limit ($\delta_i = \delta_j = 0$). Nonetheless, it is an empirical fact that, if equation (14) is used to calculate the S_{ij} for the nonpolar gas mixtures considered in this report, the agreement with experiment is distinctly poorer than when the S_{ij} are taken to be 1 (predicted viscosities are systematically too high, with an average error of 1.8 percent and a maximum error of nearly 5 percent).

Consequently, it is recommended that equation (14) be used if either δ_i or δ_j is greater than 0.1. If both δ_i and δ_j are less than 0.1, the S_{ij} should be taken as 1.

CONCLUDING REMARKS

The method developed in this report for calculating the viscosities of gas mixtures seems reasonably accurate and reliable for mixtures of both polar and nonpolar gases, with errors rarely exceeding a few percent. Consequently, it is in order to point out that there are gas mixtures for which this method is not appropriate. For example,

1. Gas mixtures containing valence-unsaturated atoms and free radicals (e.g., a partially dissociated mixture of hydrogen molecules and atoms)

The forces between such species are extremely strong; some interactions correspond to chemical bonding while other interactions are strongly repulsive. For such systems equation (14) is not appropriate and the various interactions must be considered in detail.

2. Ionized gases

Again, the various interparticle potentials must be considered in detail; in particular the coulombic cross sections are extremely large, and the ion-parent atom cross sections are large too. On the other hand, electron-atom cross sections may be very small. In

addition, in fully ionized gases, the first Chapman-Enskog approximation, the basis of this approximate method, is also inadequate (ref. 23).

Lewis Research Center,
    National Aeronautics and Space Administration,
        Cleveland, Ohio, December 20, 1967,
            129-01-02-01-22.

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TABLE I. – COMPARISON OF COMPUTED AND EXPERIMENTAL VISCOSITIES OF NONPOLAR

GAS MIXTURES

Mole fraction		Temperature, °K	Viscosity, μP ($\times 10^{-7}$ (N)(sec)/m^2)					Reference	
			Experimental	Approximate (eqs. (9) and (10))	Deviation, percent	Rigorous	Deviation, percent	Experiment	Rigorous calculation
Helium	Neon								
0	1.000	293.15	314.33	314.33	-----			5	
.259	.741		299.49	299.80	0.10				
.433	.567		285.50	285.94	.15				
.650	.350		261.82	261.79	-.01				
.846	.154		230.36	230.35	-.004				
.949	.051		208.81	208.59	-.11				
1.000	0		196.08	196.08	-----				
0	1.000	303.15	322.09	322.09	-----				
.259	.741		306.44	307.19	0.25				
.433	.567		292.51	292.97	.16				
.650	.350		268.43	268.22	-.08				
.846	.154		235.95	235.99	.02				
.949	.051		213.77	213.68	-.04				
1.000	0		201.80	201.80	-----				
Helium	Argon								
0	1.000	293.15	222.56	222.56	-----	222.56	-----	6	13
.199	.801		226.94	226.78	-0.07	226.64	-0.13		
.371	.629		230.88	229.89	-.43	230.93	.02		
.634	.366		231.58	231.02	-.24	230.58	-.48		
.807	.193		225.25	224.64	-.27	224.12	-.50		
.863	.137		220.28	219.81	-.21	219.27	-.46		
.942	.058		209.07	208.83	-.12	208.42	-.31		
1.000	0		196.05	196.05	-----	196.05	-----		
0	1.000	303.15	229.30	229.30	-----	229.30	-----		
.211	.789		233.83	233.79	-0.02	233.48	-0.15		
.423	.577		237.43	237.33	-.04	236.65	-.33		
.610	.390		238.11	237.83	-.11	236.92	-.50		
.786	.214		232.39	232.17	-.10	231.02	-.59		
.875	.125		224.32	224.30	-.01	222.97	-.60		
.939	.061		214.88	214.78	-.05	214.13	-.35		
1.000	0		200.97	200.97	-----	200.97	-----		

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TABLE I. - Continued. COMPARISON OF COMPUTED AND EXPERIMENTAL VISCOSITIES OF

NONPOLAR GAS MIXTURES

Mole fraction		Tempera-ture, ^{o}K	Viscosity, μP ($\times 10^{-7}$ (N)(sec)/m^2)					Reference	
			Experi-mental	Approxi-mate (eqs. (9) and (10))	Deviation, percent	Rigorous	Deviation, percent	Experi-ment	Rigor-ous calcu-lation
Helium	Krypton								
0	1.0000	293.15	249.50	249.50	-----			7	
.3263	.6737		259.14	258.46	-0.26				
.5076	.4924		263.64	262.42	-.46				
.6119	.3881		264.53	263.18	-.51				
.6761	.3239		263.82	262.43	-.53				
.7177	.2823		262.78	261.14	-.62				
.8091	.1909		256.38	254.64	-.68				
.8585	.1415		249.10	247.73	-.55				
.8932	.1068		241.70	240.58	-.46				
1.0000	0		196.19	196.19	-----				
0	1.0000	303.15	257.38	257.38	-----				
.3263	.6737		266.95	266.36	-0.22				
.5076	.4924		271.42	270.21	-.44				
.6119	.3881		272.01	270.81	-.44				
.6761	.3239		271.20	269.90	-.48				
.7177	.2823		270.02	268.48	-.57				
.8091	.1909		262.79	261.52	-.48				
.8585	.1415		255.27	254.24	-.40				
.8932	.1068		247.70	246.75	-.38				
1.0000	0		200.68	200.68	-----				
Helium	Xenon								
0	1.000	291.15	224	224	-----	224	----	9	9
.102	.898		229	227.5	-0.6	228	-0.4		
.208	.792		232	231.5	-.2	232	0		
.313	.687		237	235.9	-.5	237	0		
.406	.594		242	240.0	-.8	242	0		
.506	.494		245	244.5	-.2	248	1.2		
.599	.401		249	248.5	-.2	253	1.6		
.696	.304		252	251.7	-.1	257	2.0		
.799	.201		252	251.7	-.1	258	2.4		
.861	.139		248	247.4	-.2	253	2.0		
.937	.063		232	230.9	-.5	235	1.3		
1.000	0		194	194	----	194	----		

TABLE I. - Continued.   COMPARISON OF COMPUTED AND EXPERIMENTAL VISCOSITIES OF

NONPOLAR GAS MIXTURES

Mole fraction		Tempera-ture, $^\circ K$	Viscosity, μP ($\times 10^{-7}$ $(N)(sec)/m^2$)					Reference	
			Experi-mental	Approxi-mate (eqs. (9) and (10))	Deviation, percent	Rigorous	Deviation, percent	Experi-ment	Rigor-ous calcu-lation
Neon	Argon								
0	1.000	293.15	222.86	222.86	-----			5	
.099	.901		229.87	229.48	-0.17				
.332	.668		247.80	246.76	-.42				
.598	.402		271.54	269.95	-.58				
1.000	0	↓	314.33	314.33	-----				
0	1	303.15	229.63	229.63	-----				
.099	.901		236.54	236.35	-0.08				
.332	.668		254.67	253.86	-.31				
.598	.402		278.59	277.34	-.44				
1.000	0	↓	322.09	322.09	-----			↓	
Helium	Hydrogen								
0	1.000	293.15	87.5	87.5	-----	87.5	---	10	13
.3082	.6918		116.6	119.3	2.0	118.0	1.2		
.3931	.6069		125.2	128.3	2.5	126.8	1.3		
.448	.552		131.7	134.3	2.3	132.8	.8		
1.000	0	↓	197.4	197.4	---	197.4	---	↓	↓
Helium	Nitrogen								
0	1.000	293.15	175.52	175.52	----			7	
.2051	.7949		180.97	182.16	0.66				
.2749	.7251		182.85	184.55	.93				
.4995	.5005		189.50	192.45	1.56				
.7100	.2900		195.42	198.94	1.80				
.8318	.1682		197.87	200.81	1.48				
.8692	.1308		198.24	200.76	1.27				
.9639	.0361		197.38	198.38	.50				
1.000	0	↓	196.19	196.19	----				
0	1.000	303.15	180.02	180.02	----				
.2051	.7949		185.62	186.77	0.62				
.2749	.7251		187.49	189.21	.92				
.4995	.5005		194.11	197.22	1.60				
.6871	.3129		199.57	203.18	1.81				
.8318	.1682		202.46	205.57	1.54				
.8692	.1308		202.87	205.50	1.30				
.9639	.0361		202.02	202.96	.46				
1.00	0	↓	200.68	200.68	----			↓	

TABLE I. - Continued. COMPARISON OF COMPUTED AND EXPERIMENTAL VISCOSITIES OF

NONPOLAR GAS MIXTURES

Mole fraction		Temperature, °K	Viscosity, μP ($\times 10^{-7}$ (N)(sec)/m^2)					Reference	
			Experimental	Approximate (eqs. (9) and (10))	Deviation, percent	Rigorous	Deviation, percent	Experiment	Rigorous calculation
Neon	Carbon dioxide								
0	1.0000	293.15	146.81	146.81	-----			8	
.2062	.7938		169.16	167.18	-1.17				
.4350	.5650		199.81	195.55	-2.13				
.6203	.3797		230.41	224.75	-2.46				
.7103	.2897		247.02	241.65	-2.18				
.8762	.1238		283.14	279.02	-1.45				
1.000	0		313.88	313.88	-----				
0	1.0000	303.15	151.61	151.61	-----				
.2062	.7938		174.33	172.39	-1.11				
.4350	.5650		205.33	201.28	-1.97				
.6203	.3797		236.31	230.97	-2.26				
.7103	.2897		253.31	248.12	-2.05				
.8762	.1238		289.61	286.00	-1.25				
1.0000	0		321.25	321.25	-----				
Argon	Carbon dioxide								
0	1.0000	293.15	146.65	146.65	-----			7	
.0828	.9172		152.65	151.66	-0.65				
.1575	.8425		158.17	156.35	-1.15				
.3661	.6339		173.77	170.30	-2.00				
.4602	.5398		181.06	177.05	-2.22				
.6676	.3324		197.12	193.07	-2.05				
.7325	.2675		202.12	198.44	-1.82				
1.0000	0		222.59	222.59	-----				
0	1.0000	303.15	151.52	151.52	-----				
.0828	.9172		157.69	156.65	-0.66				
.1575	.8425		163.30	161.44	-1.14				
.3661	.6339		179.33	175.70	-2.03				
.4602	.5398		186.72	182.60	-2.21				
.6676	.3324		203.10	198.96	-2.04				
.7325	.2675		208.27	204.43	-1.84				
1.000	0		229.06	229.06	-----				

TABLE I. - Concluded. COMPARISON OF COMPUTED AND EXPERIMENTAL VISCOSITIES OF

NONPOLAR GAS MIXTURES

Mole fraction		Temperature, °K	Viscosity, μP ($\times 10^{-7}$ (N)(sec)/m^2)					Reference	
			Experimental	Approximate (eqs. (9) and (10))	Deviation, percent	Rigorous	Deviation, percent	Experiment	Rigorous calculation
Nitrogen	Carbon dioxide								
0	1.0000	293.15	146.65	146.65	-----			7	
.1869	.8131		152.70	151.29	-0.93				
.3118	.6882		156.70	154.56	-1.37				
.4943	.5057		162.35	159.62	-1.68				
.6899	.3101		168.08	165.42	-1.58				
.8393	.1607		172.02	170.14	-1.09				
.9262	.0738		174.07	173.01	-.61				
1.0000	0		175.52	175.52	-----				
0	1.000	303.15	151.96	151.96	-----				
.1869	.8131		158.18	156.50	-1.06				
.6899	.3101		173.36	170.27	-1.78				
.9262	.0738		179.30	177.61	-.95				
1.0000	0		180.02	180.02	-----				
Hydrogen	Nitrogen								
0	1.0000	292.15	173.9	173.9	---	173.9	---	11	13
.2021	.7979		170.3	170.7	0.3	170.5	0.1		
.5053	.4947		159.8	160.1	.2	159.6	-.1		
.6672	.3328		147.2	148.5	.9	147.8	.4		
.8077	.1923		130.5	131.6	.9	130.9	.3		
1.000	0		87.4	87.4	---	87.4	---		
Hydrogen	Freon								
0	1.00	298.15	124.0	124.0	---			12	
.25	.75		128.1	128.2	0.1				
.50	.50		131.9	133.2	1.0				
.75	.25		135.1	136.6	1.1				
.92	.08		124.1	124.3	.1				
1.00	0		88.4	88.4	---				

TABLE II. - COMPARISON OF COMPUTED AND EXPERIMENTAL VISCOSITIES OF POLAR-

NONPOLAR GAS MIXTURES

Mole fraction		Temperature, °K	Viscosity, μP ($\times 10^{-7}$ (N)(sec)/m^2)					Reference	
			Experimental	Approximate (eqs. (9), (10), (14), (17), and (18))	Deviation, percent	Rigorous	Deviation, percent	Experiment	Rigorous calculation
Ammonia	Argon								
0	1.000	293.15	222.56	222.56	-----	222.56	----	18	13
.238	.762		200.92	198.84	-1.03	195.9	-3.1		
.422	.558		176.80	175.56	-.70	171.5	-3.9		
.621	.379		154.67	153.02	-1.07	149.1	-4.7		
.780	.220		136.00	131.43	-3.36	128.5	-6.6		
.853	.147		121.62	121.04	-.48	118.9	-2.9		
.948	.052		109.15	107.07	-1.90	106.2	-3.0		
.954	.046		106.95	106.17	-.73	105.4	-1.7		
1.000	0		99.22	99.22	-----	99.22	----		
0	1.000	303.15	229.30	229.30	-----	229.30	----		
.245	.755		209.67	204.33	-2.55	201.3	-4.7		
.468	.532		184.60	178.08	-3.53	173.8	-7.1		
.662	.338		157.22	152.68	-2.89	148.7	-6.6		
.900	.100		121.10	118.41	-2.22	116.8	-4.1		
.924	.076		114.73	114.77	.04	113.5	-1.4		
.954	.046		111.05	110.18	-.79	109.4	-1.7		
1.000	0		103.03	103.03	-----	103.03	----		
Ammonia	Hydrogen								
0	1.000	293.15	87.7	87.7	-----	87.7	----	15	20
.1082	.8918		101.1	100.9	-0.2	100.6	-0.5		
.2239	.7761		107.2	107.1	-.1	106.7	-.5		
.2975	.7025		108.7	108.6	-.1	108.3	-.4		
.5177	.4823		108.0	108.1	.1	107.7	-.3		
.7087	.2913		104.7	104.7	0	104.5	-.2		
.9005	.0995		100.4	100.5	.1	100.4	0		
1.000	0		98.2	98.2	----	98.2	----		
0	1.000	523.15	129.6	129.6	----	129.6	----		
.2239	.7761		167.8	170.8	1.8	168.0	0.1		
.2975	.7025		173.7	176.9	1.8	174.0	.2		
.5177	.4823		182.3	185.0	1.5	182.6	.2		
.7087	.2913		183.7	185.5	1.0	183.9	.1		
.9005	.0995		182.5	183.1	.3	182.6	.1		
1.000	0		181.3	181.3	----	181.3	----		

TABLE II. - Continued.   COMPARISON OF COMPUTED AND EXPERIMENTAL VISCOSITIES OF

POLAR-NONPOLAR GAS MIXTURES

Mole fraction		Tempera-ture, ^{o}K	Viscosity, μP ($\times 10^{-7}$ (N)(sec)/m^2)						Reference	
			Experi-mental	Approximate (eqs. (9), (10), (14), (17), and (18))	Deviation, percent	Rigorous	Deviation, percent		Experi-ment	Rigor-ous calcu-lation
Ammonia	Nitrogen									
0	1.000	293.15	174.5	174.5	----	174.5	----		15	20
.1111	.8889		169.0	168.5	-0.3	168.1	-0.5			
.2920	.7080		158.5	157.2	-.8	156.4	-1.3			
.5638	.4362		138.3	137.1	-.9	136.1	-1.6			
.7147	.2853		125.4	124.5	-.7	123.6	-1.4			
.8883	.1117		109.2	108.9	-.3	108.4	-.7			
1.000	0		98.2	98.2	----	98.2	----			
0	1.000	523.15	262.7	262.7	----	262.7	----			
.1111	.8889		257.2	257.7	0.2	256.9	-0.1			
.2920	.7080		246.0	247.4	.6	245.7				
.5638	.4362		225.0	226.9	.9	224.8				
.7147	.2853		211.2	213.0	.8	211.1				
.8883	.1117		193.9	194.5	.3	193.6				
1.000	0		181.3	181.3	----	181.3	----			
Ammonia	Oxygen									
0	1.000	293.15	202.3	202.3	----	202.3	----		15	20
.1351	.8649		192.4	190.7	-0.9	190.2	-1.1			
.2986	.7014		178.3	175.5	-1.6	174.5	-2.1			
.4786	.5214		160.4	157.4	-1.9	156.1	-2.7			
.7079	.2921		135.0	132.5	-1.9	131.2	-2.7			
.8755	.1245		114.3	113.1	-1.0	112.4	-1.7			
1.000	0		98.2	98.2	----	98.2	----			
0	1.000	473.15	290.2	290.2	----	290.2	----			
.1351	.8649		277.3	277.6	0.1	276.6	-0.3			
.2986	.7014		260.4	260.5	0	258.5	-.7			
.4786	.5214		239.0	239.3	.1	236.8	-.9			
.7079	.2921		208.5	208.8	.2	206.7	-.9			
.8755	.1245		184.0	184.2	.1	183.0	-.5			
1.000	0		164.6	164.6	----	164.6	----			

TABLE II. - Continued. COMPARISON OF COMPUTED AND EXPERIMENTAL VISCOSITIES OF

POLAR-NONPOLAR GAS MIXTURES

Mole fraction		Temperature, ^{o}K	Viscosity, μP ($\times 10^{-7}$ (N)(sec)/m^2)					Reference	
			Experimental	Approximate (eqs. (9), (10), (14), (17), and (18))	Deviation, percent	Rigorous	Deviation, percent	Experiment	Rigorous calculation
Ammonia	Ethylene								
0	1.000	293.15	100.8	100.8	---	100.8	----	15	20
.1096	.8904		101.5	101.6	0.1	101.2	-0.3		
.2993	.7007		102.7	102.5	-.2	101.7	-.9		
.5172	.4828		103.0	102.6	-.4	101.6	-1.4		
.6961	.3039		102.2	101.9	-.3	100.9	-1.3		
.8071	.1929		101.3	100.9	-.4	100.2	-1.1		
.8867	.1133		100.1	100.0	-.1	99.5	-.6		
1.000	0		98.2	98.2	---	98.2	----		
0	1.000	523.15	166.6	166.6	---	166.6	----		
.1096	.8904		168.9	169.3	0.3	168.5	-0.2		
.2993	.7007		172.9	173.7	.4	171.7	-.7		
.5172	.4828		176.4	177.7	.8	175.2	-.7		
.6961	.3039		179.1	180.1	.6	177.8	-.7		
.8071	.1929		180.5	181.1	.3	179.2	-.7		
.8867	.1133		180.9	181.4	.3	180.2	-.4		
1.000	0		181.3	181.3	---	181.3	----		
Sulfur dioxide	Hydrogen								
0	1.000	290.15	88.8	88.8	---	88.8	----	16	20
.1676	.8324		130.4	133.2	2.1	130.6	0.2		
.2286	.7714		134.4	136.8	1.7	134.3	-.1		
.2963	.7037		137.0	138.4	1.0	136.0	-.7		
.5075	.4925		135.0	136.6	1.2	134.9	-.1		
.8215	.1785		129.3	129.7	.3	129.1	-.2		
1.000	0		125.9	125.9	---	125.9	---		
0	1.00	472.15	123.7	123.7	---	123.7	----		
.1512	.8488		195.3	196.2	0.4	190.6	-2.4		
.3265	.6735		209.8	214.6	2.3	209.6	-.1		
.4905	.5095		212.1	216.9	2.3	213.1	.5		
.6760	.3240		211.8	214.4	1.2	212.0	.1		
1.000	0		207.1	207.1	---	207.1	----		

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TABLE II. - Concluded. COMPARISON OF COMPUTED AND EXPERIMENTAL VISCOSITIES OF POLAR-NONPOLAR GAS MIXTURES

Mole fraction		Temperature, °K	Viscosity, μP ($\times 10^{-7}$ (N)(sec)/m^2)					Reference	
			Experimental	Approximate (eqs. (9), (10), (14), (17), and (18))	Deviation, percent	Rigorous	Deviation, percent	Experiment	Rigorous calculation
Hydrogen chloride	Hydrogen								
0	1.000	294.15	89.5	89.5	----	89.5	----	17	20
.2031	.7969		134.2	133.3	-0.7	134.0	-0.2		
.5042	.4958		147.1	146.1	-.7	147.6	-.3		
.7179	.2821		146.9	146.2	-.5	146.5	-.3		
.8220	.1780		146.1	145.4	-.5	145.6	-.3		
1.000	0		143.4	143.4	----	143.4	----		
0	1.000	523.15	132.2	132.2	----	132.2	----		
.2991	.7009		228.1	228.9	0.3	227.5	-0.3		
.5178	.4822		245.4	246.8	.6	245.8	.2		
.6312	.3688		250.7	250.7	0	249.9	-.3		
.7947	.2053		252.7	253.0	.1	252.6	0		
1.000	0		253.0	253.0	---	253.0	----		
Methylene chloride	Carbon tetrachloride								
0	1.000	293.15	98.21	98.21	-----	98.21	----	19	20
.1484	.8516		99.12	99.09	-0.03	98.3	-0.8		
.3114	.6886		99.98	100.00	.02	98.6	-1.4		
.5014	.4986		101.27	100.96	-.31	99.2	-2.1		
.6985	.3015		101.59	101.77	.18	100.1	-1.5		
.8425	.1575		102.07	102.21	.13	101.1	-1.0		
1.000	0		102.48	102.48	-----	102.48	----		
0	1.000	413.15	136.26	136.26	-----	136.26	----		
.1261	.8739		136.83	137.33	0.37	136.9	0.1		
.2904	.7096		138.24	138.67	.31	137.9	-.3		
.5262	.4738		141.08	140.40	-.48	139.3	-1.3		
.7118	.2882		140.29	141.54	.89	140.6	.2		
.8485	.1515		142.46	142.19	-.19	141.5	-.7		
1.000	0		142.66	142.66	-----	142.66	----		

Mole fraction		Temperature, °K	Viscosity, μP ($\times 10^{-7}$ (N)(sec)/m^2)					Reference	
			Experimental	Approximate (eqs. (9), (10), (14), (17), and (18))	Deviation, percent	Rigorous	Deviation, percent	Experiment	Rigorous calculation
Water	Methanol								
0	1.000	373.15	122.3	122.3	----			21	
.020	.980		122.8	122.5	-0.2				
.150	.850		124.9	124.0	-.7				
.310	.690		126.8	125.6	-1.0				
.475	.525		126.7	126.6	-.1				
.635	.365		126.5	127.1	.5				
.850	.150		126.1	126.7	.5				
1.000	0		125.5	125.5	----				
Water	Ethanol								
0	1.000	373.15	108.0	108.0	----			21	
.032	.968		111.4	108.8	-2.4				
.081	.919		113.9	109.9	-3.5				
.166	.834		116.3	112.0	-3.7				
.302	.698		118.3	115.2	-2.6				
.460	.540		119.7	118.7	-.8				
.629	.371		122.6	122.0	-.5				
.743	.257		123.8	123.9	-.1				
.826	.174		125.2	124.9	-.3				
.910	.090		125.8	125.5	-.3				
1.000	0		125.5	125.5	----				
Methyl chloride	Sulfur dioxide								
0	1.000	308.15	132.8	132.8	----	132.8	----	22	22
.153	.847		131.0	129.8	-0.9	129.7	-1.0		
.232	.768		129.2	128.3	-.7	128.2	-.8		
.310	.690		127.3	126.7	-.5	126.6	-.5		
.396	.604		125.6	125.0	-.5	124.8	-.6		
.508	.492		123.1	122.8	-.3	122.5	-.5		
.631	.369		120.6	120.3	-.3	120.1	-.4		
.714	.286		118.3	118.6	.2	118.4	.1		
.833	.167		115.6	116.1	.4	116.0	.3		
.955	.045		113.0	113.6	.5	113.5	.4		
1.000	0		112.6	112.6	----	112.6	----		

POLAR GAS MIXTURES

Mole fraction		Tempera-ture, °K	Viscosity, μP ($\times 10^{-7}$ (N)(sec)/m^2)					Reference	
			Experi-mental	Approximate (eqs. (9), (10), (14), (17), and (18))	Deviation, percent	Rigorous	Deviation, percent	Experi-ment	Rigor-ous calcu-lation
Methyl chloride	Sulfur dioxide								
0	1.000	353.15	152.3	152.3	----	152.3	----	22	22
.207	.793		148.7	147.4	-0.9	147.4	-0.9		
.314	.686		145.6	144.8	-.6	145.0	-.4		
.411	.589		142.8	142.4	-.3	142.6	-.1		
.517	.483		140.0	139.9	-.1	140.0	0		
.606	.394		137.7	137.7	0	137.7	0		
.715	.285		134.3	135.0	.5	135.1	.6		
.817	.183		131.9	132.4	.4	132.5	.5		
.949	.051		128.6	129.1	.4	128.9	.2		
1.000	0		127.8	127.8	----	127.8	----		
Methyl chloride	Dimethyl ether								
0	1.000	308.15	96.6	96.6	----	96.6	----	22	22
.046	.954		97.5	97.4	-0.1	97.2	-0.3		
.222	.778		99.9	100.4	.5	100.2	.3		
.299	.701		100.9	101.6	.7	100.9	0		
.401	.599		102.4	103.3	.9	102.5	.1		
.508	.492		104.1	105.0	.9	104.2	.1		
.604	.396		105.4	106.6	1.1	105.8	.4		
.699	.301		107.0	108.1	1.0	107.4	.4		
.802	.198		108.6	109.6	.9	109.1	.5		
.877	.123		109.9	110.8	.8	110.5	.5		
1.000	0		112.6	112.6	----	112.6	----		
0	1.000	353.15	109.8	109.8	----	109.8	----		
.063	.937		110.9	111.0	0.1	111.1	0.2		
.191	.809		112.9	113.5	.5	113.4	.4		
.281	.719		114.2	115.1	.8	115.0	.7		
.400	.600		116.6	117.3	.6	117.2	.5		
.474	.526		117.6	118.7	.9	118.5	.7		
.588	.412		119.7	120.7	.9	120.5	.7		
.669	.331		121.2	122.2	.8	122.0	.6		
.761	.239		123.2	123.8	.5	123.6	.3		
1.000	0		127.8	127.8	----	127.8	----		

TABLE III. - Concluded.   COMPARISON OF COMPUTED AND EXPERIMENTAL VISCOSITIES OF

POLAR GAS MIXTURES

Mole fraction			Temperature, °K	Viscosity, μP ($\times 10^{-7}$ (N)(sec)/m^2)					Reference	
				Experimental	Approximate (eqs. (9), (10), (14), (17), and (18))	Deviation, percent	Rigorous	Deviation, percent	Experiment	Rigorous calculation
Sulfur dioxide	Dimethyl ether									
0	1.000		308.15	96.6	96.6	---	96.6	---	22	22
.058	.942			98.3	98.8	0.5	98.4	0.1		
.184	.816			103.1	103.4	.3	102.9	-.2		
.294	.706			107.0	107.5	.4	106.7	-.3		
.393	.607			110.6	111.1	.4	110.2	-.4		
.492	.508			114.5	114.7	.2	113.9	-.5		
.591	.409			117.9	118.2	.3	117.5	-.3		
.692	.308			122.0	121.9	-.1	121.0	-.8		
.782	.218			125.4	125.1	-.2	124.6	-.6		
.844	.156			127.9	127.3	-.5	126.9	-.8		
1.000	0			132.8	132.8	---	132.8	---		
0	1.000		353.15	109.8	109.8	---	109.8	---		
.049	.951			111.4	111.9	0.5	111.8	0.4		
.190	.810			116.9	118.0	.9	116.8	-.1		
.279	.721			120.4	121.8	1.2	120.6	.2		
.389	.611			125.3	126.6	1.0	125.4	.1		
.504	.496			130.5	131.5	.7	130.0	-.4		
.570	.430			133.3	134.2	.7	133.4	-.1		
.648	.352			137.7	137.6	-.1	136.8	-.6		
.748	.252			141.0	141.8	.5	142.1	.8		
.866	.134			146.4	146.7	.2	146.4	0		
1.000	0			152.3	152.3	---	152.3	---		
Methyl chloride	Sulfur dioxide	Dimethyl ether								
0.256	0.481	0.263	308.15	120.8	118.4	-2.0	118.8	-1.7	22	22
.488	.257	.255		114.5	114.1	-.4	113.7	-.7		
.335	.328	.337		115.3	114.2	-1.0	114.1	-1.1		
.252	.259	.489		110.2	110.4	.1	109.7	-.5		
.255	.492	.253	353.15	138.6	135.6	-2.2	135.1	-2.6		
.494	.262	.244		131.9	130.2	-1.3	129.6	-1.8		
.331	.336	.333		132.6	130.4	-1.7	130.8	-1.4		
.250	.249	.501		126.9	125.2	-1.3	125.8	-.9		

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