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# Thermal conductivity data for hydrogen and deuterium in the range 100–1100 °C

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**Abstract.** The conductivity column method is used to measure the thermal conductivity  $k$  of hydrogen, deuterium and nitrogen from 100 °C to 1000, 1100 and 1200 °C respectively with an overall uncertainty of  $\pm 2\%$ . The data for each gas are correlated by a quadratic polynomial in temperature ( $T$  K). These expressions are:

$$10^5 k \text{ (hydrogen)} = 20.37 + 8.20 \times 10^{-2} T + 3.56 \times 10^{-6} T^2$$

$$10^5 k \text{ (deuterium)} = 16.80 + 5.68 \times 10^{-2} T + 2.354 \times 10^{-6} T^2$$

and

$$10^5 k \text{ (nitrogen)} = 1.184 + 1.77 \times 10^{-2} T - 3.704 \times 10^{-6} T^2.$$

The  $k$  values are in  $\text{cal cm}^{-1} \text{s}^{-1} \text{K}^{-1}$ , and these are in good agreement with the limited data available in the literature as well as with the predictions of theories developed by Hirshfelder, Mason and Monchick, and Saxena, Saksena and Gambhir. This study provides a good support to the column method for the measurement of thermal conductivity. The conductivity data are also used to generate indirectly the viscosity and diffusion coefficients for these gases as a function of temperature. The results are represented in terms of explicit expressions so that the computation at any desired temperature is considerably facilitated.

## 1. Introduction

The thermal conductivity column method initiated by Blais and Mann (1960) has been used with considerable success by two different groups, namely, Timrot and Umanskii (1965) and Saksena and Saxena (1966). Since both of these groups have performed their experiments independent of each other and, further, their apparatus dimensions are very different, comparison of their results will be a very useful effort to establish this technique. This is important for there is no other established technique which is easily adoptable for gas conductivity measurements in the temperature range 1000–2500 K (Saxena 1968 and Saxena and Gandhi 1967). Timrot and Umanskii (1966) reported the thermal conductivity data for hydrogen from about 400 to 2000 K. About two years back, we completed measurements on hydrogen and deuterium and these are being reported here. Experimentation with the two isotopes of hydrogen, which differ in their masses so significantly, provides a very favourable variant to check out this technique. We also give a brief reference to our measurements on nitrogen, which have been described earlier (Saxena *et al.* 1969), and included here is only some limited information not reported before.

The details of the column method, its theory and calculation procedure, are described earlier by us in connection with the conductivity measurements on helium (Saxena and Saxena 1968 a) and neon (Saxena and Saxena 1968 b), and will not be

repeated here. However, it may be mentioned that initially it was thought that this technique was appropriate only for gases having large conductivity values because in such cases a major portion of the input energy is conducted through the gas while heat losses due to end conduction, convection etc., are relatively small. On the other hand, if the gas conductivity is low, the temperature profiles along the axial hot wire in the presence and absence of the gas will resemble each other to a greater degree. Consequently, in a carefully designed and fabricated apparatus it should be possible to determine even the thermal conductivity of low-conducting gases with enough accuracy. Indeed our experiments with argon (Saxena and Saxena 1968 c) and krypton and xenon (Saxena and Saxena 1969) have confirmed this intuitive argument. Theoretical calculations of Saxena and Davis (to be published) will provide quantitative answers to many such questions, as the temperature profiles have been explicitly calculated for different wire radii, input powers, gases, etc.

It will also be interesting to point out here some of the basic essentials and general differences between the well-known hot-wire method and the conductivity column method. In both methods a wire is axially stretched in a cylindrical container and these act as isothermal hot and cold walls respectively. In both methods it is attempted to keep the convection loss at a negligible level, the energy flow to be radial, and radiation loss is determined either by measurements in vacuum or is calculated. In the case of the hot-wire method, the difference in the temperatures of the hot and cold surfaces is small and the conductivity  $k$  of the gas is determined from a knowledge of the energy  $W_c$  conducted from the wire, and this refers to some average temperature between the hot- and cold-wall temperatures. In the conductivity column method the difference in the temperature of the two surfaces is large and the conductivity at the hot-wall temperature is determined in terms of the derivative of  $W_c$  with respect to temperature. This can be better appreciated by the following mathematical treatment of the common starting heat balance equations for the two main methods.

In the notation and context of our earlier paper (Saxena and Saxena 1968 a) the thermal energy conducted away from the wire per unit length is

$$W_c = -2\pi rk \frac{d\theta'}{dr}. \quad (1)$$

This is simply the well-known Fourier's law, where  $\theta'$  is the temperature at a distance  $r$  from the axis of the hot wire. This relation may be rearranged so that

$$\int_0^\theta k d\theta' = \frac{\ln(r_1/r_2)}{2\pi} W_c. \quad (2)$$

Here  $r_1$  and  $r_2$  are the radii of the cylindrical surfaces at temperatures 0 and  $\theta$  respectively. In the hot-wire method, equation (2) is directly integrated so that  $k$  at some average temperature  $\bar{\theta}$  in the range 0 to  $\theta$  is given by

$$k(\bar{\theta}) = \frac{\ln(r_1/r_2)}{2\pi\bar{\theta}} W_c. \quad (3)$$

Usually  $\bar{\theta}$  is taken as  $\theta/2$  and this in many instances is of little consequence as  $\theta$  is quite small. In the column method equation (2) is differentiated so that

$$k(\theta) = \frac{\ln(r_1/r_2)}{2\pi} \left( \frac{dW_c}{d\theta} \right)_{r=r_2}. \quad (4)$$

Thus, the problem of temperature assignment is overcome at the expense of accurately determining  $W_0$  as a function of  $\theta$  so that the derivative in equation (4) may be computed with sufficient reliance.

## 2. Experimental details

We have taken measurements on two conductivity columns which primarily differ only in length. The longer one is referred to as column I. The various geometrical dimensions of these columns are reported in table 1. The platinum wire was supplied

Table 1. The constants of the conductivity columns

	Specimen I	Specimen II
Length of the axial platinum wire of column I at 32 °C	91.05 cm	—
Length of the axial platinum wire of column II	63.04 cm (32 °C)	63.50 cm (26 °C)
Radius of the platinum wire	0.2460 mm	0.2643 mm
Resistance per unit length of platinum wire at 0 °C	$5.9972 \times 10^{-3}$ $\Omega \text{ cm}^{-1}$	$5.4477 \times 10^{-3}$ $\Omega \text{ cm}^{-1}$
Constant $A$ of the platinum wire	$33.55 \times 10^{-4}$ per degC	$38.25 \times 10^{-4}$ per degC
Constant $B$ of the platinum wire	$-49 \times 10^{-8}$ per degC <sup>2</sup>	$-49 \times 10^{-8}$ per degC <sup>2</sup>
Internal radius of the column tube	0.427 cm	
External radius of the column tube	0.512 cm	

by Ravindra Heraeus & Co., Bombay, and was 99.99% pure. Two different supplies were received and these are distinguished by referring to them as specimen I and specimen II respectively. The use of two different specimens of platinum wire is entirely a matter of chance. As soon as the stock of specimen I platinum wire was exhausted, attempts were made to replace it with specimen II. The overall available facilities warranted further experimental work only with column II and this was felt completely satisfactory because of the established success and faith in getting conductivity values from the data on a single column. Their experimentally determined geometrical and electrical constants are accordingly reported in table 1, where  $A$  and  $B$  are the constants of the quadratic relation giving the variation of resistance with temperature, i.e.

$$R_t = R_0(1 + At + Bt^2). \quad (5)$$

Here,  $R_t$  and  $R_0$  are the resistances of a given length of platinum wire at temperatures  $t$  and 0 °C respectively. The constants  $R_0$ ,  $A$  and  $B$  were computed by measuring the resistance at three known temperatures, namely, the ice, steam and sulphur points. The fact that the constants  $A$  and  $B$  are so different from the standard literature values, and also the constant  $A$  for the two specimens, is of some concern. Whether or not it is due to the impurities in the samples is not known because no independent check of the same was made by us and the above stated purity is as specified by the supplier. We did determine the values of the constants at different times, and at one instance by two different workers, and found the results to be completely reproducible. Further, we successfully checked the resistance at two other known intermediate temperatures. Extrapolation of equation (5) with the above constants for temperatures

Table 2. Record of electrical power  $W$  ( $W \text{ cm}^{-1}$ ) fed to the wires of columns I and II to heat them to different temperatures  $t$  ( $^{\circ}\text{C}$ ) in the presence of hydrogen at different pressures  $p$  (cm mercury).  $T_1$  is the temperature of cold wall in  $^{\circ}\text{C}$

	Column I specimen I		Column II specimen I		Column II specimen II				
	$t$	$W \times 10^2$	$t$	$W \times 10^2$	$t$	$W \times 10^2$		$t$	
	$p = 17.3, T_1 = 32.0$	$p = 17.3, T_1 = 32.0$	$p = 16.5, T_1 = 26.0$	$p = 16.5, T_1 = 26.0$	$p = 25.6, T_1 = 26.0$	$p = 25.6, T_1 = 26.0$	$p = 35.6, T_1 = 26.0$		
46.0	5.746	45.7	5.741	40.6	6.295	28.6	1.444	40.6	6.312
68.2	14.96	67.7	14.94	52.6	9.896	57.3	8.156	55.6	9.312
96.8	27.74	96.5	27.74	70.6	17.59	59.9	12.79	87.2	28.00
129	43.07	128	42.90	96.7	29.79	74.9	19.29	101	32.68
158	57.34	158	57.34	123	43.96	96.2	29.88	131	44.54
171	63.42	170	63.42	158	60.69	122	42.82	162	61.30
200	78.91	201	79.13	219	92.05	137	47.60	181	71.00
218	94.54	217	94.45	290	132.7	167	63.22	203	83.43
252	108.7	250	108.1	307	143.9	187	74.00	228	96.68
272	119.7	274	120.6	359	177.1	253	110.4	260	114.6
310	142.8	312	143.0	475	259.1	301	142.0	289	133.5
323	149.7	325	150.2	555	323.4	387	196.5	386	167.9
346	164.2	349	165.4	616	380.5	474	262.8	406	207.1
385	191.9	385	192.0	695	449.9	545	315.8	452	245.3
404	203.1	407	204.3	791	553.0	509	286.7	509	286.7
432	222.5	433	223.3	905	684.2	567	331.8	567	331.8
473	253.7	474	254.2	949	741.2	640	399.5	640	399.5
518	282.5	520	283.1	1040	856.4	716	462.0	716	462.0
550	309.6	552	310.4			843	588.2	843	588.2
610	363.9	613	365.5			870	640.8	870	640.8
673	417.6	676	418.6			899	678.1	899	678.1
745	476.8	749	478.1			953	744.8	953	744.8
						1035	855.3	1035	855.3

Table 3. Record of electrical power  $W$  ( $W \text{ cm}^{-1}$ ) fed to the wires of columns I and II to heat them to different temperatures  $t$  ( $^{\circ}\text{C}$ ) in the presence of deuterium at different pressures  $p$  (cm of mercury).  $T_1$  is the temperature of cold wall in  $^{\circ}\text{C}$

$t$	Column I specimen I		Column II specimen I		Column II specimen II	
	$W \times 10^2$	$p = 26.4, T_1 = 32.0$	$W \times 10^2$	$p = 26.4, T_1 = 32.0$	$W \times 10^2$	$p = 26.0$
39.3	1.803	40.1	1.812	33.4	2.214	35.0
58.2	6.058	58.2	6.183	50.1	5.061	52.1
73.3	12.74	74.1	12.81	78.4	13.77	76.9
95.3	19.88	96.0	19.95	119	26.14	123
145	36.85	147	36.91	168	44.25	166
178	49.14	180	49.31	220	64.76	196
239	74.18	240	74.51	280	90.90	277
291	96.77	292	97.05	374	133.7	349
348	122.8	350	123.7	445	168.7	384
418	157.6	420	158.1	551	232.7	459
451	176.0	455	177.1	631	286.5	508
505	207.5	506	207.5	721	357.9	546
534	227.9	536	228.7	748	379.7	593
597	263.3	600	264.0	857	467.2	679
638	292.5	640	293.1	919	535.7	735
687	325.7	689	326.0	959	583.2	776
733	359.0	736	360.2	1007	632.8	834
779	392.7	780	393.2	1047	682.0	916
815	421.9	818	422.7	1109	652.7	960
916	514.3	917	515.2	1165	818.2	1023
						1070
						1107
						1144
						1023
						706.8
						750.8
						798.7
						897
						863
						826
						454.2
						422.1
						384.3
						368.0
						322.7
						282.9
						240.1
						208.0
						188.8
						162.3
						142.6
						114.2
						76.51
						66.85
						48.94
						24.62
						15.57
						9.848
						1.529

above the sulphur point is again open to some fine criticism but we felt that, at this stage of our work with this technique, the effort as described here will be in order. The hydrogen gas was supplied by British Oxygen Co., England, and was stated to be spectroscopically pure. The deuterium gas was supplied by the Bhabha Atomic Research Centre, Bombay, and a mass-spectrometric analysis indicated its composition as 98.6% deuterium, 0.8% hydrogen and the remainder as water vapour.

The electrical power required to heat the wire to different temperatures in the presence of hydrogen and deuterium at different pressures is reported in tables 2 and 3 respectively. This tabulation helps in recognizing even any small variation from one run to another as gas pressure or other parameters are changed. We do not report such data for vacuum runs because somewhat similar information is already available in our earlier work. In our work with helium some doubt persisted as to the presence of the temperature jump effect. We have consequently taken measurements with these two gases at a number of gas pressures and found neither any systematic nor even appreciable variation. This should be regarded as very substantial evidence of the almost complete absence of convection and temperature jump effects in our apparatus. This is not surprising in view of the discussion and detailed calculations presented in earlier papers (Saxena and Saxena 1968 a, b, 1969). The simple theory of the temperature jump effect as given by Kennard (1938) gives the correction for conductivity, which amounts to 4.6% for hydrogen in the worst case ( $T = 1300$  K and  $p = 16.5$  cm of mercury), and 4.1% for deuterium, again for the most unfavourable case ( $T = 1400$  K and  $p = 15.4$  cm of mercury). Here  $p$  refers to the gas pressure. In these calculations we have used the accommodation coefficients as given by Amdur *et al.* (1944) and which are in substantial agreement with the earlier results of Archer (1938). As explained previously by us (Saxena and Saxena 1968 a) the favourable surface condition of the wire can reduce the jump effect appreciably. The more sophisticated theories of such an effect and its related physics have started developing in recent years, e.g. Wachman (1962), Goodman and Wachman (1967), and Harris (1967), and once a reliable theory is available the data of tables 2 and 3 may be re-considered, if found necessary; though it may be remarked that within the limits of our experimental precision no jump effect could be detected for gas pressures above about 10 cm of mercury. The gas pressure is deliberately kept low so that the convection losses are small. The temperature of the wire was computed from its resistance and from equation (5).

The computed values of thermal conductivity are reported in table 4 for both the gases. The conductivity values listed in columns 3 to 7 are obtained from the data on the two individual columns—which are of different lengths but are otherwise similar. The conductivity values, obtained by taking the difference in the electrical power required to heat the wires of the two columns to the same temperature, are reported in column 8 and are referred to as 'Differential'. It will be noted that the different sets of conductivity values are in good agreement with each other. The maximum scatter is 2.4% and 3% for hydrogen and deuterium respectively. This indicates that any end effect if at all significant is quite small. This is not surprising in view of our previous approximate theoretical calculations (Saxena and Saxena 1966) which are further strongly supported by more vigorous numerical calculations of Saxena and Davis (to be published). The different sets of conductivity data were therefore graphically smoothed by giving equal weight to all the data points for the two gases, and are listed in column 9 of table 4 under 'Smooth'. In the next column of this table are given the corresponding conductivity values after the application of the

Table 4. Uncorrected  $k'$  and corrected  $k$  experimental values of thermal conductivity<sup>a</sup> ( $\text{cal cm}^{-1} \text{s}^{-1} \text{K}^{-1}$ ) of hydrogen and deuterium at different pressures  $p$  ( $\text{cm of mercury}$ ) as a function of temperature  $t$  ( $^{\circ}\text{C}$ ).

Gas	$t$	$10^5 k'$		$10^5 k'$ Column II ( $p = 16.5$ ) <sup>b</sup> ( $p = 25.6$ ) <sup>c</sup> ( $p = 35.6$ ) <sup>c</sup> ( $p = 17.3$ ) <sup>b</sup> ( $p = 17.3$ )	$10^5 k'$ Differential ( $p = 17.3$ )	$10^5 k'$ Smooth	$10^5 k'$ Corrected for wall effect	$10^5 k'$ (equation (6))
		Column I ( $p = 17.3$ )	Column II ( $p = 25.6$ ) <sup>b</sup> ( $p = 35.6$ ) <sup>c</sup> ( $p = 17.3$ ) <sup>b</sup> ( $p = 17.3$ )					
H <sub>2</sub>	100	49.8	48.8	50.5	49.8	50.2	50.5	51.4
	200	59.0	59.2	59.0	60.1	58.5	58.5	59.9
	300	66.8	68.2	67.8	67.8	68.5	67.0	68.5
	400	74.0	76.0	76.5	76.0	73.6	73.8	77.2
	500	84.7	85.6	84.5	85.0	84.6	84.3	86.0
	600	92.4	92.5	—	92.2	92.2	92.2	94.6
	700	100.5	98.2	—	98.5	99.6	99.8	103.5
	800	—	110.8	—	111.6	—	—	112.4
	900	—	119.5	—	118.2	—	—	121.4
	1000	—	125.0	—	127.4	—	—	130.5
D <sub>2</sub>	100	37.6	38.4	38.0	38.3	38.0	38.0	38.3
	200	42.8	44.0	43.4	44.0	43.8	43.2	44.2
	300	50.3	49.2	48.8	50.2	49.5	49.8	50.1
	400	55.0	54.6	54.7	55.5	55.5	54.3	56.1
	500	59.7	60.4	61.2	60.2	59.6	59.5	62.1
	600	67.8	66.5	67.8	67.2	67.2	67.2	68.2
	700	70.8	73.0	73.2	72.8	70.8	71.3	74.3
	800	79.2	80.8	81.4	81.2	79.0	80.2	80.5
	900	84.2	87.0	86.8	—	85.5	84.8	86.7
	1000	—	92.0	92.2	—	—	—	92.9
1100	—	97.6	96.8	—	—	—	99.1	
								(equation (7))

<sup>a</sup> To convert these conductivity values into  $\text{mW cm}^{-1} \text{K}^{-1}$  multiply by 0.041 868.

<sup>b</sup> The platinum wire of specimen I.

<sup>c</sup> The platinum wire of specimen II.



correction due to the wall effect. The magnitude of this correction is 1.2% and 3.2% at 100 °C and 1000 °C respectively for hydrogen, and 0.8% and 2.4% at 100 °C and 1000 °C respectively for deuterium.

These final smooth and corrected conductivity values are well correlated by a quadratic polynomial in temperature ( $T$  K). For hydrogen this relation is

$$10^5 k = 20.37 + 8.20 \times 10^{-2} T + 3.56 \times 10^{-6} T^2 \quad (6)$$

where  $k$  is in  $\text{cal cm}^{-1} \text{s}^{-1} \text{K}^{-1}$ . Equation (6) can reproduce the conductivity values of column 10 within average absolute and maximum deviations of 0.2% and 0.8% respectively. Similarly for deuterium we get

$$10^5 k = 16.80 + 5.68 \times 10^{-2} T + 2.354 \times 10^{-6} T^2. \quad (7)$$

This relation predicts the conductivity data of column 10 within average absolute and maximum deviations of 0.1% and 0.3% respectively. In the last column of table 4 are listed the computed conductivity values at rounded temperatures from equations (6) and (7). We estimate the accuracy of our final conductivity values, equations (6) and (7), to be better than  $\pm 2\%$ . This uncertainty assignment has taken into consideration the various possible sources of error, magnitudes of different corrections and scatter of the points, and is consistent with the general guidance received from a comparison of the present data with other measurements and theory. The latter is covered in the next section and in table 5.

### 3. Discussion

A number of workers have reported thermal conductivity data for hydrogen, but in most of the cases below 300 °C. Gambhir and Saxena (1967) critically evaluated the existing information and recommended a smooth set as a function of temperature. At the Thermophysical Properties Research Center (TPRC) a similar effort (Touloukian 1966, Touloukian *et al.* 1969) has been made. In table 5 we compare our experimental values with the recommendations of these two different groups. In the second column are given the values as obtained from equation (6). In columns 3 and 4 are listed the percentage deviations of the recommended values of TPRC (Touloukian 1966, Touloukian *et al.* 1969) and Gambhir and Saxena (1967) from our values (column 2) respectively. These deviations are marked positive when the recommended conductivity values are found greater than the present experimental values of column 2, and negative in the other cases. The agreement between the present results and these two sets is almost equally good, the average absolute deviation being 2.8% in both cases.

Timrot and Umanskii (1966) determined the thermal conductivity of hydrogen using a somewhat similar procedure as here and synthesized their data using the following equation:

$$k = 0.127 + 0.1816 \times 10^{-3} T + 0.05916 \times 10^{-6} T^2 \quad (8)$$

where  $k$  is in  $\text{kcal m}^{-1} \text{h}^{-1} \text{K}^{-1}$ . The percentage deviations of their  $k$  values from our data are given in column 5 of table 5. Their low-temperature values are in substantial disagreement with our data. As in this temperature range data from standard and established techniques are available, we feel that the Timrot and Umanskii (1966) values are unreliable. The agreement becomes reasonable beyond 500 K. We feel that the primary source where Timrot and Umanskii (1966) lose accuracy of their data is the presence of jump effect in their apparatus. We also feel that their apparatus

Table 5. Comparison of present experimental thermal conductivity data with those of other workers and with theory

$T$ (K)	Hydrogen				$k(\text{H}_2)$ $k(\text{D}_2)$	Present work
	Experimental Gambhir and Saxena	Timrot and Umanskii	Theoretical Mason and Monchick	Saxena <i>et al.</i>		
	$10^5 k$					
350	49.5 <sup>a</sup>	-1.8 <sup>†</sup>	-10.9 <sup>‡</sup>	+0.2 <sup>‡</sup>	+0.6 <sup>‡</sup>	1.34
400	53.7	-1.7	+8.2	+1.3	+2.0	1.35
500	62.2	-1.4	+3.6	+1.0	+3.4	1.36
600	70.8	-1.8	+1.0	+4.1	+3.9	1.37
700	79.5	-2.4	-1.1	+2.6	+3.8	1.38
800	88.2	-2.5	-2.3	+2.0	+3.2	1.38
900	97.0	-3.0	-3.1	+1.2	+2.5	1.39
1000	105.9	-3.4	-3.5	+0.4	+1.8	1.39
1100	114.9	-3.9	-3.7	-0.5	+1.0	1.40
1200	123.9	-4.5	-3.6	-1.4	+0.3	1.40
1300	132.9	-4.9	-3.2	-2.0	-0.4	1.40

<sup>†</sup> TPRC = Thermophysical Properties Research Center (Touloukian 1966, Touloukian *et al.* 1969).

<sup>‡</sup> These are percentage deviations from experimental values of column 2.

<sup>a</sup> To convert these conductivity values which are in  $\text{cal cm}^{-1} \text{s}^{-1} \text{K}^{-1}$  into  $\text{mW cm}^{-1} \text{K}^{-1}$  multiply by 0.041 868.

is not long enough, with the result that, in spite of their thin wire, a sufficiently long region in the central portion of the wire does not exist where isothermal temperature conditions hold. A more critical discussion of this point will be presented by Saxena and Davis at a later date. In the light of these comments it is interesting to appreciate the success and promise of the column method when one recalls the reasonable agreement between the present data and the results of Russian experiments which have been taken on conductivity columns of widely different design and dimensions.

The theories of Hirschfelder (1957), Mason and Monchick (1962) and Saxena *et al.* (1964) were also used to compute the thermal conductivity of hydrogen as a function of temperature. In these calculations we have used the modified Buckingham  $\exp - 6$  potential with potential parameters given by Mason and Rice (1954). Instead of reporting the directly calculated values we have listed their percentage deviations from our experimental values in table 5 to be brief and clear. The agreement between theory and experiment is quite good as the deviations are about as large as the uncertainty in the experimental data. Further, a very refined agreement is not expected owing to the fact that hydrogen is a linear molecule and a theory primarily developed for spherically symmetric molecules is bound to fall short in describing its properties with high precision.

These measurements also establish that the Blais and Mann (1960) data for hydrogen, like helium, is systematically greater than the true values, as pointed out first by Saxena and Agrawal (1961). The discrepancy is 16% at 1200 K. The Timrot and Umanskii (1966) data also confirm this view for over almost the whole temperature range, 1200–2000 K.

For deuterium there are not enough data available in the literature for direct comparison. The TPRC (Touloukian 1966, Touloukian *et al.* 1969) recommended values at 350 and 400 K agree with our directly measured values within 2.7% and 5.3% respectively. Further, in view of the limited purity of our deuterium sample we expect only a fair agreement, about  $\pm 4\%$ , and consequently we can evaluate our data on the basis of hydrogen as a good approximation. In the last column of table 5 is listed the ratio of the conductivity values of hydrogen to deuterium as a function of temperature. There is a systematic small increase in the conductivity ratio as the temperature is increased. It is difficult to assess this small trend because of the impurities in deuterium and our overall uncertainty in the individual conductivity values of  $\pm 2\%$ . If we assume the validity of the Chapman–Enskog kinetic theory of spherically symmetric molecules and identical intermolecular force field for hydrogen and deuterium, this ratio should have the constant value of about 1.41. Both these assumptions are not rigorously correct and the last one has been questioned by a number of workers—Barua and Saran (1963), Kestin and Nagashima (1964), and Mason *et al.* (1965). Consequently the agreement between thermal conductivity values of hydrogen and deuterium should be regarded as quite good, and this is valid evidence in establishing and strengthening the promise of the column method for the determination of thermal conductivity of gases.

One of the other homonuclear diatomic gases we investigated was nitrogen of spectral purity. The detailed results have already been reported—Saxena *et al.* (1969). The final results in the temperature range 350 to 1500 K were correlated within an average absolute and maximum deviation of 0.4% and 1.0% respectively by the following relation:

$$10^5 k = 1.184 + 1.77 \times 10^{-2} T - 3.704 \times 10^{-6} T^2. \quad (9)$$

Here  $k$  is in  $\text{cal cm}^{-1} \text{s}^{-1} \text{K}^{-1}$ . It may be noted that for nitrogen the term containing the second power of  $T$  is negative, unlike the above two gases but in conformity with what Saxena and Gupta (1969) found for carbon monoxide and oxygen.

Reliable interrelations exist between the three elementary transport properties of gases (Hirschfelder *et al.* 1964). Explicit relations for computing viscosity ( $\eta$ ) and diffusion ( $D$ ) coefficients from thermal conductivity and other related data have been elaborated by Mathur and Saxena (1966), and Saxena *et al.* (1969). For brevity, we do not reproduce these expressions here except quote our final results as obtained from theory and experimental data. These indirectly generated values of  $\eta$  in the temperature range of conductivity measurements could be correlated by expressions similar to equation (9). For hydrogen, with no average absolute deviation, the relation is

$$10^6 \eta = 42.84 + 16.5 \times 10^{-2} T - 6.424 \times 10^{-6} T^2 \quad (10)$$

while for nitrogen the equation

$$10^6 \eta = 31.14 + 50.6 \times 10^{-2} T - 1.307 \times 10^{-4} T^2 \quad (11)$$

represents the data within an average absolute deviation of 0.2%. Here  $\eta$  is in  $\text{g cm}^{-1} \text{s}^{-1}$ . Similarly, diffusion coefficients for hydrogen and nitrogen are correlated by the expressions

$$D = 9.17 \times 10^{-5} T^{1.691} \quad (12)$$

and

$$D = 1.557 \times 10^{-5} T^{1.715} \quad (13)$$

respectively. The percentage average absolute deviations in the two cases are 1.2 and 1.3 respectively. Here  $D$  is in  $\text{cm}^2 \text{s}^{-1}$  and the values refer to one atmosphere. It is implied that similar relations for deuterium can be generated from the corresponding expressions for hydrogen with the multiplication of appropriate numerical factors. In the absence of directly measured values these estimates are our best guides.

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