NATIONAL BUREAU OF STANDARDS REPORT

3163

The Thermodynamic and Transport Properties of Liquid Hydrogen and Its Isotopes. Part I

Abraham S. Friedman and Joseph Hilsenrath
Thermodynamics Section
Division of Heat and Power

U. S. DEPARTMENT OF COMMERCE
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Sponsored by
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Introduction

The tables contained herein and those to follow are part of a new project in the Thermodynamics Sectiop of the Heat and Power Division devoted to the correlation and compilation of thermodynamic and transport properties of molecular hydrogen and its isotopes in the liquid and gaseous state. This program is sponsored by The Los Alamos Scientific Laboratory, and is part of the program of the NBS-AEC Cryogenic Engineering Laboratory at Boulder, Colorado. The tables are being distributed as soon as they become available because of the urgent need for these data. It is planned to reissue them, with such modifications as are required, in the form of a more formal publication as various phases of the compilation are completed.

PVT Relationships for Liquid Hydrogen*

T **	25.5	26.0	26.5	27.0	27.5	28.0	28.5	29.0
°K	atm	atm	atm	atm	atm	atm	atm	atm
15	34.86	14.87						
15.5	39.81	19.68						
16	44.76	24.49	7.88					
16.5	49.71	29.30	12.55					
17	54.66	34.11	17.22					
17.5	59.61	38.92	21.89	7.19				
18	64.56	43.73	26.56	11.72				
18.5	69.51	48.54	31.23	16.25				
19	74.46	53.35	35.90	20.78	9.16			
19.5	79.41	58.16	40.57	25.31	13.55			
20	84.36	62.97	45.24	29.84	17.94	7.28		
20.5	89.31	67.78	49.91	34.37	22.33	11.54		
21	94.26	72.59	54.58	38.90	26.72	15.80		
21.5	99.21		59.25	43.43	31.31	20.06	10.08	
22	104.16	82.21	63.92	47.96	35.50	24.32	14.21	
22.5	109.11	87.02	68.59	52.49	39.89	28.5%	18.34	9.94
23	114.06	91.83	73.26	57.02	44.28	32.84	22.47	13.94
23.5	119.01	96.64	77.93	61.55	48.67	37.10	26.60	17.94
24	123.96	101.45	82.60	66.08	53.06	41.36	30.73	21.94
24.5	128.91	106.26	87.27	70.61	57.45	45.62	34.86	25.94
25	133.86	111.07	91.94	75.14	61.84	49.88	38.99	29.94
25.5	138.81	115.88	96.61	79.67	66.23	54.14	43.12	33.94
26	143.76	120.69	101.28	84.20	70.62	58.40	47.25	37.94
26.5	148.71	125.50	105.95	88.73	75.01	62.66	51.38	41.94
27		130.31	110.62	93.26	79.40	66.92	55.51	45.94
27.5		135.12	115.29	97.79	83.79	71.18	59.64	49.94
28		139.93	119.96	102.32	88.18	75.44	63.77	53.94
28.5		144.74	124.63	106.85	92.57	79.70	67.90	57.94
29		149.55	129.30	111.38	96.96	83.96	72.03	61.94
29.5			133.97	115.91	101.35	88.22	76.16	65.94
30			138.64	120.44	105.74	92.48	80.29	69.94
30.5			143.31	124.97	110.13	96.74	84.42	73.94
31			147.98	129.50	114.52	101.00	88.55	77.94
31.5				134.03	118.91	105.26	92.68	81.94
32				138.56	123.30	109.52	96.81	85.94
32.5				143.09	127.69	113.78	100.94	89.94
33				147.62	132.08	118.04	105.07	93.94

*These tables *are* preliminary to the preparation of tables of molar volumes and compressibility factors as a function of temperature and pressure;

**cc/mole

PVT Relationships for Liquid Hydrogen* - Cont.

T \ V**	29.5	30.0	30.5	31.0	31.5	32.0	32.5	33.0
°K	atm	atm	atm	atm	atm	atm	atm	atm
23	6.13							
23.5	10.00							
24	13.87	6.88						
24.5	17.74	10.63						
25	21.61	14.38	8.79					
25.5	25.48	18.13	12.42	7.51				
26	29.35	21.88	16.05	11.03				
26.5	33.22	25.63	19.68	14.55	9.99			
27	37.09	29.38	23.31	18.07	13.40	9.50		
27.5	40.96	33.13	26.94	21.59	16.81	12.80	9.45	
28	44.83	36.88	30.57	25.11	20.22	16.10	12.65	9.69
28.5	48.70	40.63	34.20	28.63	23.63	19.40	15.85	12.79
29	52.57	44.38	37.83	32.15	27.04	22.70	19.05	15.89
29.5	56.44	48.13	41.46	35.67	30.45	26.00	22.25	18.99
30	60.31	51.88	45.09	39.19	33.86	29.30	25.45	22.09
30.5	64.18	55.63	48.72	42.71	37.27	32.60	28.65	25.19
31	68.05	59.38	52.35	46.23	40.68	35.90	31.85	28.29
31.5	71.92	63.13	55.98	49.75	44.09	39.20	35.05	31.39
32	75.79	66.88	59.61	53.27	47.50	42.50	38.25	34.49
32.5	79.66	70.63	63.24	56.79	50.91	45.80	41.45	37.59
33	83.53	74.38	66.87	60.31	54.32	49.10	44.65	40.69

°K	33.5	34	35	36
28	7.08			
28.5	10.08	7.81		
29	13.08	10.72		
29.5	16.08	13.63	9.82	
30	19.08	16.54	12.55	9.48
30.5	22.08	19.45	15.28	12.04
31	25.08	22.36	18.01	14.60
31.5	28.08	25.27	20.74	17.16
32	31.08	28.18	23.47	19.72
32.5	34.08	31.09	26.20	22.28
33	37.08	34.00	28.93	24.84

Compressibility Factor for Liquid Hydrogen*

T \ V**	25.5	26.0	28.5	22.0	27.5	28.0,	28.5	29.0
°K								
15	.7222	.3141						
15.5	.7982	.4023						
16	.8693	.4850	.1591					
16.5	.9362	.5627	.2456					
17	.9992	.6358	.3271					
17.5	1.0585	.7047	.4040	.1352				
18	1.1146	7	.4765	.2142				
18.5	1.1676	.8314	.5452	.2890				
19	1.2179	.8897	.6102	.3599	.1616			
19.5	1.2655	.9450	.6719	.4271	.2329			
20	1.3108	.9976	.7305	.4909	.3006	.1242		
20.5	1.3539	1.0476	.7862	.5517	.3650	.1921		
21	1.3949	1.0953		.6095	4	.2567		
21.5	1.4340	1.14	.8900	.6647	.4849	.3184	.1628	
22	1.4713	1.1840	.9383	.7173	.5408	.3772	.2243	
22.5	1.5070	1.2254	.9845	.7676	.5945	.4334	.2831	.1561
23	1.5411	1.2651	1.0287	.8157	.6452	.4872	.3393	.2142
23.5	1.5738	1.3030	1.0709	.8618	.6941	.5387	.3931	.2698
24	1.6051	1.3	1.1115	.9060	9	,5880	.4447	.3231
24.5	1.6351	1.3742	1.1503	.9483	.7859	.6354	.4942	.3742
25	1.6639	1.4077	1 1877	0	.8290	.6808	.5417	.4232
25.5	1.6916	1.4399	1.2235	1.0280	.8704	.7245	.5873	.4704
26	1.7183	1.4708	1.2580	1.0656	.9103	.7664	.6312	.5157
26.5	1.7439	1.5006	1.2912	1.1017	.9486	.8068	.6734	.5593
27		1.5292	1.3231	1.1365	.9855	.8457	.7141	.6013
27.5		1.5568	1.3539	1.701	1.0211	.8832	.7532	.6418
28		1.5835	1.3836	I.2024	1.0554	.9194	.7910	.6808
28.5		1.6092	1.4122	1.2336	1.0885	.9542	.8275	.7185
29		1.6340	1.4399	1.2631	1.1205	.9879	.8627	.7548
29.5			1.4666	1.2928	1.1514	1.0204	.8967	.7900
30			1.4924	1.3210	1.1812	1.0519	.9295	.8239
30.5			1.5174	1.3482	1.2101	1.0823	.9613	.8568
31			1.5416	1.3745	1.2380	1.1117	.9921	.8885
31.5				1.4000	1.2651	1 1402	1.0219	.9193
32				1.4247	1.2913	1.1678	1.0508	.9491
32.5				1.4487	1.3167	1.1946	1.0787	.9780
33				1.4719	1.3413	1.2206	1.1058	1.0060

*These tables are preliminary to the preparation of volumes and compressibility factors as a function of temperature and pressure.

**cc/mole

Compressibility Factor for Liquid Hydrogen* - Cont.

T	29.5	30.0	30.5	31.0	31.5	32.0	32.5	33.0
°K								
23	.0958							
23.5	.1530							
24	.2078	.1048						
24.5	.2603	.1586						
25	.3108	.2103	.1307					
25.5	.3592	.2599	.1810	.1113				
26	.4058	.3077	.2294	.1603				
26.5	.4507	.3536	.2760	.2074	.1447			
27	.4939	.3978	.3209	.2528	.1905	.1327		
27.5	.5355	.4404	.3641	.2966	.2347	.1815	.1361	
28	.5756	.4815	.4058	.3388	.2772	.2242	.1789	.1392
28.5	.6143	.5212	.4460	.3795	.3182	.2655	.2203	.1805
29	.6517	.5595	.4849	.4188	.3579	.3053	.2602	.2204
29.5	.6878	.5965	.5224	.4568	.3962	.3437	.2987	.2589
30	.7227	.6322	.5587	.4935	.4333	.3809	.3360	.2961
30.5	.7565	.6668	.5937	.5290	.4691	.4168	.3720	.3321
31	.7892	.7003	.6277	.5634	.5037	.4516	.4069	.3670
31.5	.8208	.7327	.6606	.5967	.5373	.4853	.4407	.4008
32	.8515	.7641	.6924	.6289	.5698	.5179	.4734	.4335
32.5	.8812	.7945	.7233	.6601	.6013	.5496	.5051	.4651
33	.9100	.8240	.7532	.6904	.6319	.5802	.5359	.4959

°K	33.5	34	35	36
28	.1032			
28.5	.1444	.1135		
29	.1841	.1532		
29.5	.2225	.1914	.1420	
30	.2596	.2284	.1784	.1386
30.5	.2955	.2642	.2137	.1732
31	.3303	.2989	.2478	.2066
31.5	.3639	.3324	.2808	.2390
32	.3965	.3649	.3128	.2704
32.5	.4281	.3964	.3439	.3008
33	.4587	.4269	.3739	.3302

The P-V-T Relationship of Liquid H_2

The compressibility of liquid hydrogen as a function of pressure has been determined by E. Bartholome (Z. Physik Chem., B 33, 387 (1936)) at the boiling point of H_2 and at 18.24" and 16.43°K. A comprehensive study of the P-V-T relationships of liquid H_2 has been completed by H. L. Johnstoq, Wm. E. Keller and A. S. Friedman (J. A. C. S. in press (1954)). These data cover the temperature region from the boiling point to the critical temperature and the pressure range from the saturation vapor pressure to above 100 atmospheres.

A plot of the reported data on P vs V coordinates gave smooth isotherms from which dues were obtained for replotting on P vs T coordinates for the selected isochores. Since these were straight lines within the experimental error, smooth values could easily be read off at the temperatures and molar volumes tabulated here. The compressibility factor table was computed from the table of pressures by using the relation $Z = PV/RT$. A retabulation of the data to yield density and compressibility factors in terms of temperature is in process. In the interim it is felt that these tables will be found useful.

Vapor Pressures of Liquid DT and T_2

$T^{\circ}K$	DT	T_2
	P (atmos.)	
20	0.214	--
21	0.324	--
22	0.473	0.380
23	0.667	0.546
24	0.914	0.761
25	1.22	1.03
26	1.58	1.35
27	2.02	1.75
28	22-52	2.22
29	3.10	2.78
30	3.83	3.45
31	4.65	4.19
32	5.60	5.00
33	6.67	5.97
34	7.86	7.02
35	9.15	8.24
36	10.61	9.53
37	12.28	11.09
38	14.07	12.76
39	16.09	14.62
40	--	16.61

The only vapor pressure measurements of tritium reported in the literature are those of E. R. Grilly (J. Am. Chem. Soc. 73, 845 (1951)), who determined the vapor pressures up to three atmospheres. There have been no experimental measurements of the vapor pressures of DT.

R. Lunbeck (Dissertation, Univ. of Amsterdam, 1951) and E. F. Hammel (J. Chem. Phys. 18, 228 (1950)) have each calculated vapor pressure constants for the hydrogen isotopes on the basis of DeBoer's modified law of corresponding states. Their results, however, are in disagreement with the available experimental data for some of the isotopes.

A. S. Friedman, D. White, and H. L. Johnston (J. Chem. Phys. 19, 126 (1951)) have computed on the basis of an inverse square root of the mass ($M^{-1/2}$) relationship, the vapor pressures, critical constants, boiling points, and triple point constants of the six isotopic hydrogen molecules. On the basis of this treatment, the vapor pressures and the related constants of HT should, in the first approximation, be the same as those of D2. The very meager experimental data on HT (W. F. Libby and C. A. Barter, J. Chem. Phys. 10, 184 (1942)) verify this. It is therefore recommended that the vapor pressure values for D_2 be used for those of HT.

The appended tables of DT and T_2 were computed from the equation;

$$\log_{10} P = a + \frac{b}{T} + \delta.$$

The constants a and b are derived from the aforementioned mass relationship. δ is the predicted departure of the vapor pressure for these isotopes from the linear representation in terms of $\log_{10} P$ and $1/T$. These δ's were obtained from a plot of corresponding departures observed for H_2 and D_2.

Thermal Conductivity of Liquid Hydrogen

$k = (1.702 + .05573T)10^{-4}$ cal cm^{-1} sec^{-1} deg^{-1}

	$k \times 10^4$	$k \times 10^4$	$k \times 10^2$
°K	cal cm^{-1} sec^{-1} $°K^{-1}$	Joules cm^{-1} sec^{-1} $°K^{-1}$	Btu ft^{-1} hr^{-1} $°F^{-1}$
16	2.594	10.85	6.271
17	2.649	11.08	6.404
18	2.705	11.32	6.539
19	2.761	11.55	6.675
20	2.817	11.79	6.810
21	2.872	12.02	6.943
22	2.928	12.25	7.078
23	2.984	12.49	7.214
24	3.040	12.72	7.349
25	3.095	12.95	7.482
26	3.151	13.18	7.618
27	3.207	13.42	7.753
28	3.262	13.65	7.886
29	3.318	13.88	8.021
30	3.374	14.12	8.156

The Thermal Conductivity of Liquid Hydrogen

The only experimental data on the thermal conductivity of liquid hydrogen are those of Mattox, Powers, and Johnston (Ohio State University Technical Report TR 264-10), who have made measurements over the range 15° to 27°K on both liquid normal and liquid para hydrogen. No significant difference was observed between the two liquids and it is concluded that the thermal conductivity is independent of the ortho-para composition within the experimental errors.

The authors fitted a least squares line to their data and give the equation:

$$k = (1.702 + 0.05573T)10^{-4} \text{ cal cm}^{-1} \text{ sec}^{-1} \text{°K}^{-1}$$

The tables were computed from this equation. The maximum error is 3.5% and the probable error is 2%.

Thermal Conductivity of Liquid Deuterium

$k = (2.020 + 0.04965T)10^{-4}$ cal cm^{-1} sec^{-1} deg^{-1}

	$k \times 10^4$	$k \times 10^4$	$k \times 10^2$
°K	cal cm^{-1} sec^{-1} °K^{-1}	Joules cm^{-1} sec^{-1} °K^{-1}	Btu ft^{-1} hr^{-1} °F^{-1}
20	3.013	12.61	7.284
21	3.063	12.82	7.405
22	3.112	13.03	7.523
23	3.162	13.23	7.644
24	3.212	13.44	7.765
25	3.262	13.65	7.886
26	3.311	13.85	8.004
27	3.361	14.06	8.125
28	3.411	14.27	8.246
29	3.460	14.48	8.365
30	3.510	14.69	8.485

The Thermal Conductivity of Liquid Deuterium

The only experimental measurements of the thermal conductivity of liquid deuterium are those of Powers, Mattox, and Johnston (Ohio State University Report TR 436-1, April 23, 1951). Measurements were made in a parallel-plate apparatus for normal and ortho deuterium over the temperature interval 19° - 26°K and were found to give a positive temperature coefficient. Within the experimental uncertainty ($< 2.5\%$) the ortho-para composition had no effect on the thermal conductivity. The authors have fitted their data to line having the equation

$$k = (2.020 + 0.04965T)10^{-4} \text{ cal cm}^{-1} \text{ sec}^{-1} \text{ °K}^{-1}$$

The values tabulated here were computed from this equation. The maximum uncertainty is 2.5% and the standard deviation is 0.9%.

THE NATIONAL BUREAU OF STANDARDS

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