ADDENDUM TO AN INVESTIGATION OF THE EQUILIBRIUM PRESSURE ALONG UNEQUALLY HEATED TUBES

By

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FOREWORD

The authors wish to acknowledge the assistance of W. H. Carden in obtaining new experimental data.

ABSTRACT

This report presents results of an investigation of the error introduced in very low pressure measurements when small tubes with axial temperature gradients connect pressure transducer and the point where knowledge of the pressure is desired.

The experiments reported in AEDC-TDR-62-26 were extended with air, argon, and helium to include higher Knudsen numbers and to include data taken with the pressure transducer at the hot end of the tube. Although the form of the pressure-temperature relationship was specified with good accuracy to a Knudsen number of 5.0, the degree of scatter for larger Knudsen numbers was such (± 5%) that it was not possible to fix accurately the free molecule limit.

Also in the present analysis, what is considered to be a more accepted definition of mean free path has been used, and the opportunity was taken to recalculate the earlier work using this definition.

PUBLICATION REVIEW

This report has been reviewed and publication is approved.

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NOMENCLATURE

A	$\dfrac{\Delta p}{p_{avg}} \Big/ \dfrac{\Delta T}{T_{avg}}$
Kn	Knudsen number = λ / r
M	Molecular weight, g/g-mole
p	Pressure, microns of mercury unless otherwise stated
Δp	$p_h - p_c$ (unless stated otherwise)
R	Gas constant
r	Inside radius of the tube, inches
T	Absolute temperature, °K
ΔT	$T_h - T_c$
λ	Mean free path of the gas, inches
μ	Viscosity
σ	Zero energy collision diameter
$\Omega^{(2,2)*}$	Reduced collision integral for viscosity

SUBSCRIPTS

avg	Average value
c	Cold end of the tube
h	Hot end of the tube
ℓ	Large tube
s	Small tube
t	Tank

1.0 INTRODUCTION

This report presents some additional data which extend the work reported in Ref. 1. The mean free path was recalculated using a more generally accepted formula, and some errors in Ref. 1 were corrected. Complete details of the apparatus, experimental procedures, and analysis of the test data are given in Ref. 1.

2.0 DISCUSSION

2.1 MEAN FREE PATH

As was pointed out in Ref. 1, there are various tables and formulas for mean free path. As long as one definition is used for mean free path, no problems will arise in correlating experimental data. However, a review of the available literature on the estimation of mean free path shows that the values quoted in Ref. 1, which were based on data in Ref. 2, are not truly representative of current usage. It was decided that the definition quoted in Ref. 3:

$$\lambda = \frac{16}{5\sqrt{2\pi}} \frac{\mu}{p} \sqrt{RT} \tag{1}$$

should be the one used in the present study. It may be written as:

$$\lambda = 11.4985 \; \mu \frac{\sqrt{RT}}{p} \text{ in.} \tag{2}$$

where μ is in poise, R is in $ft^2/sec^2/°K$, p is in microns of mercury, and T is in °K.

The data presented herein are given as a function of Knudsen number based on the mean free path as calculated by Eq. (2). It is important to note this change from Ref. 1.

It can be seen that this definition of mean free path depends upon the viscosity of the gas. The viscosity of a large number of gases is given in Ref. 4. Viscosity may be written in the form:

$$\mu \times 10^6 = \frac{26.693\sqrt{MT}}{\sigma^2 \, \Omega^{(2,2)*}} \text{ poise} \tag{3}$$

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where the reduced collision integral $\Omega^{(2,2)*}$ has been derived using the Lennard-Jones (12-6) potential and has been tabulated in terms of temperature in Ref. 5. In this process a definition of mean free path derived on the basis of a billiard ball molecular model is used in conjunction with a viscosity-temperature relationship based on a more complete gas model. It is considered that this inconsistency is permissible in the present case. Values of the mean free path for various gases over a range of temperatures are given in Fig. 1. The value for hydrogen is in good agreement with that used by Knudsen in Ref. 6.

2.2 DISCUSSION OF PREVIOUS RESULTS

In Figs. 2a to 2e and Table 1, the data contained in Ref. 1 have been replotted and retabulated using the above formula for mean free path. It will be noted that there is a difference between the present data and Knudsen's, although it must be emphasized that at a particular Knudsen number the difference is on the order of five percent for temperature ratios up to 2.62.

2.3 ADDITIONAL TESTS

In Ref. 1 some difficulties were experienced in accurately measuring the pressure below 40 microns of mercury. For pressures lower than this there seemed to be some scatter in the data and also a tendency for the pressure ratio (p_c/p_h) to increase with increase of Knudsen number when the Knudsen number was greater than 5.0. In Ref. 1 it was suggested that this apparently anomalous behavior could be explained by the existence of a pressure increment caused by the desorption of gas from the surface of the small tube.

To minimize this effect the whole system was kept at a pressure of 0.01 microns of mercury for four weeks before taking any data. Also the junction of the small tube and the large tube was kept at an elevated temperature for this time to speed up any outgassing that was occurring. After this pump down and bake out time, measurements were taken over an extended period of time for three gases: air, argon, and helium. Great care was taken to ensure that the hot and cold junctions of the tubes were kept at constant temperatures for these three gases.

An improvement in the pressure measuring accuracy was made by connecting the pressure transducer output to a strip chart recorder. This visual record of the transducer output made it easier to determine when the pressure in the transducer had stabilized.

The results of the tests carried out at a temperature ratio of 1.955 are shown in Fig. 2f and Table 2. It can be seen that, up to a Knudsen number of 5.0, the degree of scatter in the data is very small. This confirms the validity of Knudsen number as a correlating parameter. For Knudsen numbers greater than 5.0 the degree of scatter increases to approximately ± 5% about a mean curve through the experimental data. It is not possible because of this large degree of scatter to predict whether any particular theoretical free molecule value has been achieved, despite the fact that measurements were made at Knudsen numbers up to 100 based on tube radius.

Some further tests were carried out at temperature ratios of 3.843 and 1.523. These ratios were obtained by cooling the junction with liquid nitrogen and a dry ice-acetone mixture, respectively, the other ends of the tubes being at room temperature. The results of these tests are shown plotted in Fig. 2g and tabulated in Table 2.

All the results have been used to draw the working charts shown in Figs. 3 and 4. It will be noted that the cold-junction results agree well with the hot-junction results over the range of temperature ratio achieved in the present tests.

2.4 ERRATA TO REF. 1

When the relationship

$$\frac{\Delta_p}{p_{avg}} \Big/ \frac{\Delta_T}{T_{avg}} = \left[\frac{T_h}{T_c} + 1\right] \Big/ \left[\frac{T_h}{T_c} + 2\sqrt{\frac{T_h}{T_c}} + 1\right] = A \qquad (4)$$

was plotted as Fig. 5 in Ref. 1, the parameter A was erroneously shown to be 0.5 at $T_h/T_c = 0$ instead of at $T_h/T_c = 1.0$. The corrected curve is shown plotted in Fig. 5 of this report.

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TABLE 1

PREVIOUS EXPERIMENTAL DATA

HELIUM

r_ℓ = 0.46 in. T_c = 301°K $\frac{T_h}{T_c}$ = 2.606

r_s = 0.0315 in. T_h = 785°K

p_{cs}	$p_{c\ell}$	Kn_{cs}	$(p_{c\ell}/p_h)_{Kn_{c\ell}}$	p_c/p_h
16	18.4	12.0	.742	.645
16.6	18.7	11.5	.743	.660
26.7	33.8	7.16	.795	.628
26.8	33.0	7.13	.794	.645
27.5	34.0	6.96	.796	.644
36.8	47.6	5.20	.833	.644
36.8	46.5	5.19	.873	.690
48.8	65.4	3.91	.873	.651
51.0	66.4	3.78	.875	.672
71.7	96.5	2.69	.913	.678
71.7	97.3	2.69	.914	.674
100.3	136	1.92	.943	.697
101	137	1.90	.943	.694
103	140	1.86	.944	.695
105	145	1.83	.948	.687
179	246	1.07	.972	.707
180	245	1.06	.972	.714
260	346	.736	.982	.738
262	345	.730	.982	.746
395	505	.484	.990	.774
398	506	.481	.990	.779
476	596	.401	.992	.792
480	600	.400	.992	.794
671	805	.286	.997	.831
677	818	.285	.997	.825
1196	1333	.161	1.0	.897
1198	1335	.160	↓	.897
1784	1912	.107	↓	.933
1799	1918	.107	↓	.938
2289	2400	.0836	↓	.954
2292	2409	.0836	↓	.951
3045	3153	.0628	↓	.966
3051	3160	.0627	↓	.966
4004	4110	.0478	↓	.974
4011	4110	.0477	↓	.976
5960	6037	.0321	↓	.987
5993	6060	.0319	↓	.989
9380	9425	.0204	↓	.995
9410	9460	.0204	↓	.995

TABLE 1 (Continued)

HELIUM

r_ℓ = 0.46 in. T_c = 300°K $\frac{T_h}{T_c}$ = 2.43

r_s = 0.0135 in. T_h = 728°K

p_{cs}	$p_{c\ell}$	Kn_{cs}	$(p_{c\ell}/p_h)Kn_{c\ell}$	p_c/p_h
16.1	17.5	27.7	.771	27.7
16.9	17.5	26.3	.771	26.3
17.2	17.8	25.8	.772	25.8
39.4	48.0	11.3	.864	11.3
39.8	48.2	11.2	.864	11.2
49.6	64.6	8.96	.892	8.96
50.2	64.8	8.87	.892	8.87
60.7	80.1	7.33	.910	7.33
61.1	80.0	7.29	.910	7.29
86.0	115	5.17	.938	5.17
88.3	116	5.04	.938	5.04
95.4	128	4.67	.945	4.67
95.6	129	4.65	.945	4.65
112	155	3.99	.955	3.99
115	156	3.87	.955	3.87
140	192	3.19	.965	3.19
141	192	3.16	.965	3.16
156	214	2.86	.970	2.86
157	214	2.83	.970	2.83
171	236	2.60	.974	2.60
171	237	2.60	.974	2.60
216	295	2.06	.983	2.06
216	295	2.06	.983	2.06
232	319	1.92	.986	1.92
232	320	1.92	.986	1.92
300	410	1.48	.992	1.48
301	410	1.48	.992	1.48
431	571	1.03	.998	1.03
485	568	.917	.998	.917
590	763	.754	.999	.754
590	763	.754	.999	.754
840	1055	.530	1.00	.530
847	1055	.525	↓	.525
1163	1402	.383		.383
1165	1402	.382		.382
1717	1980	.259		.259
1725	1982	.258		.258
2372	2634	.188		.188
2390	2655	.186		.186
3472	3738	.128		.128
3472	3730	.128		.128
5300	5540	.0839		.0839
7525	7710	.0591		.0591
7580	7760	.0587		.0587
11380	11520	.0428		.0428
11410	11560	.0428		.0428

TABLE 1 (Continued)

HELIUM

$r_\ell = 0.46$ in. $T_c = 300^\circ K$ $\frac{T_h}{T_c} = 1.776$

$r_s = 0.0135$ in. $T_h = 533^\circ K$

p_{cs}	$p_{c\ell}$	Kn_{cs}	$(p_{c\ell}/p_h)_{Kn_{c\ell}}$	p_c/p_h
53.6	62.4	8.30	.939	.807
55.4	64.4	8.03	.942	.810
79.9	96.1	5.56	.965	.802
79.9	95.6	5.56	.965	.807
105	129	4.25	.977	.793
105	130	4.20	.977	.793
130	159	3.43	.983	.801
130	159	3.42	.983	.803
200	245	2.22	.991	.809
201	246	2.21	.991	.808
229	281	1.94	.992	.810
229	281	1.94	.992	.809
310	378	1.43	.995	.816
312	379	1.43	.995	.818
464	555	.958	.997	.833
468	558	.951	.997	.836
619	724	.719	.998	.852
620	720	.717	.998	.859
919	1049	.484	.999	.875
921	1049	.483	.999	.877
1548	1691	.287	1.0	.915
1550	1691	.287	↓	.917
2064	2220	.216	↓	.930
2064	2220	.216	↓	.930
2650	2775	.168	↓	.955
4030	4140	.110	↓	.971
4030	4150	.110	↓	.971
5640	5740	.0789	↓	.983
5665	5775	.0785	↓	.981
8290	8375	.0536	↓	.990
8290	8375	.0536	↓	.990

TABLE 1 (Continued)

HELIUM

r_ℓ = 0.46 in. T_c = 299°K $\frac{T_h}{T_c}$ = 1.766

r_s = 0.0315 in. T_h = 528°K

p_{cs}	$p_{c\ell}$	Kn_{cs}	$(p_{c\ell}/p_h)_{Kn_{c\ell}}$	p_c/p_h
6.21	6.21	30.5	.812	--
8.38	6.98	22.7	.815	--
12.5	12.8	15.2	.835	.815
12.7	13.2	14.9	.836	.806
31.1	34.9	6.11	.890	.793
31.1	34.9	6.11	.890	.791
45.4	52.8	4.18	.920	.791
45.8	52.4	4.15	.920	.804
55.9	64.8	3.40	.935	.806
57.3	66.0	3.31	.936	.813
57.9	68.1	3.28	.939	.798
58.2	68.4	3.26	.939	.798
84.9	100	2.24	.960	.814
84.9	101	2.24	.960	.810
95.2	113	1.99	.967	.812
96.0	114	1.98	.968	.814
130	155	1.46	.979	.822
131	155	1.45	.979	.825
215	253	.883	.991	.844
216	253	.881	.991	.844
218	253	.871	.991	.852
293	337	.649	.996	.873
294	339	.645	.996	.864
371	425	.512	.998	.870
372	423	.510	.998	.878
476	538	.400	1.00	.882
479	541	.396	↓	.883
707	773	.269	↓	.914
710	775	.267	↓	.916
1090	1152	.174	↓	.946
1094	1160	.174	↓	.943
1512	1572	.126	↓	.962
1512	1572	.126	↓	.962
1968	2028	.0965	↓	.971
1977	2038	.0960	↓	.971
2618	2668	.0725	↓	.982
2621	2670	.0724	↓	.982
3378	3411	.0562	↓	.990
3390	3429	.0560	↓	.989
3991	4022	.0475	↓	.993
4001	4030	.0474	↓	.993
5062	5090	.0375	↓	.995
5074	5100	.0374	↓	.995

TABLE 1 (Continued)

AIR

r_ℓ = 0.46 in. T_c = 300°K $\frac{T_h}{T_c}$ = 2.616

r_s = 0.0135 in. T_h = 785°K

p_{cs}	$p_{c\ell}$	Kn_{cs}	$(p_{c\ell}/p_h)_{Kn_{c\ell}}$	p_c/p_h
3940	3990	.0385	1.0	.987
3920	3960	.0388		.990
2700	2775	.0564		.973
2696	2770	.0564		.973
1845	1930	.0824		.956
1835	1924	.0832		.954
1182	1274	.129		.927
1178	1272	.129		.927
740	832	.205		.889
740	832	.205		.889
495	583	.307		.849
494	578	.308		.854
322	399	.472		.807
316	398	.481		.794
216	276	.704		.782
215	277	.708		.774
147	198	1.03	.999	.742
144	195	1.06	.999	.734
106	141	1.43	.993	.746
75.4	104	2.01	.984	.716
75.4	102	2.01	.983	.725
55.6	76.1	2.73	.972	.710
55.1	75.6	2.76	.971	.707
42.6	58.5	3.57	.959	.698
41.2	56.5	3.69	.956	.697
31.7	41.2	4.79	.938	.722
30.7	40.7	4.95	.937	.706
20.2	24.9	7.54	.901	.730
19.7	24.4	7.73	.898	.722
12.0	13.9	12.7		
11.5	13.4	13.2		

TABLE 1 (Continued)

AIR

r_ℓ = 0.46 in. T_c = 302°K $\frac{T_h}{T_c}$ = 2.598

r_s = 0.0315 in. T_h = 785°K

p_{cs}	$p_{c\ell}$	Kn_{cs}	$(p_{c\ell}/p_h)_{Kn_{c\ell}}$	p_c/p_h
4983	4997	.0132	1.0	.998
4914	4927	.0134		.998
4484	4498	.0147		.998
4463	4473	.0146		.998
3449	3463	.0190		.996
3112	3132	.0211		.994
3090	3112	.0213		.993
2510	2526	.0262		.993
2495	2519	.0263		.991
1880	1903	.0350		.988
1876	1906	.0350		.984
1230	1260	.0534		.977
1214	1245	.0541		.975
1210	1241	.0543		.975
1079	1114	.0609		.969
931	964	.0706		.966
756	796	.0869		.950
586	629	.112		.933
584	626	.113		.933
455	498	.145	.999	.913
454	498	.145	.999	.911
380	424	.173	.998	.893
379	424	.174	.998	.891
330	375	.199	.998	.879
330	375	.199	.998	.879
240	284	.273	.997	.844
240	283	.274	.997	.846
172	212	.383	.993	.805
171	212	.385	.993	.800
131	166	.502	.991	.782
130	166	.506	.991	.776
90.8	120	.724	.984	.743
90.5	119	.726	.984	.745
76.2	103	.863	.981	.726
77.9	104	.843	.981	.737
65.3	87.7	1.00	.977	.727
63.6	85.6	1.03	.975	.724
56.7	75.4	1.18	.970	.729
56.7	75.4	1.18	.970	.729
56.6	77.7	1.16	.970	.707
55.6	75.2	1.18	.970	.717
46.0	63.2	1.43	.964	.702
42.3	57.8	1.55	.959	.701
41.4	56.7	1.59	.958	.700
40.1	55.7	1.64	.959	.692
38.5	50.6	1.69	.951	.724
38.2	50.7	1.72	.951	.715
36.5	48.9	1.80	.949	.708
36.4	49.6	1.81	.950	.697
34.2	46.3	1.92	.946	.698
33.0	43.7	1.99	.942	.712
32.6	46.2	2.02	.946	.667
31.4	42.6	2.09	.939	.692
26.1	33.8	2.52	.920	.710
25.6	33.0	2.57	.918	.705
24.5	32.2	2.68	.915	.696
18.9	25.6	3.47	.894	.661
18.7	24.8	3.53	.892	.671
18.1	24.8	3.63	.892	.652
13.4	16.6	4.91	.848	.685
12.8	15.4	5.14	.838	.697
11.6	13.8	5.66	.824	.693
7.8	9.0	8.46	.778	.674
6.5	7.4	10.3	.760	.657
5.4	6.4	12.2	.748	.631

TABLE 1 (Continued)

AIR

r_ℓ = 0.46 in. T_c = 302°K $\frac{T_h}{T_c}$ = 2.04

r_s = 0.0315 in. T_h = 615°K

p_{cs}	$p_{c\ell}$	Kn_{cs}	$(p_{c\ell}/p_h)_{Kn_{c\ell}}$	p_c/p_h
5.33	5.60	12.3	.818	.779
6.13	6.13	10.7	.822	.822
9.87	10.9	6.63	.859	.776
10.9	11.7	6.00	.863	.804
11.2	12.5	5.85	.869	.776
14.9	17.3	4.38	.898	.774
16.0	18.4	4.09	.904	.786
18.7	22.9	3.51	.925	.753
18.9	22.9	3.46	.925	.764
20.5	24.0	3.19	.928	.793
28.0	33.8	2.34	.950	.786
28.8	34.6	2.27	.951	.790
36.2	45.3	1.81	.965	.771
37.3	45.8	1.75	.966	.786
50.3	60.9	1.30	.978	.808
51.4	61.7	1.29	.978	.815
62.3	75.4	1.05	.983	.811
63.9	77.5	1.02	.985	.811
73.1	89.1	.895	.988	.810
73.1	88.3	.895	.988	.813
76.6	93.1	.854	.989	.814
78.1	94.2	.837	.989	.820
84.9	103	.770	.991	.820
85.3	103	.767	.991	.820
106	127	.616	.994	.833
107	127	.610	.994	.837
149	174	.438	1.00	.856
151	176	.432		.862
243	270	.269		.900
244	271	.268		.900
339	369	.193		.920
340	368	.193		.925
388	417	.168		.931
392	420	.167		.932
533	560	.122		.952
534	560	.122		.952
657	680	.0995		.966
657	681	.0995		.966
912	932	.0717		.979
914	937	.0715		.975
1120	1138	.0584		.985
1122	1144	.0582		.981
1366	1386	.0479		.986
1866	1878	.0350		.994
1870	1884	.0350		.994
2488	2493	.0263		.998
2503	2508	.0261		1.00
3427	3434	.0191		.998
3461	3468	.0189		.998
4650	4656	.0140		.999

TABLE 1 (Continued)

AIR

r_ℓ = 0.46 in. T_c = 297°K $\frac{T_h}{T_c}$ = 1.792

r_s = 0.0135 in. T_h = 533°K

p_{cs}	$p_{c\ell}$	Kn_{cs}	$(p_{c\ell}/p_h)_{Kn_{c\ell}}$	p_c/p_h
14.1	15.6	10.7	.929	.843
16.0	17.0	9.44	.933	.880
23.1	26.9	6.54	.953	.819
23.6	27.4	6.41	.955	.823
30.2	36.3	5.00	.967	.804
30.6	36.8	4.94	.967	.805
40.0	47.6	3.78	.975	.819
41.0	48.1	3.68	.976	.832
57.0	68.8	2.65	.984	.815
57.5	69.3	2.63	.984	.817
66.5	79.2	2.27	.988	.829
90.0	107	1.68	.992	.836
91.2	108	1.66	.992	.836
122	145	1.24	.996	.840
124	145	1.22	.996	.850
186	215	.813	1.0	.867
190	218	.798		.869
270	304	.743		.888
364	402	.416		.905
369	406	.410		.908
377	420	.401		.897
384	421	.394		.912
529	572	.287		.924
531	571	.285		.930
743	790	.204		.940
743	790	.204		.940
1163	1210	.130		.963
1165	1210	.130		.963
1890	1930	.080		.979
2686	2714	.056		.990
2690	2725	.056		.988
3860	3880	.039		.995
3860	3880	.039		.995

TABLE 1 (Concluded)

AIR

$r_\ell = 0.460$ in. $\quad T_c = 300^\circ K \quad \dfrac{T_h}{T_c} = 1.648$

$r_s = 0.0315$ in. $\quad T_h = 495^\circ K$

p_{cs}	$p_{c\ell}$	Kn_{cs}	$(p_{c\ell}/p_h)_{Kn_{c\ell}}$	p_c/p_h
6.48	6.48	10.1	.882	.882
10.3	11.0	6.35	.916	.855
10.5	11.1	6.18	.916	.867
19.9	22.3	3.27	.952	.850
21.5	24.0	3.03	.956	.858
30.0	34.1	2.17	.970	.854
30.0	34.15	2.17	.970	.852
39.4	45.9	1.65	.980	.840
53.3	61.1	1.22	.987	.861
53.7	61.1	1.21	.987	.867
72.3	82.8	.901	.993	.867
73.0	83.2	.892	.993	.871
96.0	109	.620	.996	.877
97.2	109	.670	.996	.886
135	149	.484	↓	.904
136	151	.481		.899
183	200	.355		.918
184	200	.354		.922
235	251	.278		.934
237	254	.275		.935
295	312	.221		.944
295	314	.221		.939
381	395	.171		.963
387	397	.168		.959
568	583	.115		.974
721	737	.090		.979
717	732	.091		.980
1031	1045	.063		.990
1335	1345	.049		1.0
2277	2278	.029	↓	1.0

TABLE 2
EXPERIMENTAL DATA

ARGON

r_ℓ = 0.46 in. T_c = 287°K $\frac{T_h}{T_c}$ = 1.955

r_s = 0.0135 in. T_h = 561°K

p_{cs}	$p_{c\ell}$	Kn_{cs}	$(p_{c\ell}/p_h)_{Kn_{c\ell}}$	p_c/p_h
5710	5730	.0264	1.00	.997
4475	4500	.0337		.995
4085	4100	.0372		.997
3370	3410	.0449		.989
2508	2550	.0603		.984
2065	2100	.0731		.983
1677	1730	.0901		.970
1443	1500	.105		.964
1140	1200	.133		.953
869	930	.174		.934
869	930	.174		.934
639	700	.236		.913
634	700	.238		.906
507	567	.298		.894
503	567	.300		.887
402	455	.376		.885
401	455	.376		.881
320	372	.472		.860
277	325	.546		.851
278	325	.543		.855
277	325	.545		.853
214	255	.707		.838
175	211	.861		.831
175	211	.864		.829
139	170	1.09		.815
107	135	1.41	.998	.795
87.1	110	1.74	.992	.785
85.2	110	1.78	.992	.767
82.3	105	1.84	.992	.777
68.9	87.0	2.19	.989	.783
59.2	75.0	2.55	.984	.777
58.8	75.0	2.57	.984	.770
59.3	75.0	2.55	.984	.778
57.3	73.0	2.64	.984	.773
56.9	73.0	2.65	.984	.767
44.9	56.0	3.36	.978	.785
43.9	56.0	3.44	.978	.766
44.2	56.0	3.42	.978	.772
32.9	42.0	4.59	.965	.756
33.7	42.0	4.48	.965	.774
31.2	40.5	4.85	.962	.740
24.3	30	6.22	.942	.763
23.6	29	6.41	.940	.764
23.4	29	6.47	.940	.757
22.9	29	6.61	.940	.741
23.2	28	6.46	.938	.777
22.0	28	6.87	.938	.738
23.0	28	6.58	.938	.769
19.2	24	7.89	.926	.739
18.8	24	8.04	.926	.725
18.7	24	8.08	.926	.721
19.5	24	7.77	.925	.749
18.9	24	7.98	.925	.730
17.8	21	8.47	.915	.777
17.2	20	8.77	.912	.785
16.8	20	8.99	.912	.765
12.7	15	11.9	.892	.755
12.7	15	11.9	.892	.754
8.87	10	17.0	.865	.767
8.25	9.5	18.3	.862	.749
7.93	9.2	19.1	.860	.741
5.76	6.8	26.2	.842	.713
5.67	6.5	26.7	.840	.733
5.59	6.5	27.0	.840	.722
4.80	5.5	31.5	.830	.724
4.41	5.1	34.3	.825	.712
4.36	4.9	34.7	.822	.731

TABLE 2 (Continued)

AIR

r_ℓ = 0.46 in. T_c = 287°K $\frac{T_h}{T_c}$ = 1.955

r_s = 0.0135 in. T_h = 561°K

p_{cs}	$p_{c\ell}$	Kn_{cs}	$(p_{c\ell}/p_h)_{Kn_{c\ell}}$	p_c/p_h
6080	6110	.0237	1.0	.995
4065	4100	.0354	↓	.991
3030	3080	.0475	↓	.984
1969	2020	.0732	↓	.975
1144	1200	.126	↓	.953
855	910	.168	↓	.939
610	665	.236	↓	.917
516	580	.279	↓	.890
397	448	.363	↓	.886
395	448	.365	↓	.881
314	368	.459	↓	.853
223	265	.644	↓	.843
132	158	1.09	.994	.824
131	158	1.10	.994	.830
91.2	115	1.58	.989	.784
60.1	75	2.40	.981	.786
53.6	69	2.70	.979	.760
47.35	59	3.04	.981	.786
47.2	59	3.05	.975	.782
30.5	40	4.74	.962	.733
28.8	35	5.0	.955	.786
27.3	35	5.27	.955	.745
28.2	35	5.11	.955	.770
28.2	35	5.12	.955	.768
25.1	33	5.74	.952	.760
25.4	35	5.69	.955	.692
22.8	30	6.32	.949	.721
22.7	28	6.36	.946	.767
22.8	28	6.32	.946	.772
21.7	28	6.64	.946	.733
17.5	20	8.24	.924	.807
18.2	22	7.91	.930	.770
18.2	22	7.94	.930	.768
18.2	22	7.91	.930	.769
11.5	14	12.6	.898	.735
11.6	14	12.4	.898	.744
12.2	14	11.8	.898	.785
10.7	12	13.5	.885	.790
10.7	12	13.5	.885	.790
10.7	12	13.5	.885	.787
10.4	12	13.9	.885	.765
10.7	11.5	13.4	.882	.823
10.5	11.5	13.7	.882	.805
10.4	11.5	13.9	.882	.793
10.3	11.5	14.0	.882	.787

TABLE 2 (Continued)

HELIUM

r_ℓ = 0.46 in. T_c = 287°K $\frac{T_h}{T_c}$ = 1.955

r_s = 0.0135 in. T_h = 561°K

p_{cs}	$p_{c\ell}$	Kn_{cs}	$(p_{c\ell}/p_h)_{Kn_{c\ell}}$	p_c/p_h
12800	12845	.0334	1.0	.997
7700	7800	.0555		.987
5460	5600	.0783		.975
4035	4180	.106		.965
3303	3450	.130		.957
2680	2850	.159		.940
2690	2850	.159		.944
2030	2200	.211		.923
2030	2200	.211		.923
1655	1820	.258		.909
1662	1820	.257		.913
1472	1640	.290		.898
1464	1640	.292		.893
1058	1200	.403		.882
1047	1200	.409		.873
1053	1200	.406		.878
943	1100	.453		.857
675	810	.633		.833
523	653	.817		.801
539	653	.794		.825
532	653	.803		.814
387	483	1.11	.998	.798
383	483	1.12	.998	.790
314	395	1.36	.996	.792
315	395	1.36	.996	.795
221	275	1.93	.990	.796
215	275	1.99	.990	.767
216	275	1.98	.990	.776
197	250	2.17	.988	.780
197	250	2.17	.988	.777
161	200	2.66	.982	.790
158	200	2.71	.982	.775
156	200	2.74	.982	.767
128	163	3.34	.976	.765
127	163	3.37	.976	.760
122	155	3.50	.974	.765
121	155	3.53	.974	.761
86.5	111	4.94	.962	.750
86.5	111	4.94	.962	.750
90.1	112	3.85	.962	.774
90.2	112	4.74	.962	.774
89.7	112	4.77	.962	.771
57.6	72	7.42	.940	.753
57.8	72	7.40	.940	.755
58.5	72	7.65	.940	.765
37.4	48.0	11.4	.921	.717
37.6	48.0	11.4	.921	.722
38.0	48.0	11.3	.921	.728
38.6	47.0	11.1	.920	.754
38.3	47.0	11.2	.920	.748
38.4	47.0	11.1	.920	.751
28.6	35.0	14.9	.883	.721
21.9	26.0	19.5	.854	.721
21.3	26.0	20.4	.854	.699
22.1	25.0	19.4	.850	.750
21.4	25.0	20.0	.850	.727
15.9	19.0	26.9	.830	.698
16.1	19.0	26.6	.830	.704
15.7	19.0	27.2	.830	.686
19.8	22.0	21.6	.840	.755
20.0	22.0	21.4	.840	.763
19.6	22.0	21.9	.840	.747
15.4	16.5	27.7	.820	.766
15.2	16.5	28.1	.820	.756
14.6	16.5	29.2	.820	.728
14.8	16.5	28.8	.820	.737
15.1	17.0	28.3	.822	.731
15.6	17.0	27.4	.822	.754
14.6	16.0	29.2	.819	.749
14.9	16.0	28.8	.819	.761
23.3	27.0	18.4	.822	.708
10.8	11.5	39.7	.801	.750
10.8	11.5	39.7	.801	.750
9.37	10.8	45.6	.799	.693
9.97	10.8	42.9	.799	.737
11.3	11.8	38.0	.801	.764
9.86	11.8	43.4	.801	.669
9.27	10.0	46.1	.795	.737
9.40	10.0	45.5	.795	.747
10.9	11.8	39.1	.801	.742
11.1	11.8	38.7	.801	.750
8.62	8.9	49.6	.790	.765
7.99	8.9	53.5	.790	.709
8.14	8.9	52.5	.790	.723
7.91	8.4	33.8	.789	.743
7.95	8.7	53.8	.790	.722
8.00	8.7	53.4	.790	.726
4.43	5.0	96.5	.772	.684
4.61	5.0	92.8	.772	.711
5.36	6.0	79.7	.778	.625

TABLE 2 (Continued)

HELIUM

r_ℓ = 0.451 in. T_c = 77°K $\frac{T_h}{T_c}$ = 3.843

r_s = 0.02025 in. T_h = 296°K

$p_{h\ell}$	p_{hs}	p_{cs}	$(p_{c\ell}/p_{h\ell})_{Kn_{c\ell}}$	Kn_{cs}	p_c/p_h
4080	4120	4080	1.00	.0177	.991
2820	2860	2820	↓	.0256	.986
2000	2050	2000	↓	.036	.975
1580	1638	1580	↓	.0456	.965
1160	1224	1160	↓	.0621	.948
860	927	860	↓	.0839	.927
482	555	482	↓	.150	.869
365	439	365	↓	.197	.832
280	352	279	.998	.258	.793
280	351	279	.998	.258	.797
240	313	238	.995	.302	.763
240	307	238	.995	.302	.777
222	288	220	.993	.328	.766
222	290	220	.993	.328	.760
172	228	170	.990	.424	.746
172	232	170	.990	.424	.734
125	179	123	.983	.586	.687
110	159	108	.980	.668	.680
110	160	108	.980	.668	.675
68	101	65.2	.960	1.11	.647
68	99.1	65.3	.960	1.11	.659
41	62.2	38.0	.928	1.90	.612
41	58.8	38.0	.928	1.90	.647
36	54.8	32.9	.913	2.19	.600
36	54.7	32.8	.913	2.20	.600
28	40.4	24.6	.88	2.93	.610
27.5	42.3	24.2	.88	2.98	.572
27.5	42.3	24.2	.88	2.98	.587
25.5	35.8	22.3	.872	3.24	.623
25.5	36.2	22.3	.872	3.24	.615
14.5	21.5	11.2	.776	6.44	.523
14.5	20.7	11.2	.776	6.38	.544
14.5	21.4	11.3	.776	6.38	.525
14.0	20.3	10.8	.773	6.68	.533
14.0	20.0	10.9	.773	6.61	.544
9.3	12.4	6.8	.730	10.6	.546
9.3	12.9	6.8	.730	10.6	.526
9.3	13.2	6.8	.730	10.6	.515
9.3	13.2	6.8	.730	10.6	.512
9.3	13.2	6.8	.730	10.6	.515

Table 2 (Concluded)

HELIUM

r_ℓ = 0.451 in. T_c = 197°K $\frac{T_h}{T_c}$ = 1.523

r_s = 0.02025 in. T_h = 300°K

$p_{h\ell}$	p_{hs}	p_{cs}	$(p_{c\ell}/p_{h\ell})_{Kn_{c\ell}}$	Kn_{cs}	p_c/p_h
4750	4770	4750	1.0	.0387	.998
4200	4220	4200	↓	.0438	.995
4200	4220	4200		.0438	.995
3300	3330	3300		.0558	.991
3300	3320	3300		.0558	.993
2300	2330	2300		.0800	.987
2300	2340	2300		.0800	.983
1500	1542	1500		.123	.973
1025	1068	1025		.179	.961
1030	1072	1030		.179	.961
965	1007	965		.191	.962
788	828	788		.234	.952
620	663	620		.297	.936
500	537	500		.368	.931
415	454	415		.444	.914
318	350	318	↓	.579	.908
240	266	239	.998	.770	.900
130	144	128.5	.990	1.43	.893
130	144	128.5	.990	1.43	.893

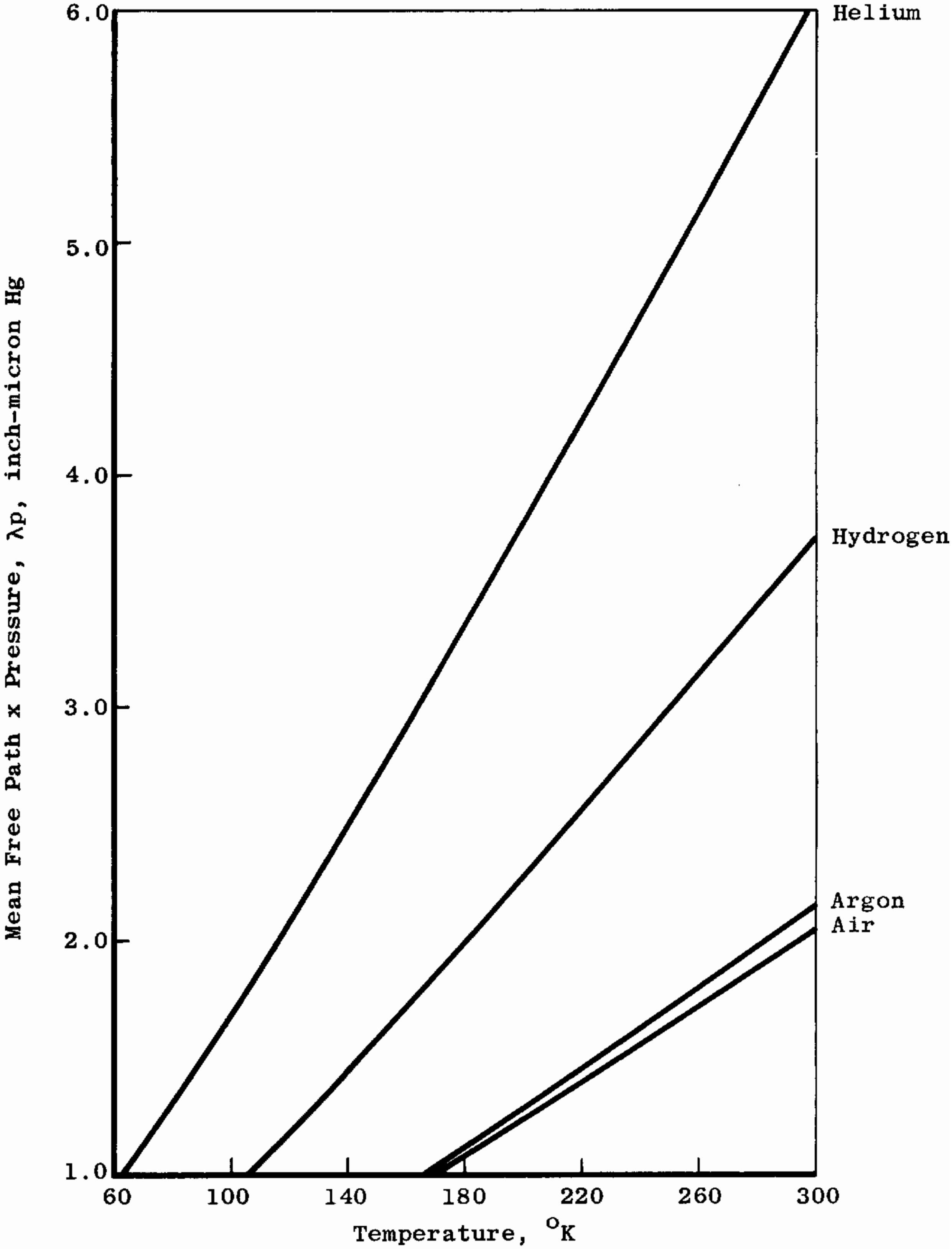

Fig. 1 Variation of the Mean Free Path of a Gas with Temperature

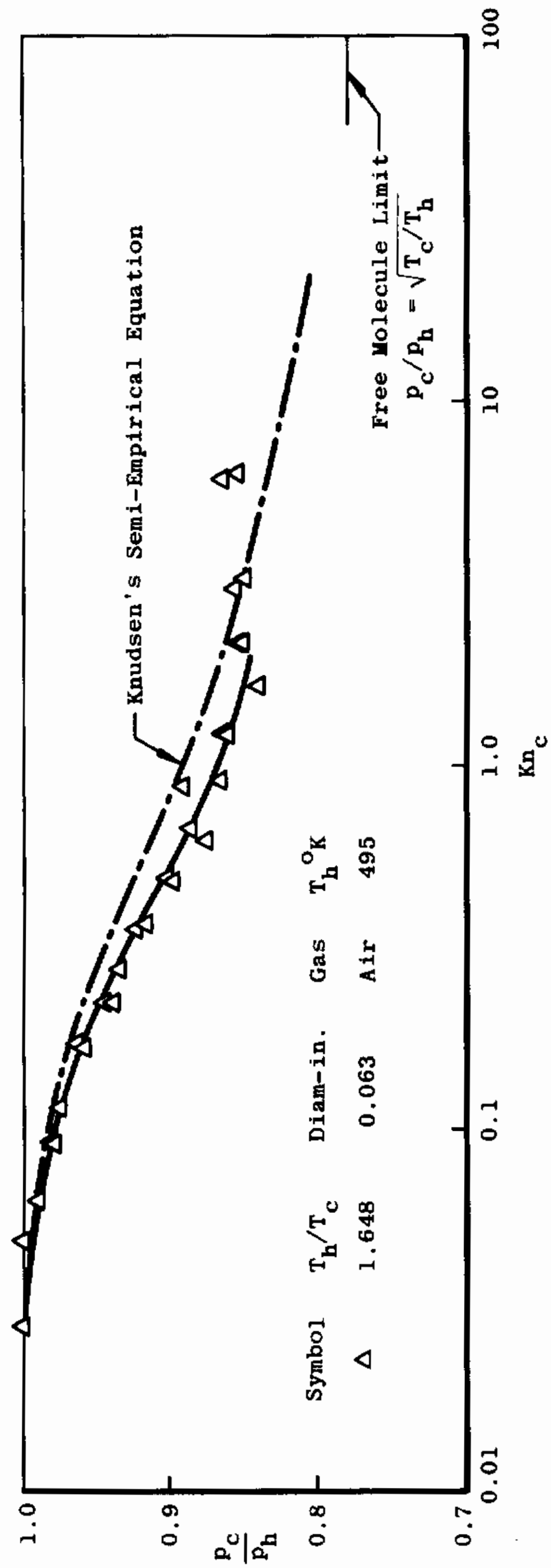

Fig. 2a Variation of Cold to Hot Pressure Ratio (Cold/Hot) with Knudsen Number (Cold)

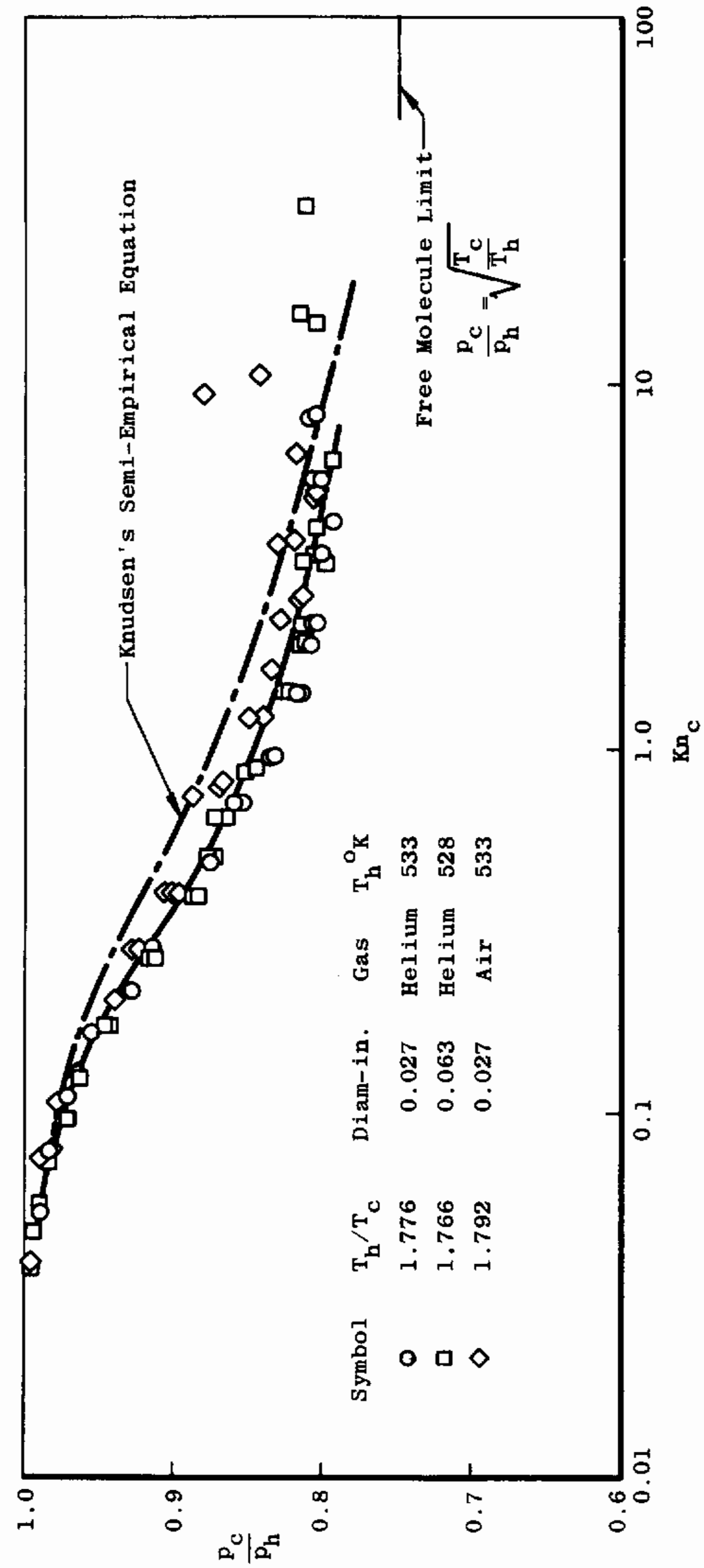

Fig. 2b Continued

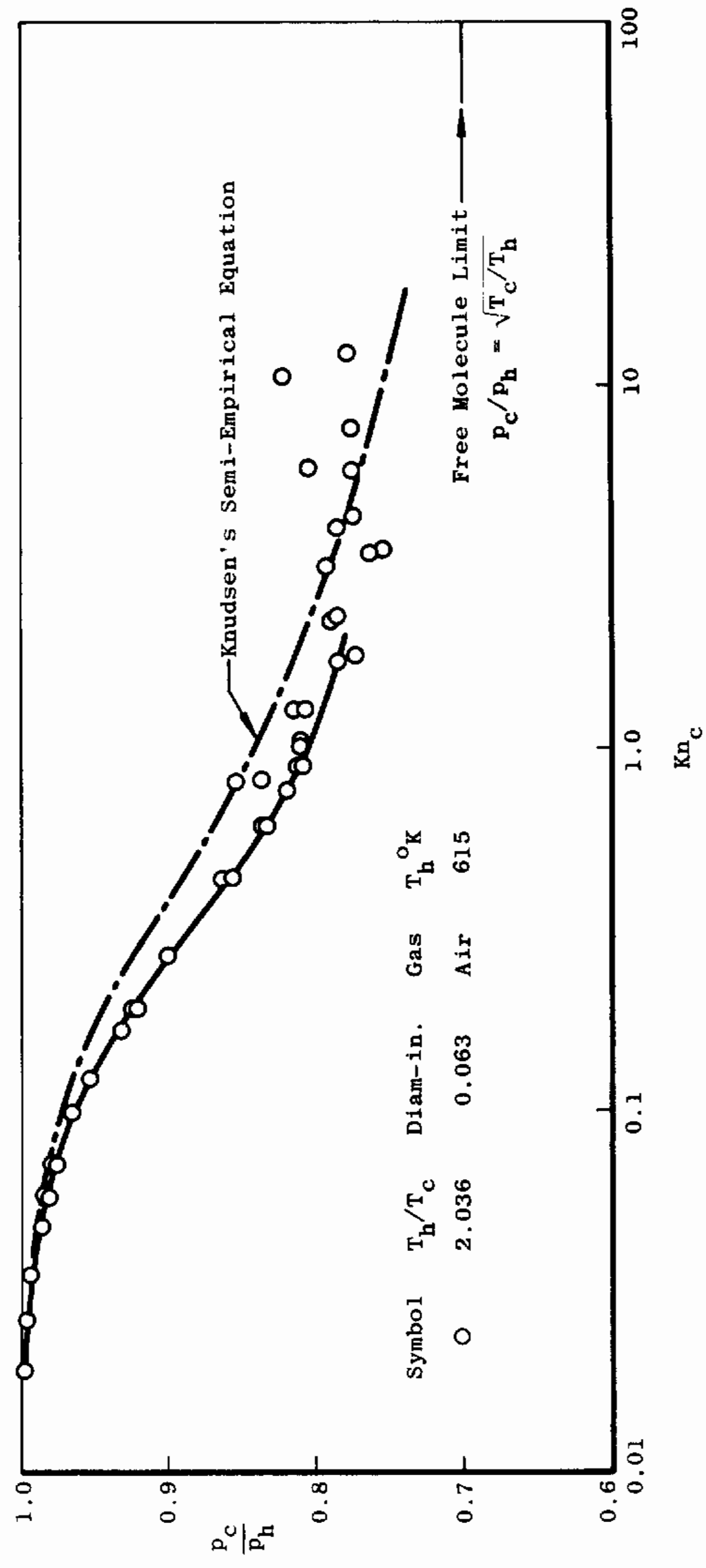

Fig. 2c Continued

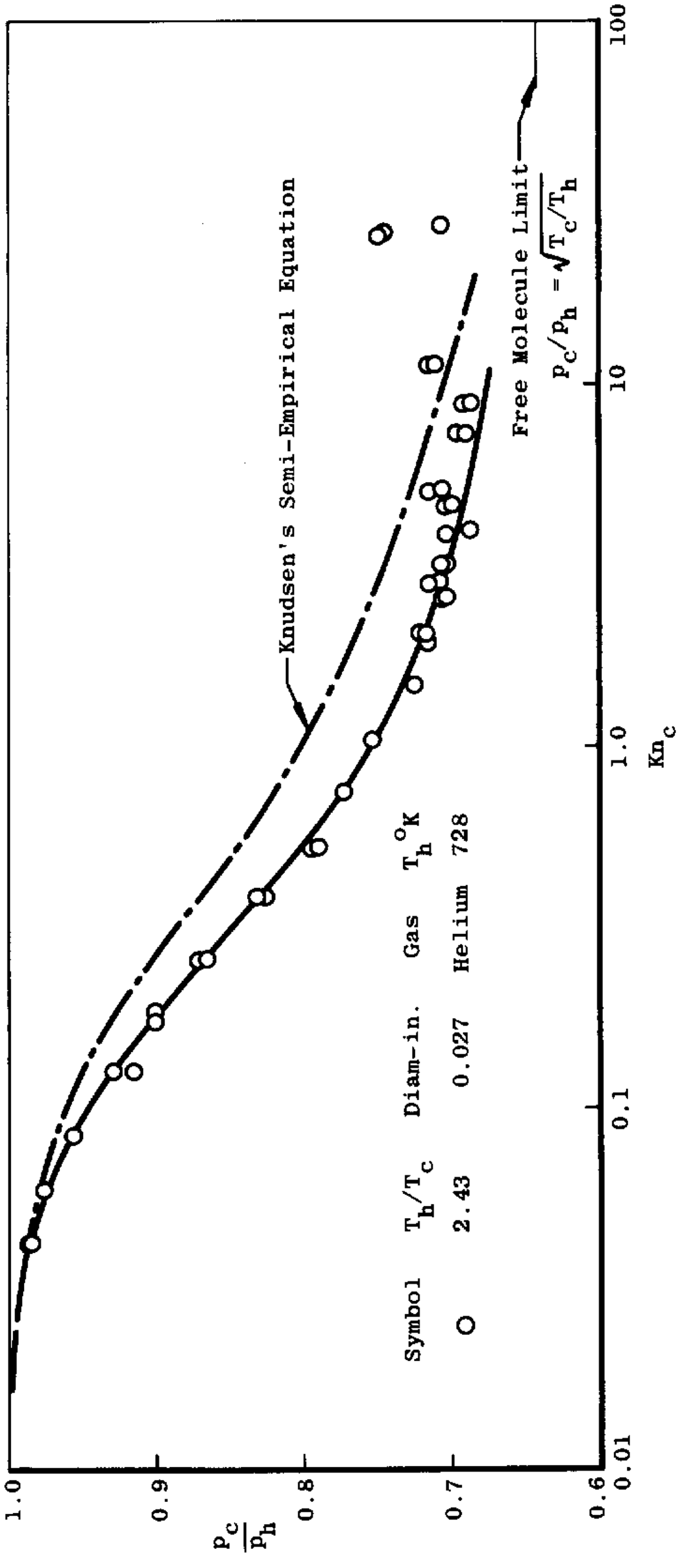

Fig. 2d Continued

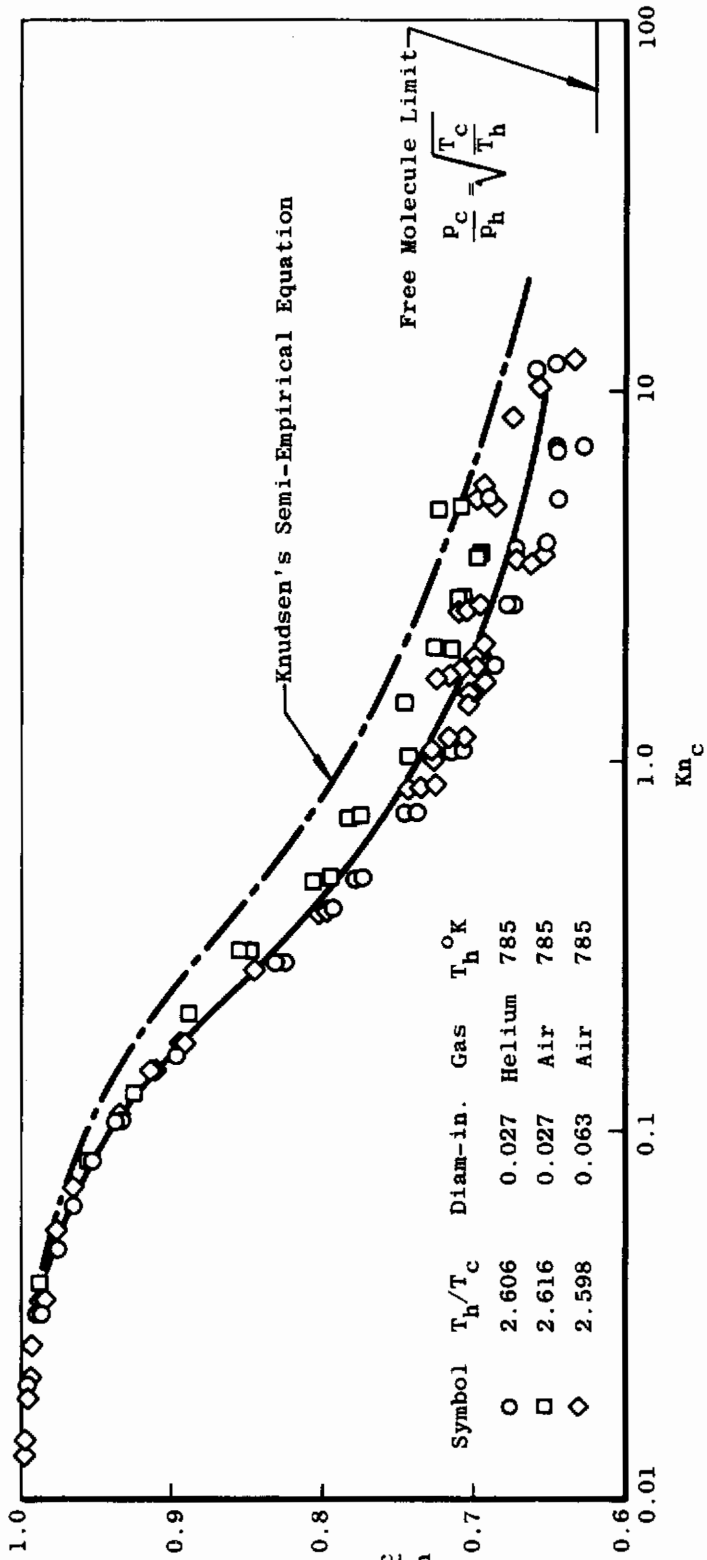

Fig. 2e Continued

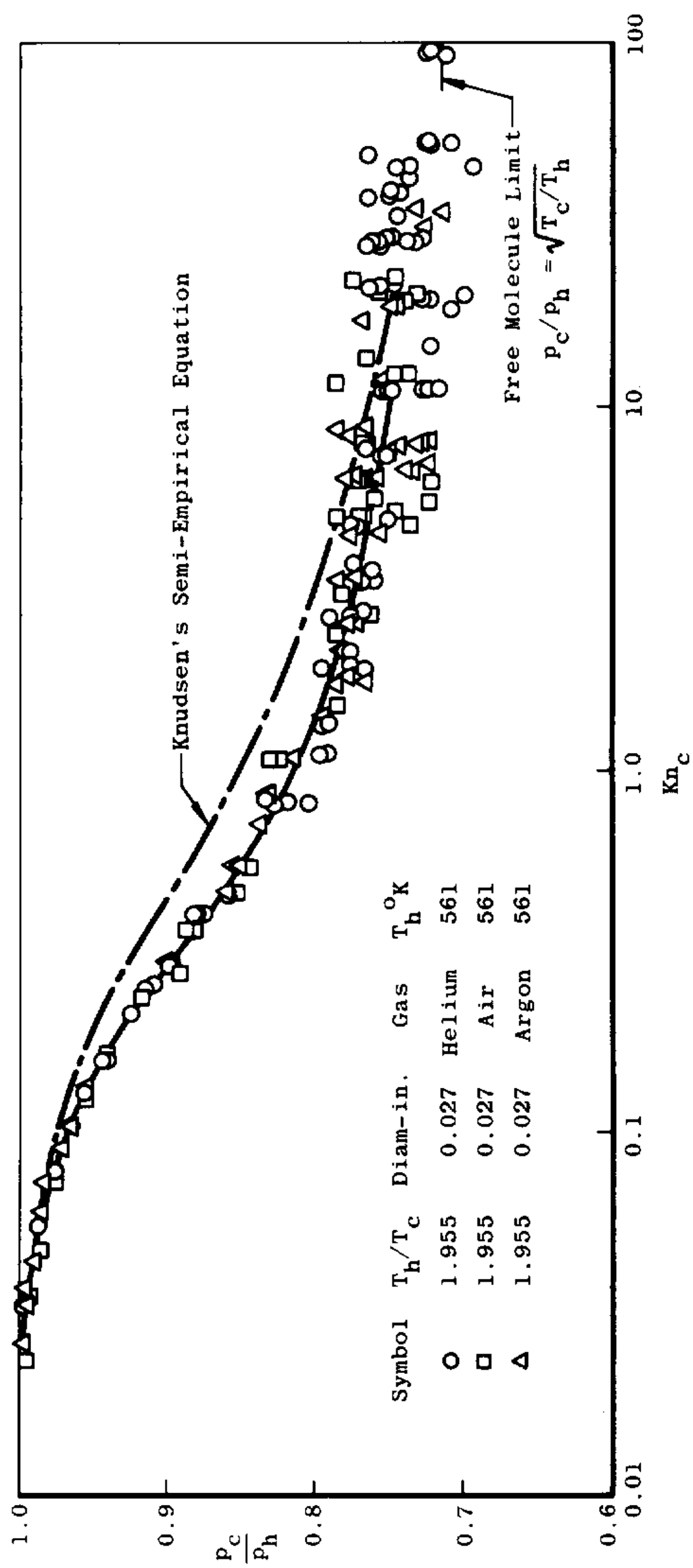

Fig. 2f Continued

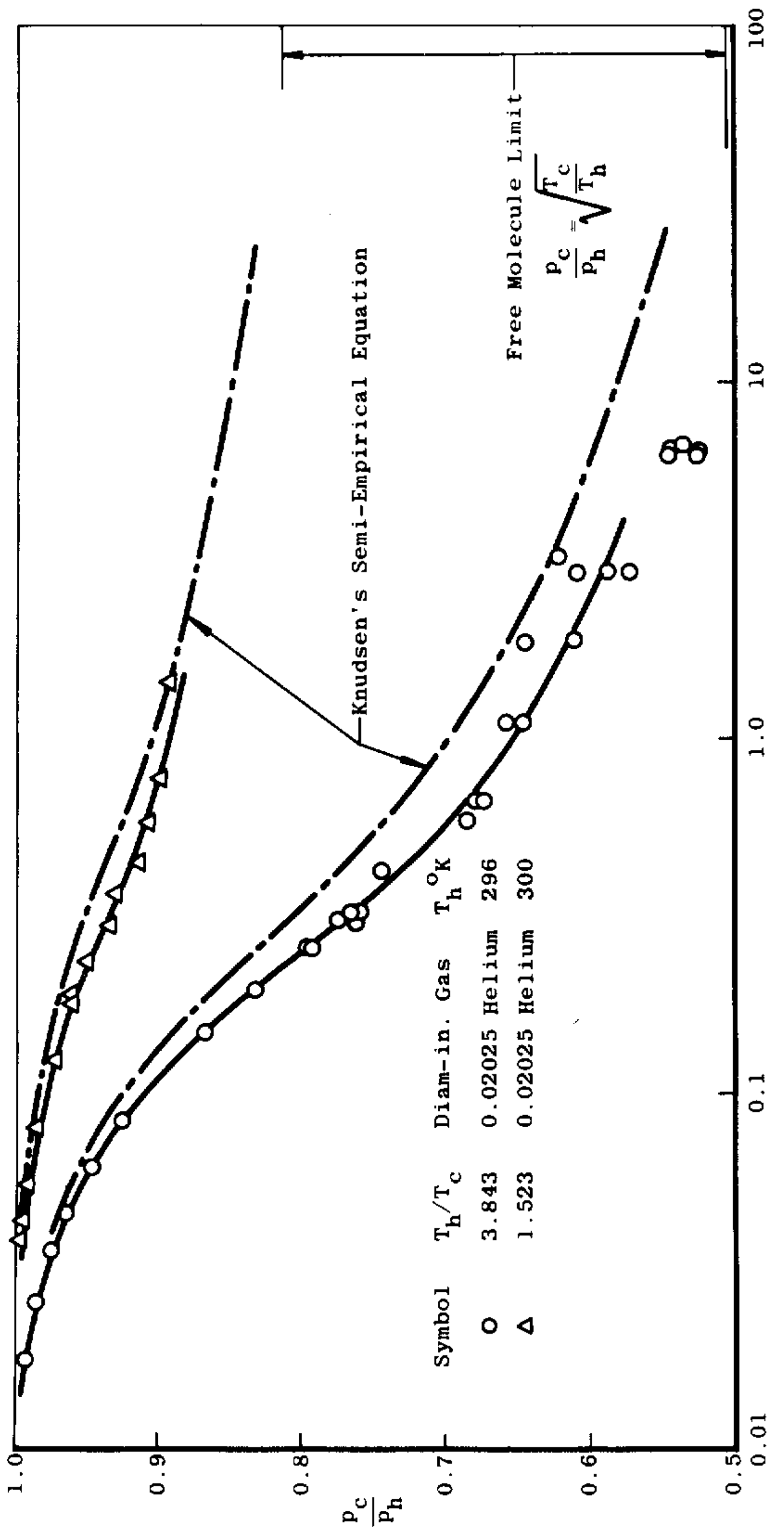

Fig. 2g Continued

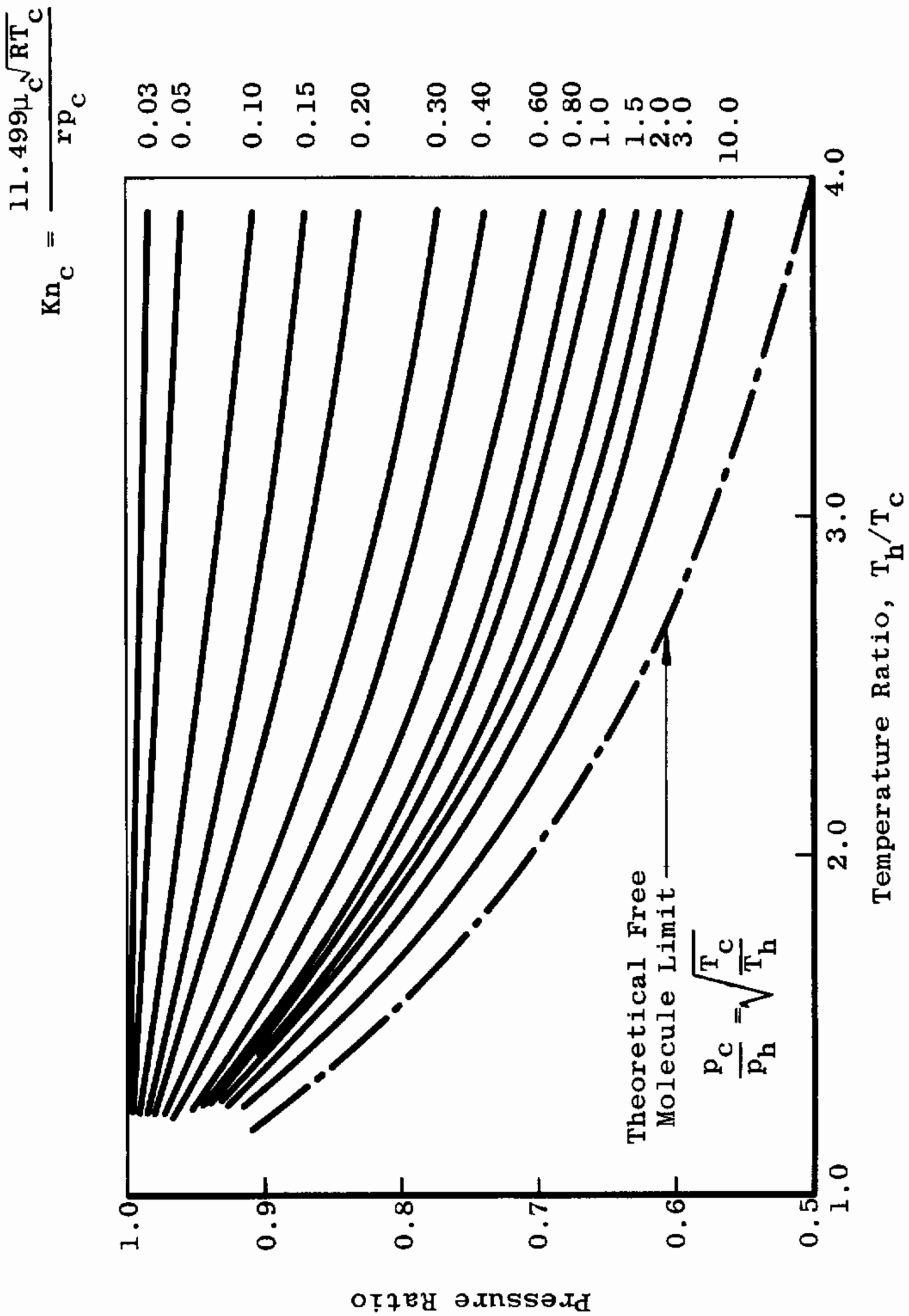

Fig. 3 A Working Chart to Correct for Thermo-Molecular Pressure Effects in Tubes (Gage at the Cold End)

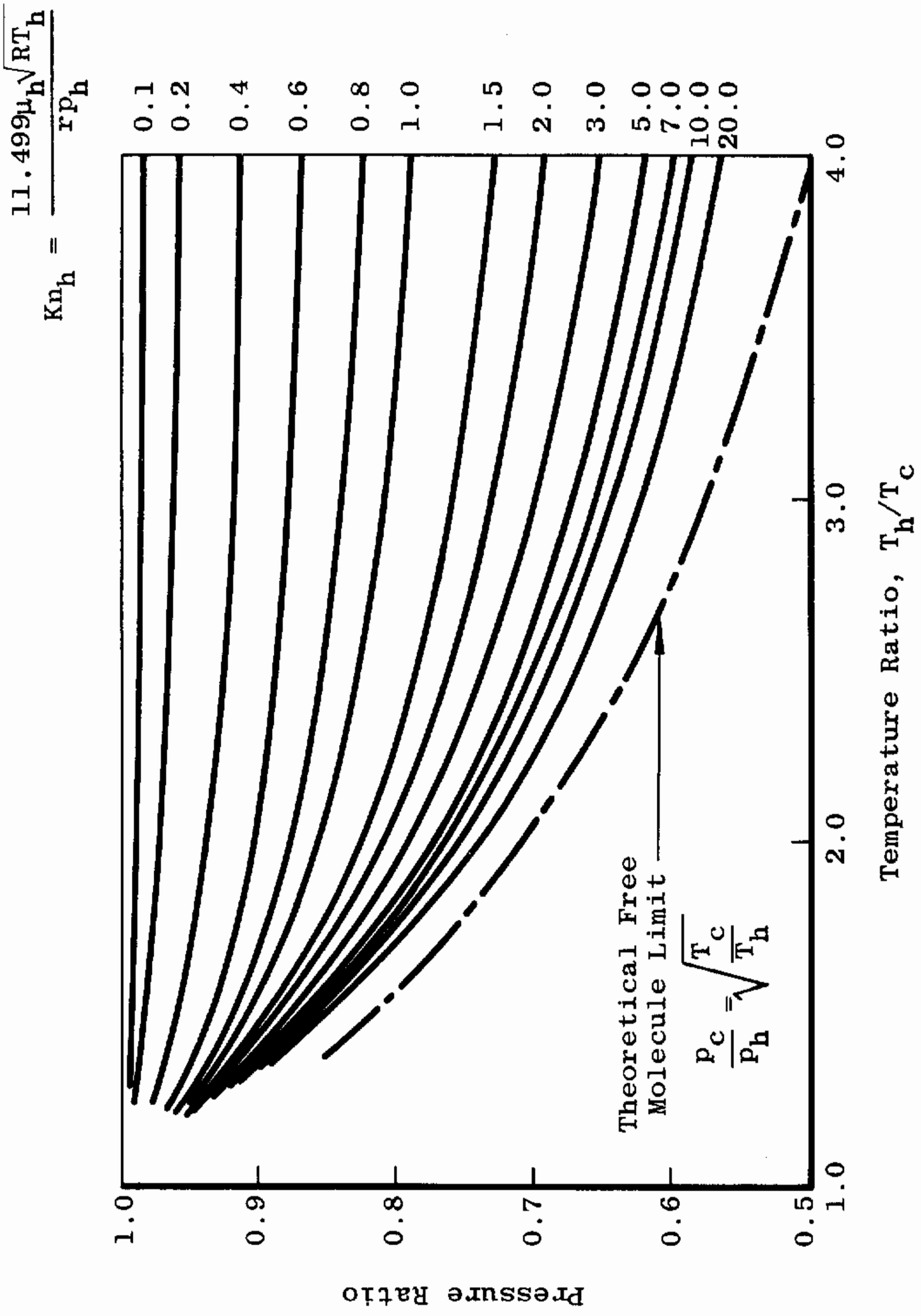

Fig. 4 A Working Chart to Correct for Thermo-Molecular Pressure Effects in Tubes (Gage at the Hot End)

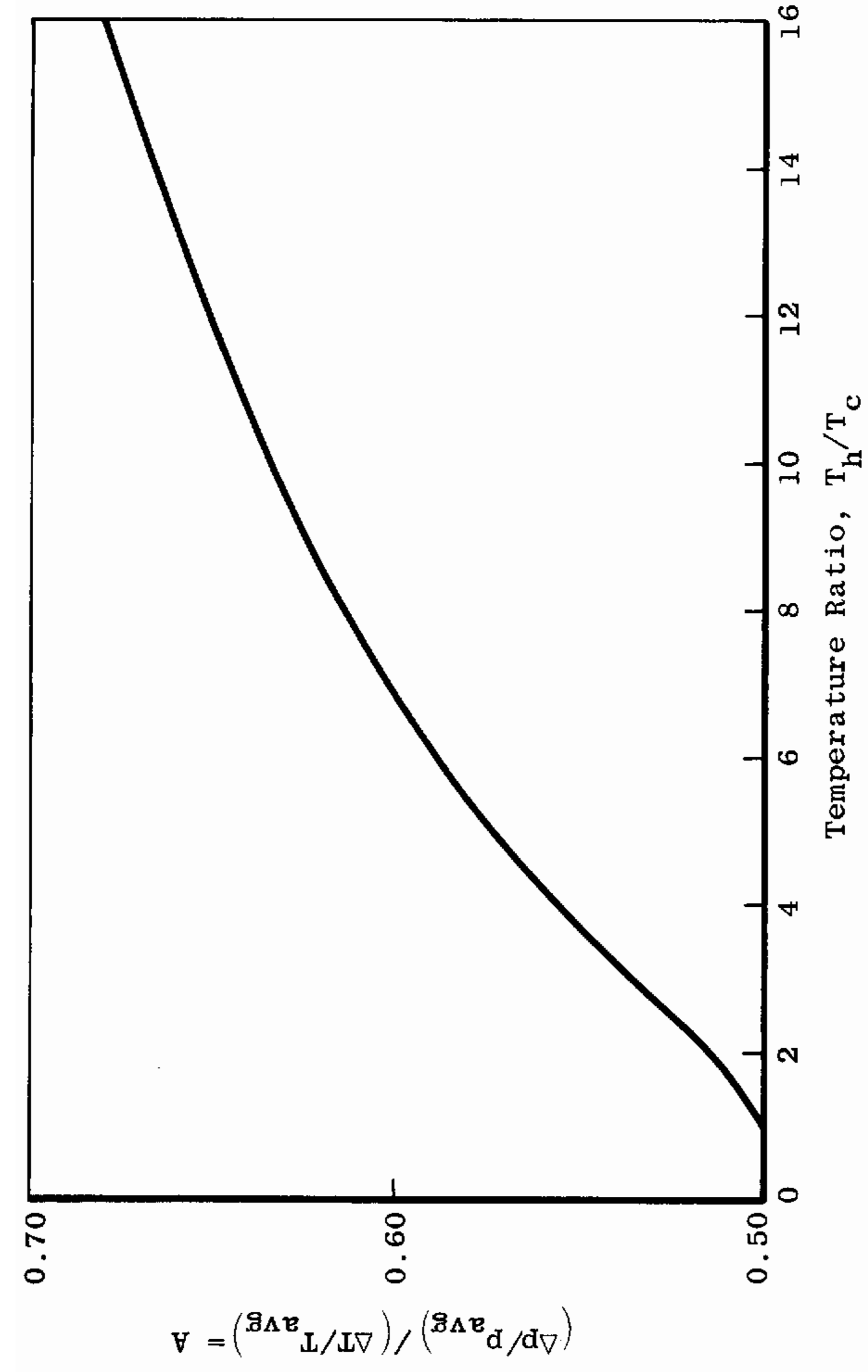

Fig. 5 Effect of Temperature Ratio on the Parameter A in the Free Molecule Flow Regime