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MEASUREMENTS OF THE THERMAL CONDUCTIVITY OF HELIUM IN THE TEMPERATURE RANGE 1600–6700°K

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Abstract—The thermal conductivity of helium in the temperature range 1600–6700°K was deduced from a set of measurements of the heat transfer to the end wall of a shock tube from the hot gas in the region between the end wall and the reflected shock wave. Pressures in the gas ranged from one half to two atmospheres. A thermal conductivity vs. temperature relation of the form $k/k_w = (T/T_w)^a$ was assumed and constants were determined by a least square fit to the data and to match the known values of k for temperatures below 600°K. The effect of variable gas density in the thermal boundary layer at the end wall was found to be significant in reducing the data; some previous investigators have neglected this effect.

1. INTRODUCTION

THE REGION behind the reflected shock wave in the shock tube has been used by several investigators for the determination of the thermal conductivity of gases at high temperatures. Hansen, Early, Alzofon and Witteborn [1], and Peng and Ahtye [2] have reported on the determination of the thermal conductivity of air and Smiley [3] on the thermal conductivity of argon. In processing the data Smiley included the effect of variations in density near the end wall whereas this effect was neglected in references 1 and 2. As the gas temperature decreases near the end wall, the associated increase in density is brought about by convection of gas from the interior towards the boundary. Recently Ahtye and Peng [4] have reported on experiments with nitrogen where they make a comparison of the conductivity deduced by including and not including this effect of variable density, based on the work of Thomson [5]. Camac, Fay, Feinberg, and Kemp [6] and Lauver [7] have reported on experiments with argon using the method described below.

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2. HEAT TRANSFER TO A WALL WITH TEMPERATURE DEPENDENCE OF THERMAL CONDUCTIVITY

The region behind the reflected shock wave is idealized to consist of a hot semi-infinite gas adjacent to a semi-infinite solid. Viscous dissipation may be neglected and the pressure assumed constant [5] in the gas boundary layer near the end wall of the tube. Under these conditions we may write the equations of continuity and energy as

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) = 0 \tag{1}$$

and

$$\rho c_p \left(\frac{\partial T}{\partial t} + u\,\frac{\partial T}{\partial x}\right) = \frac{\partial}{\partial x}\left(k(T)\,\frac{\partial T}{\partial x}\right) \tag{2}$$

where x is the coordinate in the axial direction perpendicular to the end wall, u is the velocity in the x direction, and ρ, c_p, and T, are the density, specific heat, and temperature of the gas.

The continuity equation is satisfied by introducing a stream function ψ,

$$\frac{\rho}{\rho_w} = \frac{\partial \psi}{\partial x}, \quad \frac{\rho u}{\rho_w} = -\,\frac{\partial \psi}{\partial t} \tag{3}$$

where ρ_w = density at the end wall. If we change coordinates from x to ψ, the energy equation becomes:

$$\frac{1}{a_w}\left(\frac{\partial\theta}{\partial t}\right)_\psi = \frac{\partial}{\partial\psi}\left(\frac{K(\theta)}{\theta}\frac{\partial\theta}{\partial\psi}\right) \tag{4}$$

where

$$a_w = \frac{k_w}{\rho_w c_p},\quad \theta = \frac{T}{T_w},\quad K(\theta) = \frac{k}{k_w},\quad \frac{\rho}{\rho_w} = \frac{T_w}{T}$$

Since there is no characteristic length or time in the problem, it is apparent that θ is a function only of $\psi^2/a_w t$, which implies that the wall surface temperature, T_w, is a constant.

Let

$$\eta = \frac{\psi}{(2a_w t)^{\frac{1}{2}}}$$

Then

$$\frac{\mathrm{d}}{\mathrm{d}\eta}\left(\frac{K(\theta)}{\theta}\frac{\mathrm{d}\theta}{\mathrm{d}\eta}\right) + \eta\frac{\mathrm{d}\theta}{\mathrm{d}\eta} = 0 \tag{5}$$

$$\theta(0) = 1,\quad \theta(\infty) = \frac{T_\infty}{T_w} \tag{6}$$

which was previously obtained by Smiley [3] (also see Kemp [8]).

Assuming that the thermal conductivity varies as a power law in temperature (Hirschfelder, Curtiss and Bird [9], Amdur and Mason [10]).

$$\frac{k}{k_w} = \left(\frac{T}{T_w}\right)^a \tag{7}$$

Equations (5) and (6) can be used to obtain a relation

$$\frac{T_\infty}{T_w} = f[a, q_w],\quad q_w = \left(\frac{\mathrm{d}\theta}{\mathrm{d}\eta}\right)_{\eta=0} \tag{8}$$

Equating the heat flux at $x = 0$ to the heat flux at the surface of the solid end wall it is easily shown that

$$q_w = \sqrt{\left(\frac{2}{\pi}\right)}\,\lambda\,\frac{T_w - T_s}{T_w} \tag{9}$$

where

$$\lambda = \sqrt{\left(\frac{k_s\rho_s c_s}{k_w\rho_w c_p}\right)}$$

Equation (5) has been numerically integrated for given values of q_w with a as a parameter. For $a = 1$, equation (5) has the simple solution

$$\theta_\infty = 1 + \sqrt{\left(\frac{\pi}{2}\right)}\,q_w \tag{10}$$

3. MEASUREMENTS

The measurements were made in the free piston shock tube developed at Harvard University [11]. This shock tube employs a piston compression to produce the desired driver gas temperatures and pressures behind the diaphragm. The compression process continues until the diaphragm is broken; then the compressed gas expands into the expansion section driving a shock wave down the length of the tube. The piston remains essentially stationary during the time required for the shock wave to traverse the expansion tube and reflect off the end wall.

The expansion section was a glass tube, 10 ft long with a 2-in inside diameter. Before admitting the helium into the expansion tube it was evacuated to a pressure of 5×10^{-4} mm Hg, as measured with a Consolidated Vacuum Corporation discharge gauge. The helium pressure in the expansion tube was measured with a Wallace and Tiernan absolute pressure gauge.

The shock speed was determined by means of thin film temperature detectors in combination with a raster oscilloscope display. The system was made by Mr. Rolf W. F. Gross.

The Mach number of the incident shock wave, was determined to an accuracy better than one per cent. The temperature T_∞ and the pressure P_∞ behind the reflected shock wave were calculated from the conservation equations on the basis of the Mach number of the incident shock wave and the thermodynamic tables of Emmons and Lick [12].

The temperature at the end wall, T_w, was obtained from measurements with a thin film resistance gauge located at the end wall. A detailed discussion of the thin film gauge is presented in Glass and Patterson [13]. The gauge consisted of a platinum film on a Pyrex No. 7740 glass. The gauge was baked to a temperature of

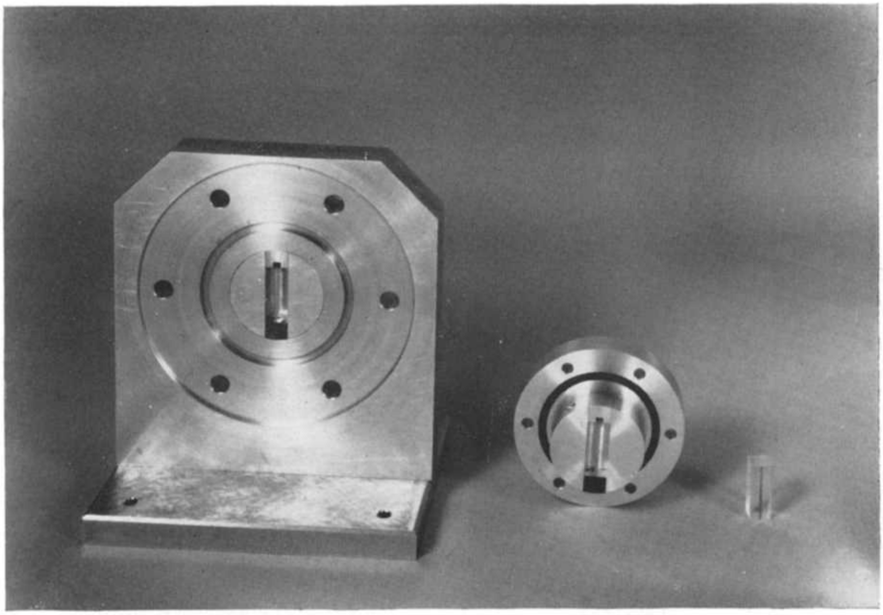

FIG. 1. Thin film resistance gauge in various stages of manufacture.

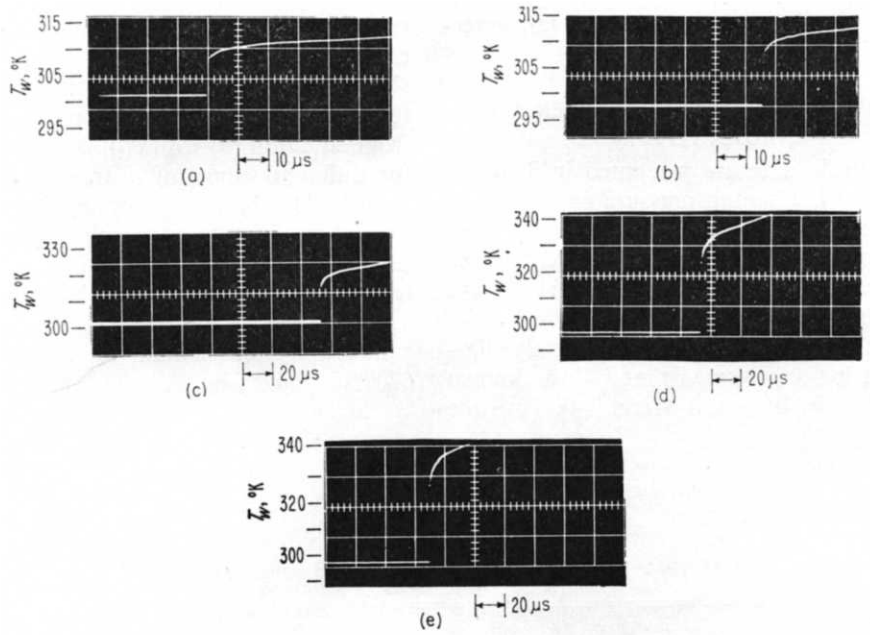

FIG. 2. Temperature records at end wall of shock tube.
(a) $M_s = 2{\cdot}85$, $P_\infty = 530$ mm Hg, $T_\infty = 1980$°K. (b) $M_s = 3{\cdot}27$, $P_\infty = 623$ mm Hg, $T_\infty = 2520$°K.
(c) $M_s = 3{\cdot}74$, $P_\infty = 802$ mm Hg, $T_\infty = 3300$°K. (d) $M_s = 4{\cdot}96$, $P_\infty = 1209$ mm Hg, $T_\infty = 5630$°K.
(e) $M_s = 5{\cdot}15$, $P_\infty = 1299$ mm Hg, $T_\infty = 6060$°K.

1200°C. The gauge in various stages of manufacture is shown in Fig. 1.

The resistance of the film was approximately 100 Ω and was found to be a linear function of its temperature, which was assumed to be the temperature of the surface of the Pyrex glass "end wall". The temperature coefficient of resistivity, was found to be 0·000843 Ω/Ω degC. The film was connected in a D.C. bridge circuit and the resulting voltage was presented on an oscilloscope. Typical records are shown in Fig. 2.

The thin film resistance gauge was calibrated in the shock tube in the following manner. A series of runs was performed in the shock tube for temperatures ranging from 1600 to 2000°K. In this temperature range the thermal conductivity of helium has been experimentally determined by Blais and Mann [14]. To obtain the dimensionless heat-transfer rate q_w, a value of the parameter a is required. A power law was fitted to the thermal conductivity of helium in the temperature range from 300 to 2000°K using the values found in Hirschfelder, Curtiss and Bird [11], Blais and Mann [14], and Mann [15]. This gave a value of a equal to 0·746 with a value of k of 0·00038 cal/cm s degK at a temperature of 320°K. Equation (9) was then used to obtain the value for $\beta_s = (k_s \rho_s c_s)^{\frac{1}{2}}$. A value of β_s equal to

$$0{\cdot}0394 \frac{\text{cal}}{\text{cm}^2 \text{ degC s}^{\frac{1}{2}}}$$

was obtained with a standard deviation of $\pm 0{\cdot}0005$.

Somers [16] and Hartunian and Varwig [17] report on the variation of β_s with temperature. Using their data we have

$$\beta_s (T_w) = \beta_s (30 \text{ degC}) [1 + 0{\cdot}003 (T_w - 30 \text{ degC})] \quad (11)$$

This allows us to compare the values we obtained for β_s with their values:

Somers ($T_w = 28$°C) $\beta_s = 0{\cdot}0363 \pm 0{\cdot}0018$

Hartunian and Varwig ($T_w = 22$°C) $\beta_s = 0{\cdot}036 \pm 0{\cdot}002$

Thus our value for β_s is seen to be in fair agreement with those previously reported.*

4. DETERMINATION OF THE THERMAL CONDUCTIVITY

All the basic data are presented in Table 1. This includes the helium pressure and temperature before the shock, the shock Mach number, the wall temperature change, and the calculated helium pressure and temperature behind the reflected shock.

The range of values of T_w was only 306–340°K and it was assumed that k_w was known from the data of Blais and Mann [14]. Thus the problem was reduced to finding a value of a for equation (7) which best fits the data. Figure 3 shows the data plotted in the dimensionless form T_∞/T_w vs. q_w. Theoretical curves computed from equation (5) with $\theta(0) = 1$ and $\theta'(0) = q_w$ for different values of a are also presented in Fig. 3. The best value of a was obtained by minimizing the sum of the squares of the deviations from the experimental data. The fit is reasonably good although the scatter is quite large. On the basis of the data then, the thermal conductivity of helium in the range 1600–6700°K is given by

$$\frac{k}{k_1} = \left(\frac{T}{T_1}\right)^a \tag{12}$$

with

* Somers reports that a value of β_s equal to 0·0364 ± 0·0066 has been determined by Vidal [18]. However, no temperature is noted.

Table 1. Basic experimental data and calculated results

	Measured				Calculated			
Run	$T_w - T_s$ (degK)	M_s	p_0 (mm Hg)	$T_s = T_0$ (°K)	T_∞ (°K)	p_∞ (mm Hg)	$q_w = \sqrt{\left(\frac{2}{\pi}\right)} \times \lambda \frac{(T_w - T_s)}{T_w}$	$\theta_\infty = \frac{T_\infty}{T_w}$
1	6·06	2·51	14·88	300·38	1560	441	3·063	5·097
2	7·29	2·64	17·76	297·18	1690	596	3·192	5·544
3	7·46	2·72	12·61	295·78	1780	463	3·677	5·880
4	7·87	2·82	12·62	295·78	1900	505	3·715	6·260
5	7·95	2·69	18·12	296·68	1750	643	3·324	5·728
6	8·18	2·74	19·03	297·58	1820	710	3·260	5·936
7	8·29	2·72	17·30	302·18	1820	637	3·486	5·869
8	8·36	2·74	18·90	297·48	1820	707	3·335	5·954
9	8·43	2·85	12·65	301·18	1980	530	3·886	6·398
10	8·63	2·91	12·71	302·18	2050	555	3·889	6·602
11	8·74	2·85	12·62	300·88	1980	523	4·058	6·388
12	8·75	2·89	14·66	301·88	2030	634	3·689	6·542
13	9·36	2·85	15·62	301·18	1980	648	3·901	6·363
14	9·80	2·82	16·43	301·38	1950	658	4·055	6·276
15	9·83	2·90	16·03	303·98	2060	700	3·945	6·577
16	10·34	2·85	18·71	299·28	1960	777	3·937	6·340
17	10·47	2·95	18·01	303·38	2120	820	3·883	6·768
18	11·48	3·23	10·65	298·28	2470	612	4·923	7·961
19	11·96	3·27	10·61	297·78	2520	623	5·091	8·123
20	12·52	3·31	10·61	297·63	2580	652	5·203	8·319
21	12·60	3·25	10·65	297·33	2490	623	5·357	8·047
22	12·80	3·34	9·83	297·96	2630	619	5·456	8·453
23	13·17	3·42	9·85	299·88	2770	658	5·183	8·861
24	13·65	3·60	9·62	298·98	3050	731	5·359	9·753
25	14·13	3·48	9·85	297·08	2830	685	5·739	9·106
26	15·02	3·64	9·60	302·03	3150	749	5·830	9·945
27	15·42	3·74	9·82	296·53	3250	820	5·716	10·409

Table 1—*continued*

Run	Measured				Calculated			
	$T_w - T_s$ (degK)	M_s	p_o (mm Hg)	$T_s \equiv T_o$ (°K)	T_∞ (°K)	p_∞ (mm Hg)	$q_w = \sqrt{\left(\frac{2}{\pi}\right)} \times \lambda \frac{(T_w - T_s)}{T_w}$	$\theta_\infty = \frac{T_\infty}{T_w}$
28	15·50	3·76	9·91	299·38	3310	837	5·687	10·506
29	16·22	3·72	9·90	299·00	3230	811	6·050	10·244
30	16·55	3·70	9·87	296·78	3190	800	6·214	10·181
31	16·87	3·74	9·61	301·23	3300	802	6·325	10·368
32	17·78	3·80	9·90	299·68	3390	856	6·454	10·666
33	18·23	3·87	9·62	302·53	3530	871	6·565	11·005
34	18·47	3·90	9·70	299·13	3560	897	6·549	11·196
35	18·87	3·90	9·70	296·48	3530	897	6·689	11·178
36	19·28	3·77	9·77	296·23	3310	826	7·127	10·478
37	20·79	4·09	8·06	289·98	3900	834	7·647	12·199
38	20·88	4·08	9·47	296·93	3840	975	7·103	12·070
39	21·04	4·12	8·06	299·73	3960	846	7·685	12·333
40	21·69	4·09	7·97	296·23	3870	825	8·034	12·160
41	21·69	4·16	7·98	297·83	4010	860	7·860	12·534
42	23·00	4·30	8·41	302·43	4340	976	7·831	13·336
43	23·29	4·25	8·41	299·23	4170	946	8·049	12·942
44	23·36	4·46	7·62	298·08	4590	960	8·014	14·279
45	24·03	4·34	9·47	297·18	4350	1125	7·614	13·527
46	24·50	4·25	9·62	300·13	4200	1082	7·917	12·941
47	25·54	4·49	8·52	300·28	4680	906	9·018	14·376
48	25·70	4·52	8·45	299·88	4740	985	8·709	14·552
49	26·18	4·53	7·46	301·88	4800	970	8·942	14·631
50	26·35	4·46	9·45	297·53	4580	1194	8·110	14·149
51	26·67	4·43	9·62	297·38	4520	1159	8·330	13·948
52	27·30	4·62	7·42	301·38	4970	1017	8·023	15·127
53	28·75	4·57	8·53	298·78	4830	1139	9·061	14·731
54	29·40	4·80	7·60	300·38	5340	1136	9·278	16·193
55	29·40	4·83	8·01	298·33	5370	1214	8·977	16·385
56	29·88	4·87	7·82	298·33	5460	1208	9·143	16·624
57	29·94	4·78	8·39	299·68	5280	1233	9·105	16·009
58	30·01	4·82	7·40	296·18	5300	1117	9·549	16·260
59	30·04	4·85	7·42	301·03	5470	1132	9·501	16·519
60	30·45	4·83	7·43	299·08	5370	1124	9·663	16·290
61	30·68	4·75	7·47	299·58	5230	1089	9·890	15·845
62	30·84	4·79	7·43	297·13	5260	1105	9·870	16·035
63	31·59	4·79	7·46	297·78	5270	1109	10·088	16·003
64	32·00	5·02	7·49	298·00	5780	1239	9·673	17·518
65	32·13	4·91	7·60	299·48	5560	1199	9·873	16·770
66	32·19	4·96	7·46	298·28	5650	1201	9·882	17·103
67	32·26	5·03	7·49	299·98	5840	1243	9·736	17·587
68	32·93	4·91	8·40	300·83	5580	1331	9·605	16·719
69	33·58	4·96	7·51	297·08	5630	1209	10·274	17·024
70	34·86	5·06	7·55	300·63	5920	1268	10·422	17·652
71	35·18	5·04	7·60	298·23	5830	1269	10·509	17·486
72	36·53	5·15	7·40	296·58	6060	1299	10·791	18·189
73	36·88	5·27	7·65	298·08	6360	1411	10·456	18·972
74	38·39	5·36	7·47	297·32	6560	1431	10·808	19·538
75	38·60	5·40	7·63	299·68	6700	1485	10·669	19·797
76	39·20	5·35	7·53	299·13	6570	1431	11·037	19·404
77	40·32	5·37	7·61	299·93	6640	1460	11·243	19·524

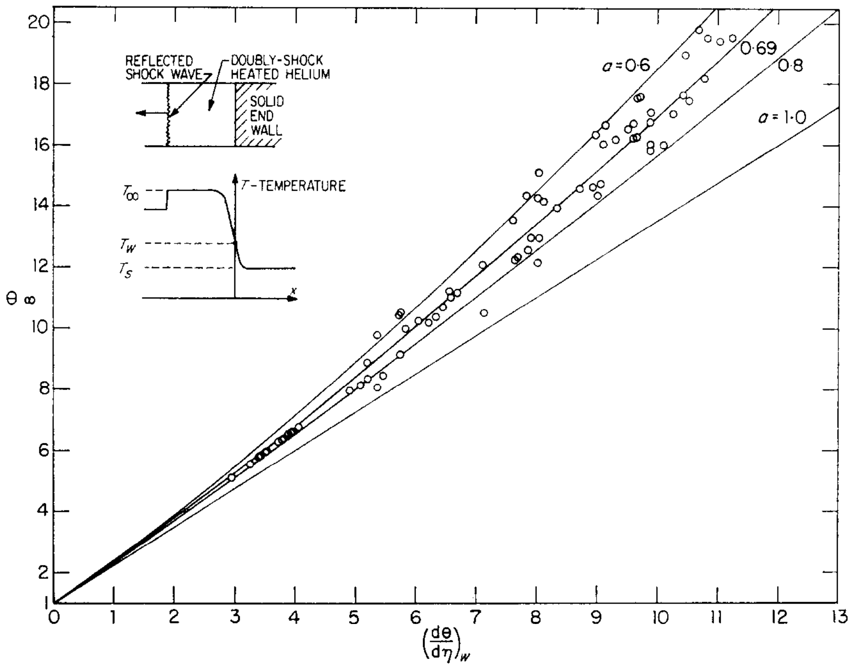

FIG. 3. Dimensionless plot of the data and the curve of best fit.

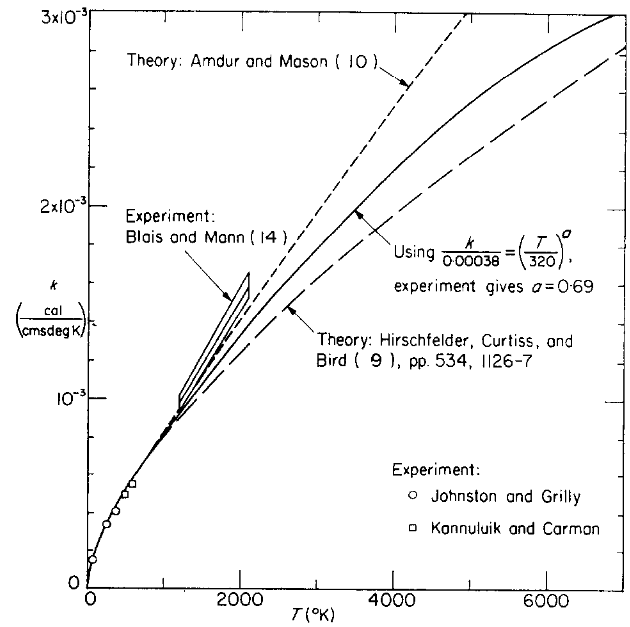

FIG. 4. Thermal conductivity of helium vs. temperature for 1600°K $\leq T \leq$ 6700°K as deduced from the measurements.

$$a = 0{\cdot}69$$
$$k_1 = 0{\cdot}00038 \text{ cal/cm s degK}$$
$$T_1 = 320°\text{K}$$

Blais and Mann [14] predict $a = 0{\cdot}799$ and Amdur and Mason [10] predict $a = 0{\cdot}837$. In Fig. 4 is presented equation (12) along with the theoretical prediction of Amdur and Mason [10] and Hirschfelder, Curtiss and Bird [9] and the low temperature experiments [20].

5. DISCUSSION

The experimental data for helium as presented in Fig. 2 indicate that the temperature at the end wall is not constant but increases with time. For several runs the experimental data first exhibited a constant temperature response for a few microseconds with a subsequent increase for increasing time.* This effect is more pronounced at the higher temperatures (higher sound speeds). Experiments in another shock tube with helium, neon, argon and krypton show the same behavior [19]. The effect is greater for the lighter gases (higher sound speeds) and is quite small for argon and krypton. The same result is also present in Fig. 9 of reference 1. As a consequence the assumption that the wall surface temperature is a constant for helium can only be considered as a first approximation. The temperature at the end wall was taken to be the value at 4 μs after the shock wave impact.

Calculations were also made omitting the effect of the convection of the gas from the interior towards the boundary, that is, a pure conduction model. Under this condition the thermal conductivity is given by

$$\frac{k}{k_1} = \left(\frac{T}{T_1}\right)^a \tag{13}$$

with

$$a = 0{\cdot}75$$
$$k_1 = 0{\cdot}00038 \text{ cal/cm s degK}$$
$$T_1 = 320°\text{K}$$

* For several runs the flat portion persisted for approximately 4 μs. However, the value did vary with the conditions behind the reflected shock wave.

The smaller thermal conductivity resulting from the convection theory, equation (12), may explain previous discrepancies.

6. CONCLUSIONS

An experiment has been performed behind the reflected shock wave to determine the thermal conductivity of helium. A least square fit to the data gave

$$\frac{k}{k_1} = \left(\frac{T}{T_1}\right)^a$$

with

$$a = 0{\cdot}69$$
$$k_1 = 0{\cdot}00038 \text{ cal/cm s degK}$$
$$T_1 = 320°\text{K}$$

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Résumé—La conductivité thermique de l'hélium dans la gamme de températures allant de 1600° à 6700°K a été déduite d'un ensemble de mesures de transport de chaleur sur l'extrémité d'un tube à choc à partir du gaz chaud dans la région située entre cette extrémité et l'onde de choc réfléchie. Les pressions dans le gaz étaient comprises entre une demie et deux atmosphères. Une relation entre la conductivité thermique et la température de la forme $k/k_w = (T/T_w)^a$ a été supposée et on a déterminé les constantes par la méthode des moindres carrés à partir des données expérimentales et des valeurs connues de k pour les températures en-dessous de 600°K. On a trouvé que l'effet de la densité variable du gaz dans la couche limite thermique à l'extrémité était sensible par une diminution des valeurs expérimentales; quelques chercheurs antérieurs ont négligé cet effet.

Zusammenfassung—Aus einer Anzahl von Messungen des Wärmeübergangs von heissem Gas an die Abschlusswand eines Stosswellenrohres im Bereich zwischen der Abschlusswand und der reflektierten Stosswelle wurde die Wärmeleitfähigkeit von Helium im Temperaturbereich von 1600°K bis 6700°K abgeleitet. Die Drücke im Gas reichten von einer halben bis zwei Atmosphären. Zwischen Wärmeleitfähigkeit und Temperatur wurde eine Beziehung von der Form $k/k_w = (T/T_w)^a$ angenommen; die Konstanten wurden über das kleinste Fehlerquadrat bestimmt, um die Messwerte auszugleichen und an die bekannten Werte von k für Temperaturen unter 600°K anzupassen. Der Einfluss der variablen Gasdichte in der thermischen Grenzschicht an der Abschlusswand ergab eine bedeutende Verkleinerung der Messwerte; einige Forscher haben in früheren Arbeiten diesen Einfluss vernachlässigt.

Аннотация—Теплопроводность гелия в диапазоне температур 1600–6700°К получена в опытах по измерению переноса тепла от горячего воздуха к стенке ударной трубы в области между стенкой и отраженной ударной волной. Давление газа изменялось от 1/2 до 2 атмосфер. Отношение теплопроводности к температуре принято в виде $k/k_w = (T/T_w)^a$. Определены постоянные методом наименьших квадратов для данных так, чтобы они соответствовали известным значениям k при температуре ниже 600°К. Найдено, что влияние переменной плотности газа в термическом пограничном слое на стенке значительно занижает данные; некоторые предыдущие исследователи пренебрегали этим эффектом.