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THE THERMAL CONDUCTIVITY OF STEAM*

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Abstract—An improved concentric cylinder silver cell was employed to obtain new conductivity values over the temperature range 139 to 380°C and to 200 atm. The thermocouples were isolated from steam contact in nitrogen filled pockets. The "zero" pressure results are in tolerable agreement with Vargaftig's measurements to 400°C but lower by several per cent. The variation of the conductivity values with temperature and density indicates clearly that the quantity $\lambda_p - \lambda_o$ or the excess, $\Delta\lambda$, of the conductivity under pressure is a function of *both* temperature and density.

INTRODUCTION

AN EARLY determination of the thermal conductivity value for steam relative to air was reported by Moser in 1913. Twenty-one years later Milverton published more extended measurements of conductivity. However, shortly before Milverton's report Schmidt and Sellschopp [1] published data for liquid water extending to 270°C. In 1940 Timrot and Vargaftig [2] published extended data over a wide range of temperature and pressure for both viscosity and thermal conductivity of steam the conductivity measurements have been continued by Vargaftig and associates to the present. In 1950 Keyes and Sandell [3] reported measurements for steam relative to nitrogen for the temperature range 100–350°C and to a pressure of 150 atm. In 1960, Vines [4] published results of work carried out in 1954, on air, argon, nitrogen, carbon dioxide and CO_2/N_2 mixtures to a temperature of 900°C and for steam to 560°C.§ The present paper reports thermal conductivities for steam in the region below 380°C and for pressures for the greater part less than 200 atm. The effect of pressure on the thermal conductivity is large in the saturation region.

STEAM MEASUREMENTS

The data resulting from the measurements listed in Table 1 were correlated by empirical analytical forms based upon the fundamental assumption that thermal conductivity and viscosity can be correlated by the relationship $\lambda = \lambda_o + f(T\rho)$ where λ_o (or viscosity η_o) is a function of temperature only for values of λ and ρ extrapolated to $\rho = 0$ or $p = 0$. It is assumed that the pressure effect can be correlated by an added term of the form $f(T\rho)$ in each transport case. The form $f(T\rho)$ or even $f(Tp)$ may be used. In the case of the early 1940 Timrot and Vargaftig data the expression $f(Tp) = c(\epsilon^{\alpha\tau^4 p} - 1)$ was employed for the U.S. Steam Tables where τ represents T^{-1} [5].

In 1950 Keyes and Sandell [3] reported exploratory measurements for the thermal conductivity of steam relative to nitrogen employing a concentric cylindrical silver cell with thermocouples encased in thin walled tubes filled with nitrogen. The procedure employed was to use nitrogen also as a cell calibrating substance. The knowledge of the thermal conductivity of nitrogen at the time proved insufficient and the steam measurements were re-evaluated when more extensive nitrogen values for thermal conductivity became available (Vines [4] and Keyes [6]).

The investigation of the thermal conductivity

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§ For all the gases studied, these "high temperature" measurements were related to accepted conductivity values at 250°C, but it now appears that the "accepted" values were themselves too high. Consequently the published results (see Table 1, [4]) should *all* be reduced by about 2½ per cent.

Table 1. Thermal conductivities of steam

p (atm)	λ_{calc} equation (7)	λ_{obs}
t = 139·25°C	λ_o = 0·0276 W/M°C	
1·16	0·0287	0·0284
1·64		0·0288
2·32		0·0295
2·93		0·0301
3·13		0·0305
3·47		0·0310
3·51	0·0310	0·0312
t = 195·95°C	λ_o = 0·0332 W/M°C	
1·16	0·0333	0·0335
2·04		0·0336
3·00		0·0337
5·58		0·0341
7·62		0·0347
11·36		0·0367
12·93	0·0380	0·0379
t = 249·2°C	λ_o = 0·0383 W/M°C	
1·84	0·0385	0·0385
4·29	0·0387	0·0387
8·10	0·0391	0·0391
17·01	0·0401	0·0407
24·90		0·0434
34·36	0·0485	0·0485
t = 299·45°C	λ_o = 0·0435 W/M°C	
7·15	0·0442	0·0442
12·65	0·0447	0·0449
13·67	0·0448	0·0449
24·29	0·0463	0·0467
32·80	0·0478	0·0482
48·65	0·0521	0·0523
62·94	0·0600	0·0575
66·68	0·0627	0·0600
79·95	0·0740	0·0691
t = 349·35°C	λ_o = 0·0483 W/M°C	
19·73	0·0481	0·0500
23·13	0·0482	0·0506
34·02	0·0494	0·0519
34·36	0·0501	0·0520
47·63	0·0525	0·0542
67·02	0·0582	0·0578
71·11		0·0590
85·40	0·0621	0·0619
102·4	0·0699	0·0687
139·2	0·0999	0·0995
t = 370·85°C	λ_o = 0·0511 W/M°C	
35·04	0·0521	0·0543
52·39	0·0544	0·0563
63·62	0·0593	0·0579
79·95	0·0622	0·0613
108·87	0·0674	0·0703
140·2	0·0823	0·0865
170·1	0·1175	0·1097
t = 380·0°C*	λ_o = 0·0517 W/M°C	
31·30	0·0623	0·0543
72·47	0·0669	0·0586
106·8	0·0788	0·0654
176·9	0·103	0·0988
204·1	0·179	0·132
272·2		Very large

All λ_o values were calculated from equation (3).

* The 380°C isotherm is not satisfactory because of a seal failure which permitted intermixing of steam and nitrogen.

of steam in the region below the critical temperature was renewed in 1960 using a redesigned concentric cylinder silver cell enclosed in an inconel case. Special thin-walled tubes (0·1 mm) of inconel were used to contain carefully calibrated Chromel P-alumel couples mounted in accurately ground Al_2O_3 rods pierced appropriately to house the 0·2 mm wires. The balancing pressure used was nitrogen with independent pressure control. The heater wires were of nickel and, like the thermocouples, were held in Al_2O_3 rods enclosed in a thin inconel tube pressurized with nitrogen. The cell case was immersed in a KNO_3, $NaNO_3$, $LiNO_3$ bath regulated automatically to 0·002°C. The steam injection to the cell was controlled by means of a piston cylinder device similar to that employed in the measurement of the *pvt* properties of steam [7]. The general form of cell was similar to that described in the 1950 paper but modified along the lines described by Guildner [8], [9]. The cell geometry was measured employing the exceptional facilities available in the Department of Mechanical Engineering at Massachusetts Institute of Technology and "blanks" for the cell were obtained over a range of temperature by prolonged evacuation of the cell system as it was essential to apply corrections for the transfer of heat by radiation etc.

The final results for steam after all relevant corrections had been applied are entered in Table 1. The extrapolation of the data to zero pressure (λ_o) is not difficult and the correlation of this information is needed to test the consistency of λ_o as a function of temperature preliminary to computing $\lambda - \lambda_o = \Delta\lambda = f(T\rho)$ where ρ is the density. The function for λ_o which has proved helpful for many years in discriminating between groups of conductivity data follows,

$$\lambda_o = \frac{c_o T^{1/2}}{1 + \dfrac{c\tau}{10^{c_1\tau}}}; \; (\tau = T^{-1}) \qquad (1)$$

where c_o, c and c_1 are constants.

This relationship may be transformed for convenience into the equation,

$$\frac{T^{1/2}}{\lambda_o} = \frac{1}{c_o} + \frac{c}{c_o}\,\tau/10^{c_1\tau}. \qquad (2)$$

The plotting of $T^{1/2}/\lambda_o$ versus $\tau/10^{c_1\tau}$ with c_1 given the magnitude for steam, 12, or other suitable value, provides a linear equation which represents the data with good approximation. Fig. 1 exhibits the result of using the indicated variables after assigning to c_1 the value 12 to give the "best" fit. The final result is the following definitive equation,

(Keyes and Vines),

$$\lambda_o\,(\text{W/M°C}) = \frac{0{\cdot}01842\,T^{1/2}}{1 + \dfrac{5485\tau}{10^{12\tau}}}. \qquad (3)$$

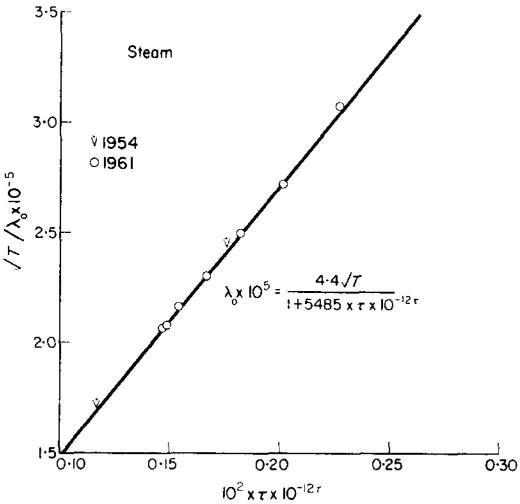

FIG. 1. Equation (3), with λ_o in cal/cm s degC, is plotted using the variables shown in equation (2). The 1961 data are from Table 1, and the 1954 data from [4] (when an all platinum cylindrical cell was employed, designed for atmospheric pressure only).

Table 2. λ_o Comparisons of present data with Vargaftig data

t °C	"obs" λ_o (W/M°C)	1	2	3	4
139·25	0·0276	0·0278	0·0275	0·0275	
195·95	0·0332	0·0332	0·0327	0·0328	
249·20	0·0383	0·0384	0·0378	0·0379	
299·41	0·0435	0·0435	0·0429	0·0429	0·0431
349·35	0·0483	0·0488	0·0480	0·0480	0·0491
370·83	0·0511	0·0510	0·0502	0·0502	0·0517
380·00	0·0517	0·0520	0·0511	0·0511	0·0528
500·00		0·0653			0·0688
600·00		0·0769			0·0834
700·00		0·0888			0·0993

1. λ_o from equation (3). 2. $\lambda_o = \dfrac{0{\cdot}01675\,T^{1/2}}{1 + \dfrac{5016\tau}{10^{12\tau}}}$ from ensemble equation (6) using all available data. 3. λ_1 from equation (4) : Vargaftig data [10] to 400°C. 4. λ_1 from equation (5) : Vargaftig data [10] above 400°C.

Table 2 provides the comparison of λ_o calc. with λ_o obs. deduced from the measurements recorded in Table 1. In column 1, λ_o calc., has been calculated from (3).

Treating Vargaftig's measurements [10] to 400°C according to the foregoing procedure, the (Vargaftig I) λ_1 equation becomes

(Vargaftig I),

$$\lambda_1\,(\text{W/M°C}) = \frac{0{\cdot}0155T^{1/2}}{1 + \dfrac{4600\tau}{10^{12\tau}}}. \quad (4)$$

The data reported by Vargaftig above 400°C and extending to over 700°C was also treated by the procedure sketched. The following equation resulted

(Vargaftig II),

$$\lambda_1\,(\text{W/M°C}) = \frac{0{\cdot}02122T^{1/2}}{-1 + \dfrac{7676\tau}{10^{12\tau}}}. \quad (5)$$

The data reported by Vargaftig [10] is exhibited in Fig. 2. The Vargaftig data could possibly be represented by a single curve but the intersection of the abscissae to the right of the zero point of the axis system requires that $\lambda = \infty$ at the point of intersection. This suggests that Vargaftig's thermal conductivity values are excessively large at high temperatures.

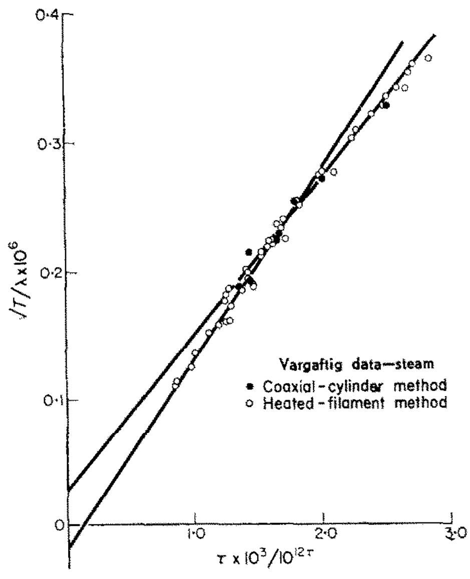

FIG. 2. The data of Vargaftig [10] to 400°C are represented by equation (4); the data above 400°C by equation (5) (λ in cal/cm s degC)

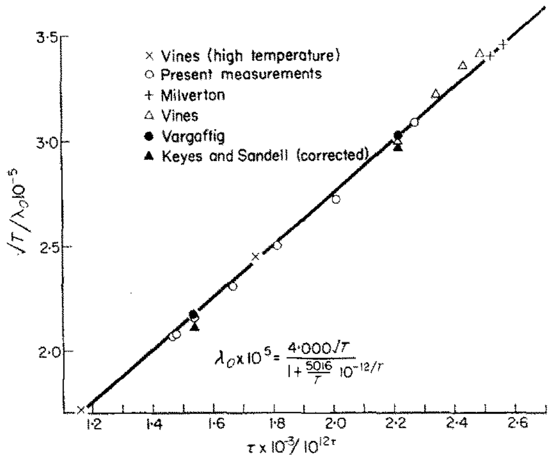

FIG. 3. The "ensemble" equation (6) embodies two points derived from equation (4) based on Vargaftig's data [10] (λ in cal/cm s degC).

An equation obtained by treating much of the available data leads to the equation (ensemble equation, Fig. 3):

$$\lambda_o\,(\text{W/M°C}) = \frac{0{\cdot}01675T^{1/2}}{1 + \dfrac{5016\tau}{10^{12\tau}}}. \quad (6)$$

THE PRESSURE EFFECT

Steam under pressure exhibits an increasingly marked augmentation of thermal conductivity. The pressure effect for steam is complicated relative to, for example, nitrogen, whereas for nitrogen, for example, the quantity $\lambda_p - \lambda_o = \Delta\lambda$ is a function of density only; for steam, it being a highly polar substance, the magnitude $\Delta\lambda$ is a function of both density and temperature. Fig. 6 shows the variation of $\Delta\lambda$ with density, for different isotherms. The nature of the relationship will be developed in the remainder of this paper.

The correlation equation employed was the same general form used with the data reported in 1950, namely,

$$\Delta\lambda = \lambda_p - \lambda_o = c(\epsilon^{\alpha\rho} - 1). \quad (7)$$

It would be anticipated from the general nature of $\Delta\lambda$ versus temperature at constant ρ that c and α would be functions of temperature but of opposite trends with respect to increasing temperatures. The inference is suggested by the fact that λ_p for constant pressure (or density) exhibits a minimum which itself is a function of temperature and density.

Rearranging (7), the equation $\Delta\lambda + c = ce^{\alpha\rho}$ results or $\log(\Delta\lambda + c) = \log c + \bar{a}\rho$ ($\bar{a} \times 2{\cdot}3026 = \alpha$). The values of $\Delta\lambda$ for steam at the constant temperatures of measurement were therefore tabulated, together with the densities corresponding to each value of $\Delta\lambda$; using estimated values for c, $\log(\Delta\lambda + c)$ was plotted against ρ at the various temperatures. From the slope of the lines obtained the values of $\bar{a}$ were determined, a necessary requirement being that intersection of the ordinate gave the intercept $\log c$. By comparing and adjusting successively, values of c and $\bar{a}$ appropriate to each temperature were collected; the functional form of c and $\bar{a}$ could then be developed. From the data in Table 1 the following equations were obtained:

$$c = 20{\cdot}93 \times 10^{-5} + 3{\cdot}673 \times 10^{-11} (t - 100)^{3{\cdot}5}, \text{(W/M°C)} \qquad (8)$$

where t is the temperature in °C.

$$\bar{a} = 4{\cdot}135 \times 10^{-3} \times 10^{2133/T} \qquad (\text{for } \rho \sim \text{g/cm}^3).$$

Thus it is perceived that as c advances (Fig. 4), α contracts (Fig. 5) with increasing temperature

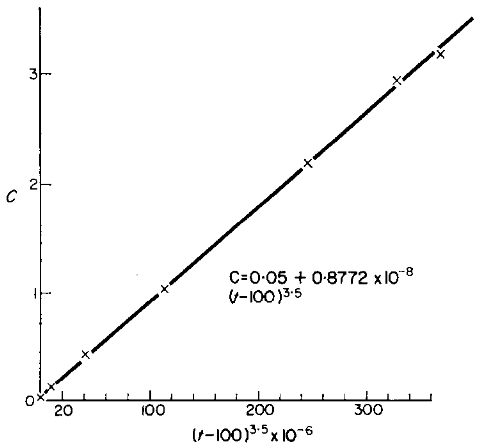

FIG. 4. Values of C from equation (8), with $\Delta\lambda$ [equation (7)] in cal/cm s degC $\times 10^5$: this graph is a companion to Fig. 5.

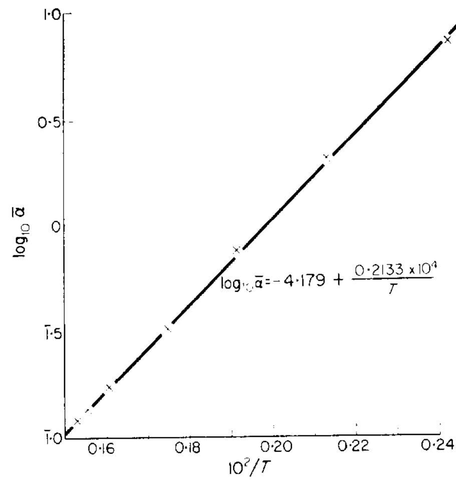

FIG. 5. A graphical representation of equation (8) of the values of the $\bar{a}$ constants derived from the Table 1 data [ρ in (7) is in lb/ft³].

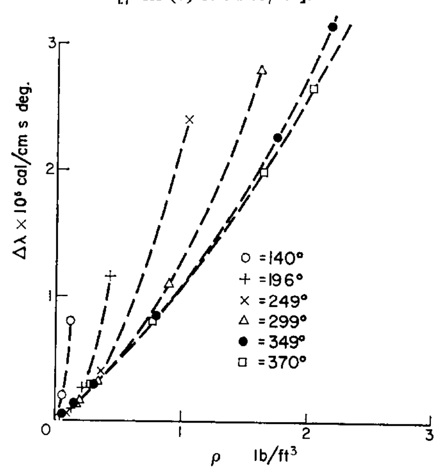

FIG. 6. Representation of the constant temperature data of Table 1.

thus for constant density there will be a temperature where $\Delta\lambda$ assumes a minimum value. The equation for $(\Delta\lambda)_{\min}$ follows where $b_1 = 3{\cdot}673 \times 10^{-6}$ and q equals $4910 = 2133 \times 2{\cdot}3026$.*

$$\Delta\lambda\,(\min) = \frac{(\epsilon^{\alpha\rho} - 1)^2 (t - 100)^{2{\cdot}5} b_1}{\frac{2}{7}\,(\epsilon^{\alpha\rho} \times \alpha\rho \times q/T^2)}. \qquad (9)$$

In Table 1 the calculated values of λ have been

* It may be remarked that q/T can be written q/RT whence q becomes 9740 cals per 18 g, a mole of steam; this is about the magnitude of the internal energy of steam at 100°C (10 800 cal).

Table 3. Δλ values for steam (Vargaftig and Tarzimanov)

t°C	p (kg/cm²)	Δλ (V and T) obs* (W/M°C × 10³)	Δλ calc† (W/M°C × 10³)	Ratio of V and T (calc)
350·19	150	55·8	72·3	0·77
362·14	50	4·7	5·4	0·87
365·51	5	0·04	0·4	0·10
445·37	350	120·4	104·7	1·15
446·69	250	47·0	44·7	1·05
449·33	150	16·5	17·6	0·94
450·88	100	9·1	9·3	0·98
498·40	500	141·1	141·8	1·00
501·00	500	136·5	133·9	1·02
503·40	400	80·5	70·7	1·14
545·59	350	47·8	34·3	1·39
552·43	100	8·7	7·7	1·13
555·60	500	85·6	71·2	1·22
558·00	500	84·1	69·1	1·22
559·60	450	68·4	56·5	1·21
560·50	400	55·0	70·3	0·77
648·32	350	31·7	25·5	1·24
651·36	200	15·8	14·7	1·07
652·11	100	8·5	7·0	1·21
720·90	300	21·6	22·5	0·96
723·62	150	8·6	9·6	0·90

* The above values of Vargaftig and Tarzimanov were taken from the tables in [11] and [12].

† λ_1 values were computed from equations (4) and (5) correlating the USSR values at unit pressure. The values Δλ were deduced from the assumed relation $\lambda - \lambda_1 = \Delta\lambda$ calculated from equations (7) and (8).

computed using the correlation equations (3), (7) and (8).

Vargaftig [10] and Vargaftig and Tarzimanov [11], [12] and Tarzimanov [13] have reported a comprehensive investigation of the thermal conductivity of steam in the temperature range 350–723°C and for pressures to 500 atm. It is of interest to compare the Δλ obs. values with similar values, Table 3, computed using equations (3), (7) and (8). In making these calculations the λ_1 values obtained from equation (4) were employed to 400°C; above 400°C equation (5) for λ_1 was used to deduce the Δλ values. The correspondence of Δλ obs and Δλ calc appears in Table 3. At 498·4°C and 501·0 kg/cm² the ratios in the last column are reasonably satisfying but poor at 552·43°C and 100 atm, whilst not unsatisfactory at 720·9°C and 300 kg/cm².

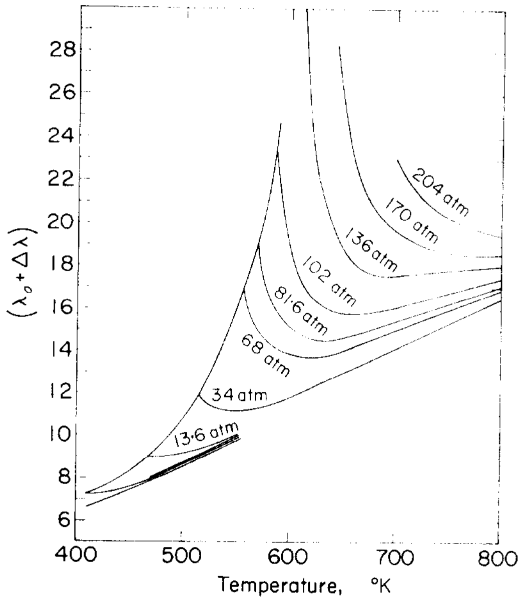

Fig. 7. The thermal conductivity of steam at various pressures (λ in cal/cm s degC × 10⁵).

There are many very large disagreements for the greater part above 501·0 where there are, however, three reversals of sign in the differences, namely at 560·5, 720·90 and 723·62°C. Otherwise values of Δλ obtained by Vargaftig and Tarzimanov exceed the Δλ's computed from equations (7) and (8). [The extrapolations of (8) exhibited in Table 3 are, of course, enormous

Table 4. Vapor saturation values of λ for steam

t (°C)	$\lambda_0 \times 10^3$ W/M°C equation (3)	$\lambda_p \times 10^3$(sat) W/M°C equations (3) and (7)
100	24·29	28·11
120	26·08	29·48
140	27·91	31·10
160	29·76	33·16
180	31·65	35·88
200	33·57	39·39
220	35·52	43·98
240	37·50	49·91
260	39·50	57·68
280	41·53	68·26
300	43·58	84·47
320	45·65	108·08
340	47·58	155·37
360	49·88	298·99

Table 5. The thermal conductivity of steam at saturation and superheat ($\lambda \times 10^3$)

t °C	λ_p (sat)	1	20	40	60	80	100	150	200	250	300	350	400	450	500
100	28·1	28·1													
150	32·1	29·0													
200	39·4	33·6													
250	53·9	38·6	41·6	53·0											
300	84·5	43·7	45·9	49·5	57·0	72·8									
350	208·3	48·9	51·0	53·0	56·6	61·0	68·0	114·2							
360	299·0	50·0	51·7	54·0	57·0	61·1	66·8	101·5							
370	660·3	51·0	52·7	54·9	57·7	61·3	66·2	90·9							
400	—	54·3	56·0	58·0	60·3	63·0	66·7	79·5	107·9						
450	—	59·8	61·3	63·0	65·2	67·3	69·9	77·4	87·9	106·3	123·8				
500	—	65·4	67·0	68·5	70·2	72·0	74·2	80·0	86·9	95·0	103·1	131·3	142·0	172·0	
550	—	71·1	72·5	74·0	75·8	77·0	79·0	83·9	89·0	95·1	100·5	116·6	120·7	133·1	147·1
600	—	76·9	78·3	79·9	81·2	82·5	84·2	88·5	93·0	98·0	102·1	113·3	116·9	124·4	132·8
650	—	82·8	84·2	85·7	87·0	88·5	90·0	94·0	97·9	102·5	105·6	114·8	117·5	123·3	129·6
700	—	88·8	90·0	91·6	93·0	94·0	95·5	99·2	102·7	107·3	109·9	117·3	120·7	125·1	130·3

Pressure in bars, temp. cel., $\lambda \times 10^3$ in watts per deg. Cel. per M.

with respect to temperature and in many instances pressure: the appropriate densities were obtained from the last edition of Professor Vukalovich's Steam Tables.]

Fig. 7 displays the minima of $\Delta\lambda$ in the range below the critical temperature. Fig. 6 represents the constant temperature versus density relationship over the same range as Fig. 7. Table 4 gives an impression of the large acceleration of the magnitude λ_p along the saturated vapor line. Table 5 gives a survey of values computed from equations (3), (7) and (8) to 700°C and 500 bars

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Résumé—On a utilisé une cellule cylindrique creuse en argent pour déterminer des données nouvelles de conductivité dans le domaine de températures compris entre 139 et 380°C sous 200 atmosphères. Pour les isoler du contact de la vapeur les thermocouples sont placés dans des cavités remplies d'azote. Les résultats à pression "zéro" sont à peu près en accord avec Vargaftig à 400°C, mais inférieurs de plusieurs %. La variation des valeurs de la conduction avec la température et la densité montre clairement que la quantité $\lambda_p - \lambda_0$ ou $\Delta\lambda$ de la conductivité sous pression est une fonction à la fois de la température et de la densité.

Zusammenfassung—Mit Hilfe einer verbesserten konzentrischen Zylinderzelle aus Silber liessen sich neue Werte der Wärmeleitfähigkeit im Temperaturbereich 139 bis 380°C und Drücken bis 200 atm erhalten. Die Thermoelemente befanden sich, isoliert gegen Dampfzutritt in stickstoffgefüllten Vertiefungen. Die Ergebnisse für den Druck „Null" stehen in erträglicher Übereinstimmung mit denen Vargaftigs bis 400°C, sie liegen allerdings einige Prozent tiefer. Der Verlauf der Werte entsprechend der Temperatur und der Dichte zeigt deutlich, dass die Grösse $\lambda_p - \lambda_o$ oder der Überschuss $\Delta\lambda$ der Wärmeleitfähigkeit bei aufgebrachten Drücken eine Funktion sowohl der Temperatur als auch der Dichte ist.

Аннотация—Усовершенствованная серебряная камера в форме кругового цилиндра использовалась для получения новых значений теплопроводности в интерале значений температуры 139-380°C при давлениях до 200 атм. Термопары были изолированы от сопротивления с паром карманами, заполненными азотом. Результаты, полученные при $p = 0$, довольно хорошо согласуются с данными Варгафтика для температур до 400°C, но на несколько процентов ниже. Изменение значений теплопроводности в зависимости от изменения температуры и плотности ясно указывает на то, что при рассматриваемых давлениях величина $\lambda_p - \lambda_o$ или избыток теплопроводности $\Delta\lambda$ есть функция и температуры и плотности.