

Physics. — *The fundamental pressure-coefficient of helium.* (Communication N^o. 188a from the Physical Laboratory at Leiden). By W. H. KEESOM and Miss H. VAN DER HORST.

(Communicated at the meeting of September 24, 1927).

§ 1. *Introduction.* The fundamental pressure-coefficient, i.e. the pressure-coefficient between the fundamental points 0° and 100° C., for helium had not been directly measured in Leiden. CATH and KAMERLINGH ONNES ¹⁾ determined the difference of the fundamental pressure-coefficients for the international helium and hydrogen thermometers with the differential gas thermometer ²⁾. They found $\alpha_{iH_2} - \alpha_{iHe} = 0.0000014$. With $\alpha_{iH_2} = 0.0036626$ ³⁾ this gives $\alpha_{iHe} = 0.0036612$ ⁴⁾.

This value only differs little from the value $\alpha_{iHe} = 0.0036614$, which was deduced from the pressure-coefficient assumed in Leiden for the Avogadro state $\alpha_A = 0.0036618$ by means of the values $B_{0^\circ C.}$ and $B_{100^\circ C.}$ determined by KAMERLINGH ONNES ⁵⁾ ⁶⁾.

However it remained desirable to measure the pressure-coefficient for helium directly. This was all the more necessary as HENNING and HEUSE ⁷⁾ deduced from direct measurements $\alpha_{iHe} = 0.0036600$.

These measurements by HENNING and HEUSE, however, are subject to serious objections. For instance their simultaneous measurements of pressure- and expansion-coefficient for helium lead to values of $B_{100^\circ C.}$, which are neither in mutual agreement nor in agreement with those of other experimenters ⁸⁾.

We have now measured successively the pressure-coefficient of helium with two different gasthermometers.

¹⁾ P. G. CATH and H. KAMERLINGH ONNES. Arch. Néerl. (III)A 6, 1, 1922. Comm. Leiden N^o. 156a.

²⁾ By international helium and hydrogen thermometer is meant the thermometer in question at constant volume with initial pressure $p_{0^\circ C.} = 1000$ mm. Cf. H. KAMERLINGH ONNES, these Proc. 10, Febr. 1908 p. 589, Comm. Leiden N^o. 102b and further W. H. KEESOM and H. KAMERLINGH ONNES, Suppl. N^o. 51a, § 2, 6 and § 9, 1.

³⁾ According to H. KAMERLINGH ONNES and M. BOUDIN, these Proc. 3, Sept. 1900, p. 299, Comm. Leiden N^o. 60, where $\alpha_{iH_2}^{0^\circ-100^\circ C.} = 0.0036627$ was found for $p_{0^\circ C.} = 1098$ mm.

⁴⁾ CATH and KAMERLINGH ONNES put $\alpha_{iH_2} = 0.0036627$, cf. Comm. N^o. 156a p. 18 note 4. Cf. Suppl. N^o. 51a, p. 13, note 5.

⁵⁾ H. KAMERLINGH ONNES. These Proc. 10, Dec. 1907, p. 445, Comm. Leiden N^o. 102a.

⁶⁾ See CATH and KAMERLINGH ONNES, Comm. Leiden N^o. 156a, p. 22, note 1.

⁷⁾ F. HENNING and W. HEUSE, Zs. f. Phys. 5, 285, 1921.

⁸⁾ From the data on this subject given by HENNING and HEUSE above referred to we find by:

$$\begin{array}{c} 0^\circ-100^\circ C. \quad 0^\circ-100^\circ C. \\ \alpha_v \quad - \quad \alpha_p \quad = \quad B_{100^\circ C.} \cdot \alpha_A \cdot p_{0^\circ C.} \end{array}$$

A. Measurements with the helium thermometer of 108 cm³.

§ 2. *The Thermometer*: The description of this thermometer with the corresponding manometer can be found in Comm. N^o. 152a 1).

The evacuation of the reservoir and connected filling tubes required a great deal of time. While heating the reservoir to 250—300° C. a condensation pump was applied for 7 or 8 hours a day. It was not till after 10 days that the reservoir was entirely free from gas. Before the real filling, first the tubes and then the reservoir were rinsed with dry heliumgas.

The helium was taken from a cylinder of compressed helium produced from liquid helium. Before entering the thermometer, the heliumgas passed through a spiral placed in liquid air, so as to eliminate the last traces of moisture.

The reservoir, marked T_3 , is made of Jena glass 16^{III}. Formerly with this reservoir frequently had already been measured. The dimensions as given by VAN AGT 2) were: volume of reservoir $V_0 = 108.267$ cm³., glass capillary up to the wider part 45 mm³., change in volume of the reservoir due to difference of internal and external pressure: 4.625 mm³. for a difference of pressure of 75.26 cm. mercury. The volume of the steel capillary we measured 459 mm³.

The volume between the horizontal plane through the top of the adjustment-point to the end of the steel capillary we determined volumetrically as given in Comm. N^o. 164 § 4. The total noxious volume, up to the horizontal plane mentioned above, is 761 mm³.

It was further necessary to measure the volume of the space between the horizontal plane through the adjustment point and the mercury

cf. Leiden Suppl. N^o. 23, equation (137), the following values of $B_{100^\circ \text{C.}}$:

$76 p_0$	$0^\circ - 100^\circ \text{C.}$ α_v	$0^\circ - 100^\circ \text{C.}$ α_p	$B_{100^\circ \text{C.}}$
111.6 cm	0.0036600	0.0036581	$+ 0.35 \times 10^{-3}$
52.1	36599	36603	$- 0.16$
110.3	36601	36582	$+ 0.36$
76.0	36598	36591	$+ 0.19$
50.5	36595	36589	$+ 0.29$

Compare with this Leiden Suppl. N^o. 51a, table I. Neither does the value for $B_{0^\circ \text{C.}}$ measured directly by HENNING and HEUSE correspond to that of other experimenters, cf. the table quoted above.

1) P. G. CATH and H. KAMERLINGH ONNES. These Proc. 20, 991, 1155, 1917. Comm. Leiden N^o. 152a.

2) Earlier calibrations see Comm. Leiden N^o. 152a p. 10, note 4, and Comm. Leiden N^o. 164 p. 19.

meniscus. This volume consists of a cylindrical portion and the residual volume, i.e. the volume between the meniscus and the horizontal plane carried through the top of the meniscus. This residual volume was calculated by means of the data given by J. PALACIOS ¹⁾).

The expansion coefficient for Jena glass 16^{III} between 0° and 100° C. was determined at our request by Miss A. F. J. JANSEN by the weight-thermometer method. Measurements

with a vessel of 100 cm³. yielded $10^{-7} \times 243.2$ and 242.6 mean 242.9
 " " " " 300 " " " 242.0 " 241.7 " 241.85

mean $10^{-7} \times 242.4$

As expansion coefficient of mercury we took $10^{-7} \times 1826.0$. For our calculations we took as expansion coefficient for Jena 16^{III} 0.00002420 ²⁾).

§ 3. *Measurements of the pressures.* The pressure of the gas in the thermometer, apart from a few corrections, was determined by the difference of height of the mercury meniscus in the two manometer tubes, increased by the pressure above the mercury in the long manometer tube. This pressure was again determined by a mercury barometer placed beside the manometer. A correction was made for the difference of level between the barometer and the manometer. The corrections for the capillary depression were borrowed from DE HAAS—LOHNSTEIN's data ³⁾). The differences of the level in the mercury menisci were read by means of a comparator calculated upon a difference of height of 1.50 M., provided with three telescopes from an invar scale of 1.50 M. length divided into mm. The scale, comparator and telescopes were furnished by the Société Genevoise.

¹⁾ J. PALACIOS. Trabajos del laboratorio de investigaciones físicas, N° 61. Annales de a Soc. Esp. de Fis. y Quim. 27, 275, 1919. Cf. International Critical Tables Vol. I, p. 72.

²⁾ Earlier values:

WIEBE and BÖTTCHER, ZS. f. Instr.kde 10, 233, 1890: 240×10^{-7} .

PULFRICH, see SCHOTT, Vortrag Ver. z. Bef. des Gewerbeff., Berlin 1892: $240.6 \times$ „

KAMERLINGH ONNES and BOUDIN, Comm. Leiden N° 60, 1900: $242 \times$ „

SCHEEL, ZS. f. Phys. 5, 257, 1921: $242.4 \times$ „

VAN AGT and KAMERLINGH ONNES, Comm. Leiden N° 176^a, 1925: $235.5 \times$ „

[For the formula given in Comm. N° 176^a for the thermal expansion of Jena-glass 16^{III}, the following coefficients are in better agreement with the experimental results, than those mentioned there:

$a = 702.6$ $c = 19.39$

$b = 47.54$ $d = 14.31$.

Added in the translation].

³⁾ W. J. DE HAAS. Thesis Leiden 1912, p. 52. It does not seem necessary to make a recalculation on the basis of the measurements recently published by the P. T. R. (Zs. f. Instrumentenkunde 47, 324, 1927). Seeing that it is here always a matter of differences, the alterations it would cause in each pressure reading would be below, except in a few unfavourable circumstances even far below 0.03 mm., which lies within the limit of accuracy finally arrived at.

§ 4. *The icepoint.* For this finely planed ice ¹⁾ of distilled water was used carefully prepared with our own freezing apparatus. The thermometer was placed in a large flower pot filled with ice, which was carefully packed round the reservoir and the stem. During the measurements the ice was constantly kept in close contact with the thermometer. The ice was kept well moistened by regularly pouring distilled water upon it. The water that ran off was collected in an earthenware saucer, from which it escaped through an opening at the side ²⁾).

The variations in the reading registered by a BECKMANN thermometer placed in ice at a small distance from the thermometer reservoir for one day, and also the differences on different days, amounted to only a couple of thousandths of a degree.

The glass capillary is placed in ice to 10 cm. below the soldering place of the steel capillary.

§ 5. *The steampoint.* The steam apparatus, described by KAMERLINGH ONNES in Comm. N^o. 27 ³⁾ has since undergone some changes, see fig. 1. The steam, after having passed by the thermometer reservoir *Th* and through the protecting mantle, is again condensed in a brass pipe *K* surrounded by a cooler, while the brass pipe reaches to within a few cm. of the bottom of the boiler.

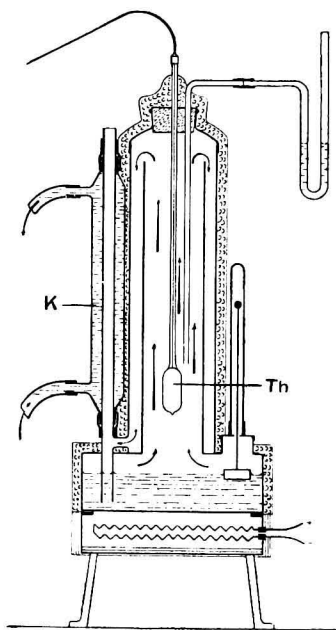


Fig. 1.

Gas is replaced by electricity for heating the water. This gives a more even temperature in the room and consequently in the mercury column in barometer and manometer.

The thermometer hangs in the vapour apparatus to within 10 cm. of the soldering place of the capillary. The protruding portion of the capillary is insulated by asbestos cord, to prevent the soldering place of Wood metal at the top of the glass capillary from getting hot.

To ascertain the pressure in the boiler a glass tube bent at right angles is introduced, one limb of which reached to the thermometer reservoir. The other limb, which is closed during the measurements can be brought into communication

¹⁾ A description will shortly be published of the rotating motor-driven ice-plane made by the Kon. Ned. Grofsmederij at Leiden, which has replaced the apparatus described by KAMERLINGH ONNES in Versl. Kon. Akad. v. Wet. Amsterdam Mei 1896, Comm. Leiden N^o. 27.

²⁾ Cf. H. KAMERLINGH ONNES, Comm. N^o. 27 § 7.

³⁾ H. KAMERLINGH ONNES, Comm. N^o. 27 § 8.

with an open water manometer by means of an india rubber tube. The air column above the water, which, when examining the pressure, is connected to the vapour in the boiler prevents the steam from condensing there, so that the manometer can be read off at ease for some minutes.

The pressure in the boiler is regulated by the cooler. During the measurements the over-pressure amounted to 1 mm. water. This was taken into consideration in determining the temperature. The height of the barometer at each observation was given by the barometer that also gave the air pressure above the long tube of the manometer.

The pressure of the water vapour was reduced to international atmospheres by means of the factor 1.00062¹⁾. The boiling point was calculated according to the table in LANDOLT—BÖRNSTEIN.

§ 6. The calculation of the pressure coefficient was made as described in Comm. N^o. 156a § 3.

§ 7. *Results.* The ice point was observed on March 19th and June 3rd 1927. On the former day the following results were obtained :

$H_0 = 986.482$ mm.
 .495
 .467
 .531 (water poured over the ice)
 .531
 .631 (a lot of water)

Accepted : 986.631 mm.

On June 3rd the melting water which ran off was regularly supplemented by pouring on distilled water. The measurements were :

$H_0 = 986.619$ mm.
 .667
 .662
 .664
 .662
 .662
 .655

mean : 986.656 mm.

For calculating the pressure-coefficient the mean of the two above values was taken : $H_0 = 986.644$ mm.

The steampoint was observed on March 16th and May 24th and 30th. The results are brought together in the following table. The 4th column contains the pressure coefficient deduced from each measurement, the last the mean of each day.

It appears that the greatest deviations occurred on May 30th, which no

¹⁾ Suppl. Comm. Leiden N^o. 51a § 3.

TABLE I.

Date 1927	H_{100} mm	Boiling point °C.	0 — 100° C. α_v	Mean
16 March	1349.233	100.377	0.00366118	0.00366114
"	.216	.373	115	
"	.235	.377	119	
"	.227	.377	111	
"	.224	.377	108	
24 May	1348.805	100.254	0.00366134	0.00366120
"	.786	.253	118	
"	.829	.258	143	
"	.805	.259	115	
"	.816	.258	130	
"	.804	.257	121	
"	.758	.251	097	
"	.760	.250	102	
30 May	1347.689	99.948	0.00366122	
"	.677	.945	120	
"	.670	.937	144	0.00366134
"	.673	.937	147	
"	.594	.926	107	
"	.628	.923	152	
"	.587	.919	126	
"	.561	.904	155	

doubt is connected with the fact that, owing to a change in the barometer height, the boiling point had considerably changed.

As general mean we found :

$$0.00366124.$$

B. *Measurements with the helium thermometer of 355 cm³.*

§ 8. KAMERLINGH ONNES and BRAAK ¹⁾ agreed that for a more accurate determination of the pressure coefficient between 0° and 100° C. a thermometer of 300 cm³. was desirable. In this case the proportion of noxious

¹⁾ These Proc. 10, Nov. 1907, p. 429, Comm. Leiden N^o. 101b, p. 14 note 3.

space to the volume of the reservoir would be more favourable and therefore the influence of uncertainties in the size and temperature of the noxious volume upon the results would be smaller. This proportion comes to 0.0030 for measurements with the thermometer of 355 cm³. as compared to 0.0080 with those of T_3 .

With a larger reservoir, moreover, the proportion of the surface to the volume is also more favourable, so that a possible surface effect will have less influence.

The diameter of the manometer tube of this thermometer was also taken larger (18 mm.) by which the uncertainties in the capillary depression were decreased ¹⁾.

Finally, for the pressure determinations with this thermometer a single manometer was used, instead of manometer and barometer, as had always been used in the former measurements ²⁾. This eliminated the necessity of the reading of two mercury menisci ³⁾.

§ 9. The arrangement of the thermometer and corresponding manometer was as in Comm. N^o. 152a to which we refer. The connection of the long manometer tube with the reservoir in ice was no longer necessary. In place of this a second tube filled with charcoal was introduced, which was used for further evacuation after the first tube.

§ 10. *Calibrations.* Reservoir (Tg_1) and glass capillary were calibrated with mercury. The result was (at 0° C.) :

Volume of reservoir from 3 weighings 355.173 cm³. ± 0.79 mm³.

Volume glass capillary between two marks from 5 measurings 39.56 ± 0.42 mm³.

With a difference of internal and external pressure of 770 mm. the change in volume in the reservoir was 21.58 mm³.

The reservoir and the capillary were made of Jena glass 16^{III}.

The volume of the steel capillary from 7 calibrations with mercury was found to be 503.67 ± 0.47 mm³.

The section of the short tube of the manometer at the adjustment-point was measured with mercury : Result of 4 measurings : 278.85 ± 0.18 mm².

The section of the long tube of the manometer was also measured with mercury at various important points. For the radius as mean of 6 measurings was found 9.22 ± 0.003 mm.

¹⁾ The inaccuracies in pressure readings due to this are actually less than 0.01 mm. (cf. note 3 p. 972). The disadvantage that the volume at the adjustment point becomes greater is exceeded by this advantage.

²⁾ This was made possible by the fact that the grant, made to us by the International Education Board enabled us to acquire the comparator and invar-scale mentioned in § 3.

³⁾ On the other hand, if there is a temperature gradient in the room the differences of temperature in the mercury become greater. It appeared to be possible, however, to keep the difference of temperature at the top and the bottom of the mercury column between 0.08 and 0.02 of a degree.

§ 11. *The filling of the thermometer.* This was done in the same way as T_3 (§ 2). The evacuation of the reservoir, however, required considerably more time. After daily pumping had been going on for four weeks and the MacLeod still registered pressure every morning, the thermometer, after being again evacuated, was put aside for a few months. When after $3\frac{1}{2}$ months the pressure was again tested, it appeared that this had by no means increased in proportion to the time, whereupon the daily pumping was again begun. At the same time the reservoir was kept heated in an electric oven to $\pm 250^\circ$ C. After pumping for a good week the MacLeod showed no pressure in the morning.

The thermometer was filled with helium gas from the same cylinder as T_3 .

§ 12. *The noxious volume.* As with T_3 the noxious volume between the adjustment-point and the soldering place of the steel capillary to the steel adjustment piece was determined volumetrically. The steel capillary was placed for this in a copper tube, to keep the temperature constant. For this portion of the noxious volume between the adjustment point and the soldering place of the steel capillary to the steel adjustment piece was found (2 measurements) 410.62 ± 0.92 mm³. The volume of the soldering place of the steel capillary to the glass capillary with the wider part of glass capillary was measured and calculated at 42.53 mm³. The volume of the steel capillary (§ 10), 503.67 mm³., added to this yields a total volume of 956.82 mm³. up to the horizontal plane through the adjustment-point.

§ 13. *The measurements.* Concerning the measurements of the pressure we have only to say (see § 8) that two fixed telescopes could be used, as only two menisci had to be observed. The vacuum in the long tube of the manometer was maintained by a tube filled with charcoal regularly renewed and plunged into liquid air, and was kept under constant observation.

For the realizing of the ice- and steampoint we refer to §§ 4 and 5.

§ 14. *Results.* The ice-point was determined on June 13th and July 5th:

June 13, 1927 :	974.110 mm.
	.188
	.191
	.180
	.181

mean 974.190 mm.

July 5, 1927 :	974.232 mm.
	.236
	.232

mean 974.233 mm.

For calculating the pressure coefficient the mean of these two values was taken : $H_0 = 974.211$ mm.

The results obtained by the determination of the steampoint, with the values for the pressure coefficient derived from it, are given in table II.

TABLE II.

Date 1927	H_{100} mm	Boiling point °C.	0° — 100° C. α_p	Mean
16 June	1331.448	100.162	0.00366100	0.00366101
"	.423	.156	097	
"	.435	.154	117	
"	.317	.126	098	
"	.296	.120	098	
"	.266	.112	097	
21 June	1331.416	100.147	0.00366112	0.00366128
"	.394	.143	115	
"	.399	.139	134	
"	.391	.138	129	
"	.374	.135	124	
"	.372	.135	122	
"	.390	.135	140	0.00366137
"	.387	.134	137	
22 June	1331.924	100.283	0.00366147	
"	.920	.283	142	
"	.927	.283	149	
"	.888	.283	109	
"	.916	.283	138	
"	.915	.283	137	0.00366107
27 June	1330.320	99.845	0.00366104	
"	.322	.845	105	
"	.340	.848	107	

As general mean 0.00366120 was found.

§ 15. *The fundamental pressure-coefficient for the international helium thermometer.* Taking into account the change of the fundamental pressure

coefficient with the initial pressure ¹⁾ the two series of observations yielded:

Thermometer reservoir	α_{iHe}
108 cm ³ .	0.00366124
355 „	366119.

From this follows as mean : $\alpha_{iHe} = 0.00366121$, which may be rounded off as 0.0036612.

A correction must still be introduced on account of the circumstance that in the boiler (§ 5) the reservoir of the thermometer was not protected against the radiation of the bottom and against any superheated drops, spattering up. From measurements, intentionally taken therefor, whereat the temperature was read off from a Beckmannthermometer, which could be protected or not by a plate of tin, suspended horizontally beneath the reservoir of the thermometer, it appeared that at the same velocity of evaporation by which the measurements with the heliumthermometer took place, without a screen the temperature was 0.003 degrees higher than with a screen. Considering this, the result will be

$$\alpha_{iHe} = 0.0036611 \text{ } ^2).$$

The remaining uncertainty in the result is due, except for accidental inaccuracies in observation, to a trace of uncertainty in the expansion coefficient of the glass ³⁾, and to that in the volume of the mercury menisci. Taking all factors together we should put the uncertainty at 2×10^{-7} at the most.

We may remark further that the value here found directly for α_{iHe} , within the limits of accuracy mentioned before, corresponds to the value, which was deduced from KAMERLINGH ONNES and BOUDIN's measurements for hydrogen and those by KAMERLINGH ONNES and CATH concerning the difference between hydrogen and helium (cf. § 1).

¹⁾ Suppl. N^o. 51a p. 20 equation (20).

²⁾ This paragraph is added to the English translation in consequence of a kind remark of Prof. Dr. F. HENNING.

³⁾ See p. 972 and the second note there.