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Physics. — "*Methods and apparatus used in the cryogenic laboratory. XVII. Cryostat for temperatures between 27° K. and 55° K.*". By Prof. H. KAMERLINGH ONNES. (Communication 151a from the Physical Laboratory at Leiden).

(Communicated in the meeting of June 24, 1916).

1. *Introduction.* In section 1 of Comm. XVI of this series (Comm. No. 147c Proc. XVIII, I, p. 507. I pointed out the importance of arrangements by which it would be possible to obtain constant and uniform temperatures in the range from about 27° K. to about 55° K. and I mentioned that a cryostat had been constructed suitable for this region of temperatures, in which for accomplishing this purpose a current of hydrogen warmed to the desired temperature was made to pass through the experimental chamber ¹⁾. The degree of constancy and uniformity of the temperatures which was obtained have exceeded our expectations, at least when it is possible to adapt the arrangement of the measurements to the requirements of the apparatus, as happened to be the case in the investigations which have so far been carried out with it. It is true that we have not succeeded in obtaining as easy and certain a regulation of the temperature with the hydrogen-vapour cryostat as would be available, if substances existed suitable for liquid baths between 55° K. and 27° K. ²⁾. But the deviations very often remained below 0.01 of a degree for a considerable time ³⁾ (a fuller account is given below in section 3). We may therefore say that the gap in the series of constant and uniform temperatures which still existed between the two regions which are easily governed by liquid oxygen and liquid hydrogen respectively ⁴⁾, has now also been filled

¹⁾ The principle of this arrangement was already used by A. Perrier and H. Kamerlingh Onnes in their research on the magnetic properties of solid oxygen above 20° K (Comm. No. 139 c. Proc. XVI, 2, p. 894).

²⁾ The possibility of using neon under pressures above the normal in special experiments — as will probably be practically realisable between 27° K and 34° K — is here left out of account.

³⁾ Compare the measurements of the vapour-pressure along the heterogeneous isothermals for different values of T in the investigation of the critical data of hydrogen (Comm. No. 151 c).

⁴⁾ Besides for the range from 27° K—55° K the hydrogen-vapour cryostat is also suitable for temperatures lower than 27° K; in many experiments it will thus for instance be able to replace the neon-cryostat for the range from 25° K—27° K; this may be of some importance considering that the dimensions of the experimental space may have to be kept smaller in the neon-cryostat than in the

up in a satisfactory manner ¹⁾. In its present construction the hydrogen-vapour cryostat is not yet suitable for experiments in which the phenomena in the experimental space have to be followed by the eye, as this space is completely surrounded by copper walls. But we hope to remove this objection by a modification of the apparatus.

Since the hydrogen-vapour cryostat has proved to fulfil its object, a helium-vapour cryostat will be built on the same principles, in order also to bridge the other gap which still remains in the series of low temperatures for which appliances are available which guarantee the constancy and uniformity of the temperature necessary for experimental work, viz. the very important ²⁾ interval from 14° K. to 4°,25 K. (freezing point of hydrogen to boiling point of helium).

§ 2. *Description of the apparatus.* The cryostat (see fig. 1) ³⁾ consists of the evaporator *V* and the cryostat-glass *B*, which latter contains the experimental chamber *E*. The air-tight german-silver caps *V_N* and *B_N*, by which the two parts are closed immovably, are connected together by means of strong tinned iron strips *g₁*, *g₂*, *g₃* (see fig. 2) and clamping rings *g₄* and *g₄*.⁴⁾

A continuous current of superheated hydrogen-vapour is needed to keep the walls of the experimental chamber as well as the gas and measuring apparatus inside at a constant and uniform temperature. This current is supplied by the evaporator.

The unsilvered lower part of the vacuumglass of this evaporator *V₀* contains liquid hydrogen. The hydrogen is transferred to the

hydrogen-vapour cryostat in view of the difficulty of providing large quantities of the gas.

(In Proc. XVIII, 1, p. 508 l. 1 from below, insert after "most experiments": "at temperatures between 25° K and 27° K"). Perhaps we shall find that it will be possible with the hydrogen-vapour cryostat to descend almost to the boiling point of hydrogen and thus to embrace the region where otherwise — as mentioned l. c. — it might be possible to use a bath of liquid hydrogen boiling under enhanced pressure.

¹⁾ The proper working of the vapour cryostat is much impeded when experiments are carried out with it, in which heat-actions take place inside the experimental chamber.

²⁾ We need only point out the desirability of this interval being filled up for accurate determinations of the critical data of helium and for deciding whether lead becomes supra-conducting continuously or, in the same way as tin and mercury, suddenly.

³⁾ The section of this figure is taken along the line shown in fig. 2.

⁴⁾ This firm connection is necessary because of two glass syphon-tubes connecting the two parts. With a view to the expansion by change of temperature of the tubes and the strips, the latter were made of iron.

evaporator in the manner commonly used in the laboratory (Comm. N°. 94^f, Proc. IX p. 156 comp. also Pl. 1 Comm. N°. 103 Proc. X p. 592) from a supply-bulb through the tube a_1 , which is closed by a small rubber tube with glass stopper. In the beginning the evaporator is filled up to X_1 ; when the liquid surface has sunk to X_2 , a fresh supply is put in. Through the copper tube b_1 gaseous hydrogen is led in from a high-pressure supply cylinder; this gas undergoes a preliminary cooling in b_2 and is then carried into the liquid hydrogen by the tube b_3 (which is made of german silver in order to reduce heat-conduction to the liquid hydrogen) and the copper tube b_4 ; this causes a continuous evolution of hydrogen vapour, which is carried to the cryostat-glass B_0 — a silvered vacuum glass — by the glass tube C_1 . On its way it passes the glass spiral C_2 and the syphon-like twice bent silvered vacuum-tube C_3, C_4, C_5 which is sealed to C_2 . Its end-piece C_6 is sealed into the supply-tube Ea_1 of the heating-chamber Ea_2 , which is the lower one of two adjoining flat horizontal copper boxes, the upper one Ea_3 , serving as regulating and adjusting chamber, the two together being attached to the hollow bottom of the experimental chamber. The two boxes are isolated from each other and similarly the upper one from the bottom of the experimental chamber by means of paper; inside each of the boxes is provided with a vertical partition running round as a spiral $Ea_{2,0}, Ea_{2,1}$, by which they are made into spirally wound tubes of rectangular section. Inside the spiral of the heating box is a heating wire of constantan of 100Ω , insulated with silk and wound round a flat spirally wound band (the wire is shown diagrammatically in fig. 6 as $Ea_{2,1}$). After passing through the heating tube the superheated hydrogen-vapour, which is now brought to the desired temperature, flows into the regulating and adjusting chamber Ea_3 , where it follows again the spiralshaped path shown it by the partition $Ea_{3,0}$. In doing so it passes along a tin wire insulated with silk and arranged as $Ea_{3,1}$, the resistance of which is measured to 0.001 on a commercial WHEATSTONE-bridge. According to the indication of the resistance of this wire the temperature is approximately adjusted. The same adjusting chamber also contains the bulb of the regulating thermometer Θ_r (see fig. 3), which will be discussed further down.

After having passed the adjusting and regulating chamber at the bottom of the experimental chamber, the gas passes (zie figs. 3, 4, 5) a copper exchange tube Eb , which consists of eight tubes alternately running up (Eb_1) and down (Eb_2) coupled by horizontal chambers (Eb_3), the whole being intimately united¹⁾ with the vessel which is

¹⁾ The tubes are soldered to the side-wall of the experimental chamber, the

formed by the side-wall Eb_0 and the bottom of the experimental chamber and is of high conductivity and comparatively large heat-capacity (the vessel with its lid weighs 1.2 k.g.) Finally the gas emerges in the experimental space immediately above the bottom at Eb_{01} and finds its way to the protecting space in the cryostat-glass above the experimental chamber through small apertures¹⁾ in the copper lid Ec (fig. 1), which closes the experimental chamber at the top.

The copper vessel Eb with its lid Ec which encloses the experimental space, together with the box attached to the bottom, occupies the lower part of the cryostat-vessel (see fig. 1), and hangs, without touching the inner wall of this vessel, by means of the vacuum-tube C_1 and the glass rod Ed from the air-tight cap B_N , which closes the vacuum-vessel B_0 in the manner commonly used in the laboratory (see previous Communications of this series). Supply of heat by conduction to the walls of the experimental space is therefore practically excluded²⁾.

Besides the measuring-apparatus, the necessary electric wires and the supply-tube of the superheated hydrogen-vapour C_1 , the cap of the cryostat-vessel B_N (see fig. 1) transmits air-tight a second doubly bent syphon-like silvered vacuum-tube $d_1d_2d_3$, through which the hydrogen flows back to the evaporator. Here it passes through the regenerator V_R , which serves to effect a preliminary cooling of the hydrogen of ordinary temperature by which the evaporator is fed³⁾; ultimately (see fig. 6) by way of e and a tap K_1 it finds its way to

wall being shaped for the tubes to fit it as nearly as possible. Moreover the conduction between tubes and wall is promoted by a thick filling of solder.

1) The lid closes the experimental chamber as nearly as possible, but is not made air-tight. The side-wall Eb_0 (see fig. 1) is provided at the top with a horizontal ring-shaped rim Ec , which is soldered to it. On to this rim a number of small copper covering-plates are screwed. 2 mm. thick and fitting the rim, of such profiles, that when the measuring apparatus are in their proper places the plates cover up the experimental chamber as completely as possible and complete the lid until only a few interstices and small holes remain, through which gas may escape while at the same time the measuring apparatus in the experimental space are protected from radiation.

2) In order to prevent a radiation from the cap to the lid of the experimental chamber, screens Ef (shown as dotted lines in fig. 1) can be fitted in the protecting space, which are cooled down by the gas which emerges from the experimental space.

3) The dimensions of the apparatus do not admit of more than a moderate degree of regeneration, as the tube b_2 cannot be very narrow in connection with a proper regulation of the supply.

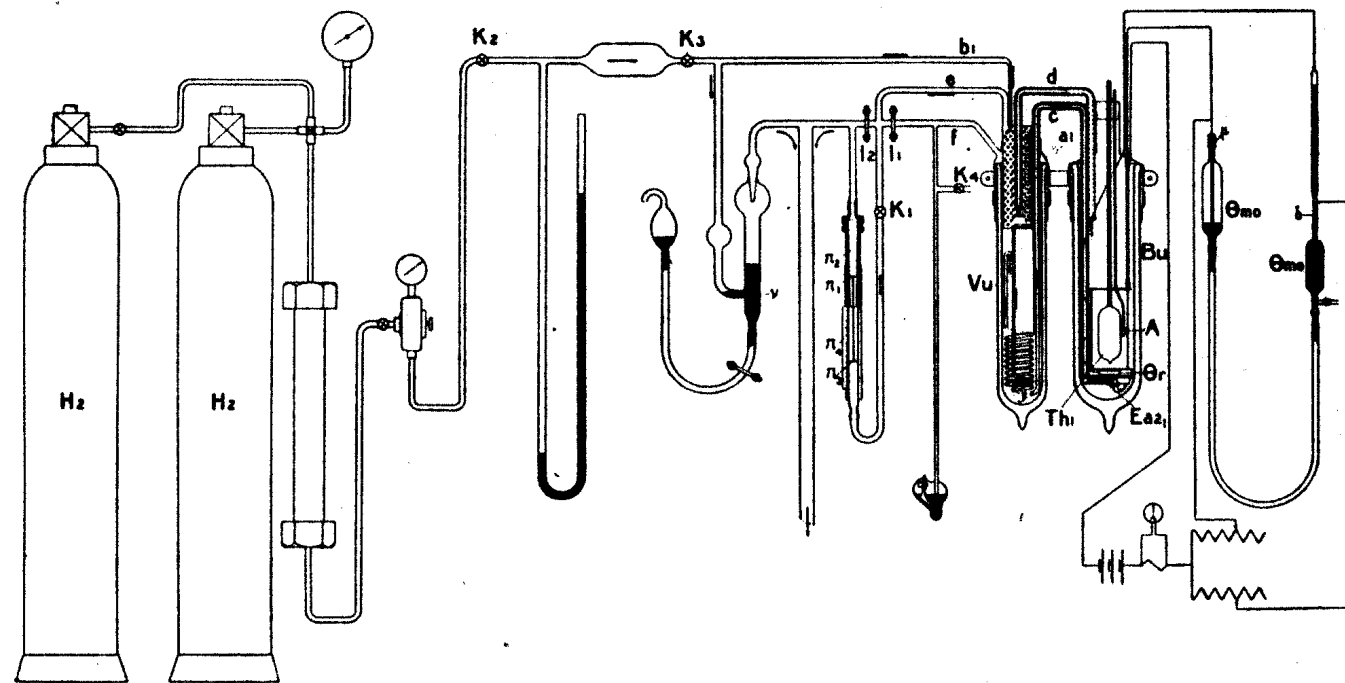


Fig. 6.



the gasometer from which it is pumped back into high-pressure supply-cylinders ¹⁾).

The uniformity of the temperature in the experimental space is checked by means of two resistance-thermometers θ_1 and θ_2 (fig. 1), consisting of platinum wires which are loosely wound on small porcelain cylinders with screw-shaped grooves and are provided with two pairs of conducting wires ²⁾. The axes of the cylinders are placed horizontally (see fig. 4) ³⁾.

The regulation of the temperature to a constant value is conducted by means of a hydrogen thermometer, the german silver bulb of which Θ_r (volume 5.2 cc, see fig. 3) is placed in the regulating and adjusting chamber. At the ordinary temperature the larger part of the quantity of the gas required is contained in the wide tube of the manometer-part Θ_{m0} (fig. 6) of the thermometer: when the thermometer-bulb has been cooled to the low temperature, the gas is transferred to it by forcing up the mercury in the manometer. For this purpose the open tube Θ_{mo} of the manometer is connected with the closed part attached to the thermometer by means of an india-rubber tube of sufficient length. The mercury is driven up, until it lifts a small glass float σ (see figs 6 and 7), which is provided with a small platinum plate and a platinum contact-wire passing through the float and brings it close to a platinum point which is sealed into the capillary. ⁴⁾ The fine adjustment can be accomplished by means of a micrometer screw μ . If the temperature in the adjusting chamber of the cryostat, which we may take to be the same as that of the experimental space, falls, the float makes contact with the platinum point ⁵⁾, and in this manner switches in a shunt-con-

¹⁾ As the figure shows, two other tubes are connected with e , viz. a leading-off-tube from the evaporator with safety tube and a tube connecting the evaporator with the gasometer independently of the "spedometer" (see section 3): both these tubes are closed by pinching screws l_1, l_2 . when the cryostat is in use, they both serve in filling the evaporator.

²⁾ So far we have not had an opportunity to exchange the thermometers and thus obtain a definite opinion as to the uniformity of the temperature, as in one of them a small change of the zero occurred, our statement that a constancy down to 0.00° has been reached is also to be taken as a provisional one founded on an estimation.

³⁾ The further apparatus which the experimental chamber will be seen to contain in the drawings are a vapour-pressure apparatus, a helium thermometer and a resistance thermometer to be examined: these are connected with measurements which will form the subject of later communications.

⁴⁾ The adjustment at this point corresponds to an initial pressure of about 8 atmospheres, the thermometer being taken as one of constant volume.

⁵⁾ This contact works best, when the small plate is amalgamated and covered

nection parallel to the main circuit (see fig. 6) by which means a rise of temperature is started and an automatic regulation of the temperature is brought about.

§ 3. *Remarks concerning auxiliary apparatus, details of working and the action of the cryostat.*

Both the evaporator and the cryostat-vessel are immersed in vacuum-glasses with liquid air; the one surrounding the cryostat B_u (fig. 6) is completely silvered in order to reduce the radiation to the experimental chamber as much as possible; in silvering the vacuum-glass in which the evaporator is placed, V_u , a strip along a generating line of the cylinder is left transparent, through which the evaporation of the hydrogen may be followed.

In starting the cryostat it is first — with a view to saving liquid hydrogen — cooled down by blowing hydrogen of ordinary temperature from a supply-cylinder ¹⁾ through a cooling coil immersed in liquid air into the evaporator.

When the tin wire thermometer in the regulating and adjusting chamber indicates, that the temperature has gone down to about -100° C., liquid hydrogen is brought into the evaporator and the supply of hydrogen of ordinary temperature is then started.

The velocity of the hydrogen flowing through the experimental space is regulated according to the indication of a "spedometer" which is joined in on the way to the gasometers; it consists of a small horizontal plate π_1 floating on the vertical gas-stream in a very slightly conical tube π_2 , (length 15 cms, diameter at the top 1.62 cms., at the bottom 1.50 cms) the height to which the plate is raised being read by means of the small horizontal ring π_3 , which serves as an index on a scale which is placed along the lower part of the measuring tube π_4 .

The current of hydrogen of ordinary temperature which is supplied from high-pressure supply-cylinders H, H_1 through a reducing valve is further reduced in the manner shown in fig. 6 by the stopcocks K_1 and K_2 in such a manner, that a regular stream of gas-bubbles (escaping to the gasometer) bubbles through a mercury column ν of an adjustable height. As an instance (applying to the measurements of which the subsequent Communications N°. 151*b* and N°. 151*c* treat) about

with a thin layer of mercury. When the contact failed to act, the shunt connection could also be closed by hand in accordance with the indication of the position of the float.

¹⁾ It will thus be seen, that use is made of pure hydrogen throughout (distilled or purified, see Comm. N°. 94*f* l. c. and 109*b*. Proc. XI, 2, p. 883.

60 cc. of gas measured under normal conditions is made to flow through the experimental chamber only $\frac{1}{7}$ th of which is accounted for by the supply of hydrogen at ordinary temperature through b_1 , the remainder being supplied by the evaporation of the liquid hydrogen.

When the adjusting-thermometer (resistance of the tin wire) indicates that the temperature has been reduced to a value slightly below the desired one, the heating current is put in action ¹⁾. According to the reading of the two checking thermometers in the experimental space, the adjustment of the automatic regulating-thermometer is then modified, until the desired temperature in the experimental space has been attained. A rise of .1 mm of the float corresponds to about .003 degree. The micrometer-screw μ thus affords a high sensitiveness of adjustment of the temperature.

The high degree of uniformity and constancy of the temperature of the measuring apparatus in the experimental space which is obtained with the apparatus and the method of working above described may be considered to be due to the following circumstances: *a)* the access of heat by radiation and conduction to the copper enclosure of the experimental space has been reduced to an extremely small amount²⁾; *b)* the interchange of heat between the gas supplied from the heating space and the walls of the experimental chamber is much promoted by the long winding path followed by the gas in the side-walls, the exchange taking place over a large surface of highly conducting material which is moreover distributed as uniformly as possible; *c)* the difference of temperature between the gas in the experimental space and the walls has been reduced to a very small value; *d)* the speed of the gas supplied from the heating space is sufficient to prevent quantities of heat which are supplied having an influence on the temperature of the experimental space; *e)* the constancy of the velocity of the

¹⁾ In the adjustment to 29° 5 K the heating current was 0.06 amp., when the float was not making contact, and 0.14 amp. when it did. At 55° K. these currents were 0.114 amp. and 0.264 respectively.

²⁾ Comp. section 1 note 4 page 1050. In using the cryostat for experiments, care has to be taken that galvanic generation of heat and supply of heat by conduction along experimental wires are reduced to a minimum; in the experiments to which the figures refer the conducting wires were taken very long and were wound in the cryostat in a manner which excluded heat-conduction to the experimental chamber. In experiments on condensation and expansion it is necessary to wait a long time before it may be assumed that temperature equilibrium has been reestablished.

gas-current in question is such as not to give rise to capricious modifications of the temperature of the experimental space; *f*) the heat-capacity of the walls of the experimental space is sufficient to efface the rapidly alternating deviations from the mean value of the temperature of the gas-current in question, which are due to the changes in the heat-development in the heating-wire, the consequence being that the walls only follow the changes of the mean value; *g*) the gas in the experimental space owing to its low temperature has a very much higher heat-capacity than under normal circumstances and finally *h*) the gas-current emerging from the heat-exchange tube in the experimental chamber keeps the gas in continual motion¹⁾ along the walls and the apparatus.

In the experiments which have been made with the cryostat so far, it was noticed that capricious disturbances from time to time interrupted the periods of constant temperature²⁾. But when the measurements were continued for a long time, generally periods of more than half an hour or longer were repeatedly found in which the temperature of the experimental apparatus and thermometers remained constant to .01 of a degree, whereas these periods are preceded by even longer ones during which the temperature did not vary by more than .02 of a degree, so that the measuring apparatus during this time were able to assume the desired temperature with very near approximation.

Physics. — *“Isothermals of mon-atomic substances and their binary mixtures. XVIII. A preliminary determination of the critical point of neon.”* By H. KAMERLINGH ONNES, C. A. CROMMELIN and P. G. CATH. (Communication N°. 151 *b* from the Physical Laboratory at Leiden).

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1. *Introduction.* The chief reason why the critical data of neon are not known yet with any degree of accuracy — notwithstanding their great importance for the comparison of its thermal properties with those of other, especially monatomic substances — is doubtlessly the fact, that so far it had been impossible to obtain temperatures

¹⁾ In cryostats with baths of liquefied gas strong stirring is necessary on other grounds.

²⁾ Each time after a fresh adjustment of temperature it is necessary to wait some time for the experimental space and the measuring apparatus to arrive at the new temperature.