SOVIET PHYSICS USPEKHI VOL. 66(1), NO. 1 SEPTEMBER-OCTOBER, 1958

New Instruments and Methods of Measurement

DIFFUSION CLOUD CHAMBERS

V. K. LYAPIDEVSKII

Usp. Fiz. Nauk **66**, 111-129 (September, 1958)

CONTENTS

THE recording of ionizing particles by means of droplets condensing on ions is one of the fundamental procedures of experimental nuclear physics. The method is based on the fact that the growth of droplets to visible dimensions on charged centers occurs at smaller supersaturation than in the case of neutral particles. In the familiar Wilson cloud chamber the adiabatic expansion of a mixture of gas and vapor is employed to achieve the supersaturation required for the condensation of droplets on ions.

A number of shortcomings limit the possibilities of the Wilson cloud chamber method, the principal one being the long period of insensitivity after expansion, the complicated construction, and the susceptibility to contamination by uncharged condensation centers. The last of these factors greatly complicates the adjustment and operation of an expansion chamber. The long recovery time after expansion makes it difficult to use Wilson chambers in conjunction with particle accelerators.

The need for an instrument free of the intrinsic shortcomings of the conventional cloud chamber has led to a search for methods of achieving supersaturation other than by adiabatic expansion. A number of attempts to construct a continuously sensitive chamber have been reported. Reference 1 describes a chamber in which supersaturation results from the interdiffusion of water vapor and hydrochloric acid. This chamber did not yield satisfactory results. Reference 2 describes the so-called diffusion cloud chamber in which supersaturation is achieved by the diffusion of vapor through a condensing gas from a heated horizontal surface to a cooled surface.

The first satisfactory photographs of particle tracks in a diffusion cloud chamber were obtained in 1951 and 1952. Since then an increasing number of papers have appeared on work done by means of diffusion chambers as well as on investigations of the physical processes that occur in such chambers. The increased interest in diffusion chambers results not only from the fact that they are largely free of the shortcomings of existing Wilson cloud chambers, but also because some of the properties of diffusion chambers permit a considerably broadened use for this method of particle registration.

1. PHYSICAL PROCESSES IN DIFFUSION CLOUD CHAMBERS

A diffusion cloud chamber is a closed vessel filled with a mixture of vapor and gas (Fig. 1). Vapor sources are located close to the upper and

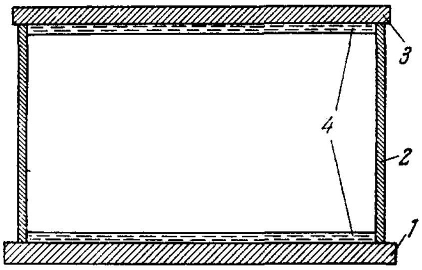

FIG. 1. Diffusion chamber: 1) Bottom; 2) Walls; 3) Cover; 4) Working liquid.

lower surfaces. When the temperature T_1 of the cover is unequal to the temperature T_2 of the bottom the following processes occur within the chamber:

1) Non-isothermal vapor diffusion through the gas from the hot to the cold surface.

2) Heat transport through the gas and vapor mixture.

3) The formation and diffusion of neutral and charged condensation nuclei.

4) Vapor condensation and droplet growth on neutral and charged nuclei.

5) Droplet motion in the gravitational field.

6) Convection (in some cases).

Amelin[3] has suggested that the temperature and partial-pressure fields in the chamber can be represented by one-dimensional equations of isothermal diffusion and thermal conduction, neglecting other processes. With these assumptions the temperature and partial pressure distributions are linear.

A better approximation was obtained by Langsdorf,[4] who took into account the temperature dependence of diffusion and thermal conductivity. Figures 2 and 3 show the temperature distribution and partial-pressure curves for two different vapor fluxes, assuming no condensation. Greater vapor flux increases both the nonlinearity of the temperature distribution and the partial pressure in the chamber. Figure 4 shows the corresponding supersaturation curves. The dot-dash curves represent the supersaturation S_1 at which droplets begin to grow on ions, and the supersaturation S_2, at which a large number of droplets are formed on uncharged nuclei.

The figure shows that supersaturation near the bottom of the chamber exceeds S_1 and S_2. The boundary of the sensitive layer is determined by the intersection of curves S_X and S_1 (points A and B on Curve 2). With greater vapor flux the partial pressure, and accordingly the supersaturation, increases (Curve 1). It is evident that as a result of condensation on charged and uncharged nuclei the true supersaturation in a diffusion chamber will be considerably smaller than is shown in Fig. 4.

a) Effect of Condensation

Condensation within the chamber results in reduced partial pressure. Moreover, the release of a large amount of heat through condensation can produce a significant change in the temperature distribution.

Succi and Tagliaferri[5] have developed Langsdorf's theory, using successive approximations to determine the effect of condensation on the temperature distribution and supersaturation distribution. Figure 5 shows the temperature distribution curves for different condensation conditions. The temperature distribution is seen to change with increasing number of condensation nuclei, the temperature rising at all distances from the bottom. The temperature increases by 15 to 20°C when the ion load is large. Argan et al have further developed Langsdorf's theory, but their results do not differ qualitatively from those of earlier investigators.

References 7, 8, and 9 describe experimental studies of the effect of condensation on the temperature distribution. The temperature distributions were compared in an operating chamber and in the same chamber without condensation (the vapor source being absent). A chamber con-

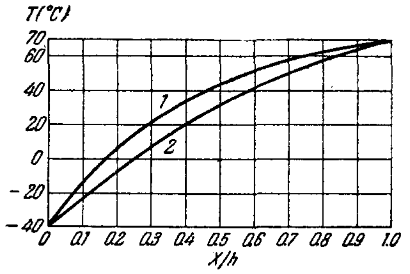

FIG. 2. Calculated temperature distributions in the volume of a chamber filled with CO_2 and CH_3OH, without condensation. Curve 1) Vapor flux 6.86×10^{-6} g/cm² sec; Curve 2) Vapor flux 2.56×10^{-6} g/cm² sec.

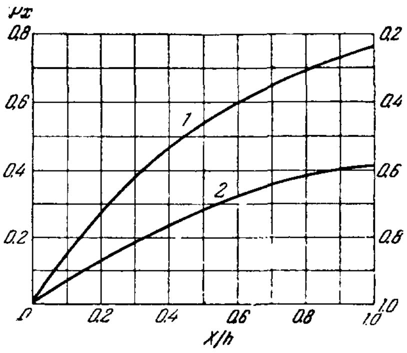

FIG. 3. Calculated partial pressure distributions, under the same conditions as for Fig. 2.

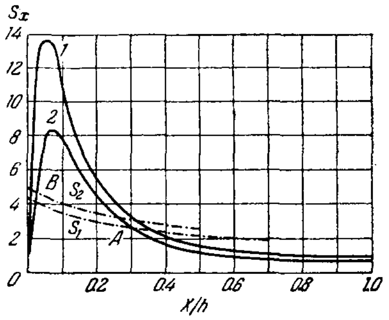

FIG. 4. Supersaturation distribution in the chamber. Curve S_2) limit of fog formation; Curve S_1) limit of condensation on ions; A and B) upper and lower boundaries of the sensitive layer.

taining rigidly fastened thermocouples was filled with air and other gases; the total pressure, vapor flux, and number of charged condensation nuclei could be varied within broad limits. It was established that when the product of the Grashof number (Gr) and Prandtl number (Pr) is at least 10^6 condensation has a negligibly small effect on the temperature distribution. When Gr Pr $\ll 10^6$ the effect of condensation on temperature distribution becomes appreciable. Figure 6 shows that when condensation occurs in a low-pressure chamber the temperature can change by as much as 20°C.

The foregoing results make it convenient to divide diffusion chambers into two types, those in which condensation has practically no effect on the temperature distribution and those in which the effect is great. The first type includes all high-pressure chambers, i.e., the great majority of those in use at the present time. Chambers with very low gas pressure are the second type. In the first type convective heat exchange with the walls plays the dominant part in the establishment of the temperature distribution. In the second type (hereinafter called low-pressure chambers) convective heat exchange with the walls plays a minor part. Langsdorf's theory[4] and similar theories,[5, 6] which neglect convection, are not applicable to the ordinary diffusion chamber but can evidently be employed in analyzing processes within low-pressure chambers.

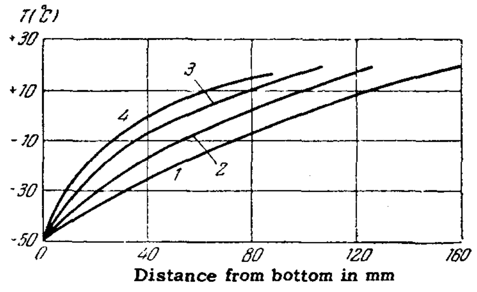

FIG. 5. Effect of condensation on temperature distribution. Curve 1) temperature distribution in the absence of condensation. Curves 2, 3, 4) temperature distribution when the number of ions passing through 1 cm² of cross section per second is 20, 60, and 180, respectively.

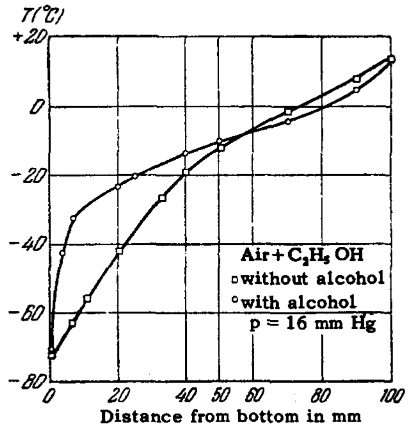

FIG. 6. Effect of condensation on temperature distribution.

Our further discussion will concern ordinary diffusion chambers. Certain characteristics of low-pressure chambers will be considered separately.

b) Temperature Distribution and Partial Pressure Distribution

There have been several investigations of the temperature distribution in diffusion chambers[7, 8, 9, 10]. In references 7 and 8 it was definitely shown that the temperature distribution in the space of a chamber practically coincides with the temperature distribution on the walls and can thus be regulated within broad limits. Figure 7 shows the temperature distribution curves within a chamber filled with air and ethyl alcohol vapor with a

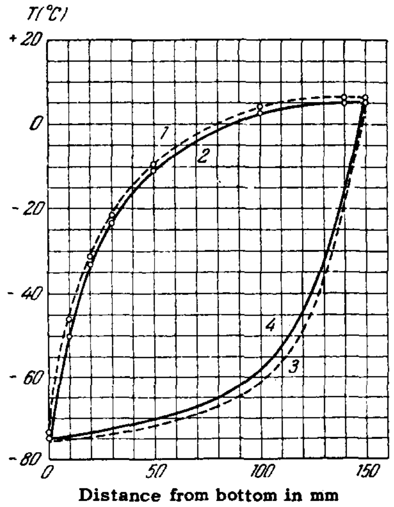

FIG. 7. Temperature distribution along walls (dashed Curves 1 and 3) and in chamber volume (Curves 2 and 4). Curves 1 and 2 were obtained in a chamber with glass walls at room temperature externally; Curves 3 and 4 were obtained in the same chamber with cooled walls.

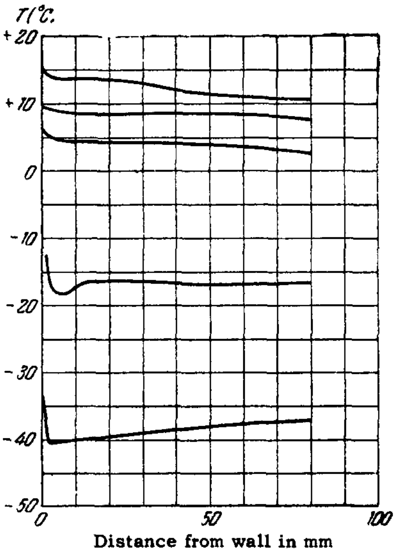

FIG. 8. Horizontal temperature distribution in a chamber that is in contact with air at room temperature.

total pressure equal to one atmosphere. Curves 1 and 2 were obtained with the outside walls of the chamber at room temperature. The temperature distribution within the chamber is seen to differ very little from that on the walls, the wall temperature at each horizontal cross section being a little higher than the temperature at the center. The temperature distribution changes sharply with outside cooling of the walls (Curves 3 and 4). In this case the wall temperature in each horizontal cross section is a little below that at the center. Figures 8 and 9 show the horizontal temperature distribution in a chamber surrounded by air at room temperature and by cold air, respectively.

When the walls are heated to room temperature externally, the gas within the chamber moves upwards. When the walls are cooled externally the direction of gas flow is reversed. There must evidently be an intermediate state when the temperature distribution on the walls coincides with the temperature distribution in the gas so that convection stops. However, it is easily seen that this will not be a stable state. A change in the number of condensation nuclei within the chamber, such as following the passage of an ionizing particle, will immediately result in the liberation of heat followed by convection. Therefore convection occurs as a rule in any real chamber.

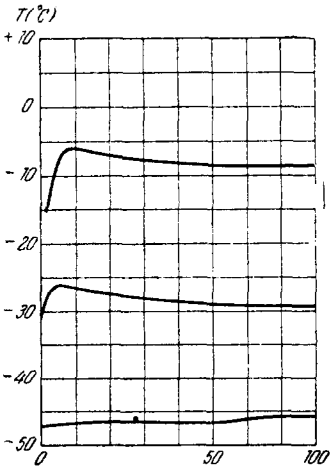

FIG. 9. Horizontal temperature distribution in a chamber with cooled walls.

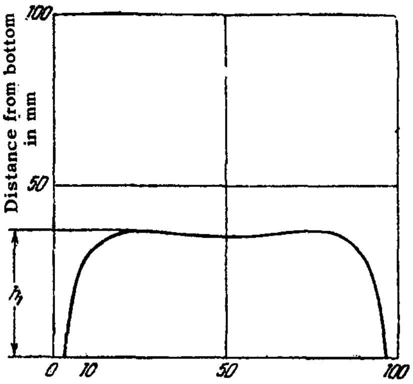

FIG. 10. Vertical section of a fog region formed after expansion.

With any change of the wall-temperature distribution or with a change of the condensation conditions in the chamber the speed and in some instances the direction of convection currents will be changed. The experimental investigation described in reference 8 showed that convection within the chamber is axially symmetrical and does not lead to inhomogeneous supersaturation in the sensitive zone when the gas moves upward along the walls. The speed of the gas moving in the working volume of the chamber is comparable with the speed of falling droplet. Therefore gas motion does not appreciably distort particle tracks during the time required for their recording. Thus the temperature distribution within the chamber can be regulated without disturbing its operation.

Convective gas motion within the chamber has an important effect on the partial pressure distribution. The partial-pressure field within an operating chamber has been investigated in two ways, through the absorption of ultraviolet radiation by a gas-and-vapor mixture[11] and by the expansion method.[12] In the first method the optical density of the gas-and-vapor mixture is measured at different heights in the chamber. In the second method the degree of expansion is determined at which a fog is formed in a given region of the chamber, in which case supersaturation exceeds S_2. The upper boundary of the fog is usually nearly parallel to the bottom of the chamber. Figure 10

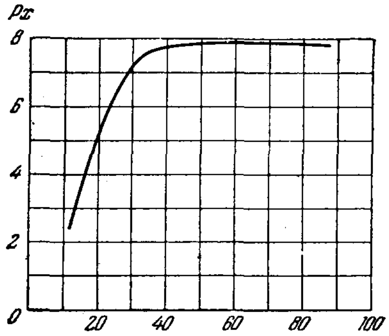

FIG. 11. Partial pressure distribution in a chamber with nonlinear temperature distribution.

shows a vertical section of a fog region formed after expansion. There is lower supersaturation in the region near the walls. The construction of the vapor source has some effect on the partial pressure distribution in the upper part of the chamber. From the distance h_1 between the upper boundary of the fog and the chamber bottom, the temperature T_{h_1} after expansion, and the supersaturation S_2 for a given gas and vapor mixture we can determine the partial pressure P_{h_1} at this boundary:

$$P_{h_1} = S_2 P_{\text{sat}}(T_{h_1}).$$

The partial pressure throughout the chamber can thus be determined by varying the degree of expansion.

Figure 11 shows a typical partial pressure distribution in a chamber with nonlinear temperature distribution. Above the condensation zone the partial pressure varies very little with height because of the strong mixing of gas and vapor.

When the temperature distribution is changed without changing the directions of convection currents the character of the partial pressure is not affected and the partial pressure above the condensation zone also remains unchanged. However, variation of the temperature distribution is accompanied by a variation of supersaturation in accordance with the change of saturated vapor pressure. This in turn affects the size of the condensation zone. For example, when the temperature distribution is varied as shown in Fig. 12, the height of the sensitive layer changes from 1.8 cm (Curve 1) to 5.5 cm (Curve 3).

It must be mentioned that a self-regulating supersaturation mechanism permits a diffusion chamber to operate in a very broad range of temperature distributions. When the temperature distribution is such that supersaturation within the chamber at any given moment is considerably above S_2 (as in Curve 1 of Fig. 4), spontaneous condensation of vapor on uncharged nuclei begins in the sensitive zone. Supersaturation decreases, reducing the number of active condensation nuclei and reducing the rate of droplet growth. The reduced consumption of vapor increases the supersaturation. As a result of this mechanism supersaturation in the sensitive zone cannot be appreciably above or below S_2 for a long time. Variation of the temperature distribution thus basically affects the magnitude of the droplet background.

In some cases the self-regulating process has a pronounced pulsating character. There are periodic variations of fog background density in the sensitive zone. This effect can be considerably reduced or entirely eliminated by a suitable change of the temperature distribution.

The operation of the chamber can also be regulated by varying the size of the vapor source through increase of the source surface or its temperature. (The vapor flux can be determined, for example, by measuring the quantity of liquid evaporated in a given time interval.) With increasing flow the partial vapor pressure must increase at each height. In the sensitive zone supersaturation cannot appreciably exceed S_2. Therefore the excess vapor is converted into the liquid phase. Thus increased vapor flow results in growth of the droplet background and has little influence on the degree of supersaturation in the sensitive zone.

Variation of the temperature distribution and vapor flow also affects the basic operating characteristics of the chamber—the maximum ion load with which the chamber can function continuously and the recovery time after a radiation pulse.

2. ION LOAD AND RECOVERY TIME

Unlike the conventional cloud chamber, the diffusion chamber is continuously sensitive. When the number of ions generated per second in one cm^3 of the chamber (ion load) does not exceed a certain limit the chamber can record all events

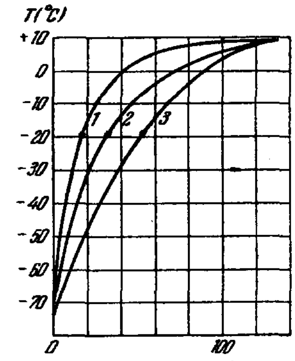

FIG. 12. Temperature distribution within chamber. The asterisk on each curve indicates the temperature at the upper boundary of the sensitive zone.

accompanied by ionization of the gas in its volume. A count of the particle tracks in a given time interval can thus be used to determine weak radioactivity in materials. Each track falls to the bottom in a few seconds, depending on the point of formation and droplet size.

Because of the continuous sensitivity and long persistence of the tracks, photographs obtained with diffusion chambers always show a certain number of background tracks. Background tracks impede analysis of the photographs and also reduce supersaturation, which for large ion loads can fall below S_1. The chamber must therefore be shielded from external radiation and the working mixture in the chamber must not be radioactive.

With small temperature gradients in the sensitive zone the chamber ceases to function at a radiation intensity comparable with the natural background. Figure 12 shows that a reduced temperature gradient is associated with increased height h of the sensitive zone. With an increase of h the number of condensation nuclei in the lower part of the chamber increases, owing to droplets falling from above. Near the bottom supersaturation decreases, resulting in the formation of an insensitive zone. Therefore the thickness of the sensitive zone in a diffusion chamber does not usually exceed 6 or 7 cm. With increasing thickness of the sensitive zone and increasing temperature gradient, the ion-load limit is raised.

Vapor flow also has an appreciable affect on the permissible ion load. Thus in a chamber filled with air and ethyl-alcohol vapor at atmospheric pressure, an increase of vapor flow by a factor of 6 increases the ion-load limit by a factor of 3. With a higher ion load the amount of vapor condensing on uncharged nuclei is reduced, thus reducing the droplet background. It is evident that the total amount of liquid condensing per unit time within the chamber remains practically constant.

Under certain operating conditions the diffusion chamber can record continuously radiation with a background that exceeds the cosmic radiation background by a factor of hundreds.[13] Under such conditions an important role is played by convection currents that transport the gas and vapor mixture from the heated top to the cold bottom.

After the passage of a charged particle through the sensitive zone, the latter contains a region with supersaturation below S_1 in the shape of a cylinder whose diameter depends on the ionizing power of the particle and the quantity of vapor at the given height. The recovery time of supersaturation after passage of a single particle is a few seconds. When many particles are involved, some of them traverse regions in which supersaturation had not received; they thus produce discontinuous tracks. When a beam consisting of very many particles passes through the sensitive zone, supersaturation can fall considerably below S_1, with the recovery time rising to 10 or 15 sec. A larger number of ions produced simultaneously in the sensitive zone is accompanied by a reduction of supersaturation and a longer recovery time. The recovery time also increases with the thickness of the sensitive zone. The recovery time can be shortened by increasing vapor flow.[14]

When the entire volume of a chamber is irradiated, condensation nuclei appear above as well as within the sensitive zone. By moving about in the chamber as far as the upper boundary of the sensitive zone, these nuclei form a more or less uniform droplet background. When the ion concentration is large, supersaturation in the sensitive zone can fall below S_1. The recovery time after cessation of irradiation depends on the nature of the vapor. This apparently indicates that the condensation nuclei are not ions but charged droplets diffusing into the sensitive zone from the region above.

Charged condensation nuclei can be swept from the space above the sensitive zone by an electric field applied between the cover serving as one electrode and a second electrode close to the upper boundary of the sensitive zone.

The chamber is cleared of uncharged condensation nuclei by migration of these nuclei into the sensitive zone, after which the drops that are formed fall to the bottom. When the number of nuclei is very large the rate of sweeping is limited by the vapor flux. When the number is small and the rate at which vapor is consumed in condensation is less than the vapor flux, the recovery time is determined by the migration rate of nuclei into the sensitive zone. Therefore recovery time depends strongly on the character of gaseous motion in the chamber and on its design. A simple chamber with a strongly nonlinear temperature distribution possesses a recovery time of the order of two minutes when filled with unpurified outside air. When the temperature distribution curve is rectified, convection velocity is reduced and the recovery time increases, reaching 20 or more minutes in some instances.

It is important to note that when a chamber contains no constant source of condensation nuclei it is more or less rapidly self-clearing. This ability clearly distinguishes the operation of a diffusion chamber and is one of its principal advantages over a conventional cloud chamber.

3. DIRECTION OF DIFFUSION

In a diffusion chamber the density varies with height and is a function of temperature and of the relative amounts of gas and vapor. When the molecular weight of the gas is smaller than that of the vapor this can result in a mixture whose density decreases in the downward direction, resulting in a singular type of convection. A system of vertical convection currents is established between the top and bottom. This occurs principally in low-pressure chambers, where the partial vapor pressure is commensurate with the total pressure.

Convection can be obviated by reversing the direction of diffusion. Chambers with a hot bottom and cold top (upward diffusion) have been described in references 15, 16, and 17. Investigations of the operation of these chambers are described in references 8 and 18.

At high gas pressures, when the vapor pressure is negligibly small compared with the total pressure, the variation of the relative composition of the mixture is small and the relation between density and height depends mainly on the temperature factor. Increase of the gas pressure or reduction of the partial vapor pressure aids stabilization of the gas in a downward-diffusion chamber. The same effect is achieved by using a gas of greater molecular weight or a vapor of smaller molecular weight. Chambers filled with hydrogen or helium are found to operate in a stable manner only when the total pressure of the mixture exceeds a few atmospheres[19] (the vapor source temperature being +10°C or +15°C). When the temperature of the top plate is reduced the partial vapor pressure is sharply lowered; this permits operation with light gases below atmospheric pressure.[20] In this last case the bottom temperature must be lowered in order to maintain the required temperature distribution of the chamber.

4. SIMILAR CHAMBERS

In high-pressure chambers, which are most widely used, the temperature distribution can be regulated over a wide range, as already mentioned, thus regulating the degree of supersaturation. Results obtained with any one chamber can be applied to another chamber of similar type. For calibration, a chamber is usually filled with air at atmospheric pressure and the optimum temperature distribution is established experimentally. This then gives optimum conditions for other gases and pressures (if Gr Pr $> 10^6$ in all cases). For chambers with the same temperature distribution the ion-load limit and recovery time will depend on the nature of the gas, the pressure, and vapor flux.

Shutt has established that the ion load and pressure are related to the gas parameters by the following equation:[21]

$$B = \mu_0 D_0^{-\frac{1}{3}} p^{\frac{1}{3}} (n_0 a Z p)^{\frac{4}{3}},$$

where B is a constant for a given temperature distribution, μ_0 is the kinematic viscosity at 273°C and normal pressure, D_0 is the diffusion coefficient of the vapor in the gas at normal pressure and 273°C, n_0 is the number of ions generated in one cm^3 of air per second under one atmosphere of pressure, a is the number of atoms per gas molecule, and Z is the atomic number of the gas.

Shutt's theory does not take neutral condensation nuclei into account. By making a suitable correction Bevan obtained a formula which takes both neutral and charged condensation nuclei into account.[22]

$$B_a = \mu_0 D_0^{-\frac{1}{3}} p^{\frac{1}{3}} [n_0 a Z p + 14.5 e^{0.116t}]^{\frac{4}{3}},$$

where t is the highest temperature within the chamber in degrees centigrade (usually the temperature of the vapor source).

Experimental tests of the foregoing relations have been described in references 8, 9, and 14. It was found that when one gas is replaced by another and the pressure is varied the relation between μ_0, D_0, a, Z, the maximum ion load, and the pressure is well described by Shutt's equation.

Shutt's theory does not allow for the effect of vapor flow on the operation of the chamber; in references 8 and 14 this effect was shown to be significant. The variation of vapor flux (by increasing the surface of the vapor source) can multiply the ion load limit several times and greatly reduce the recovery time.

Bevan's equation does not allow for the fact that the flow of vapor is enhanced when the vapor-source temperature is increased at the same time as the number of neutral nuclei is increased. Therefore Bevan's equation has not been confirmed experimentally. For example, with an increase of source temperature the ion-load limit in a number of instances increases[8] instead of decreasing as would follow from Bevan's equation.

According to Shutt[21] a minimum temperature gradient exists for operation of the chamber under given conditions. Bevan experimentally determined the relation between the minimum temperature gradient G in the sensitive zone and the parameter B.[22] However, his results appear to have limited application since B depends not only on the temperature gradient in the sensitive zone but also on the temperature distribution within the entire chamber volume. For chambers of different design with the same temperature gradient in the sensitive zone, the temperature distribution within the chamber volume can differ appreciably. This evidently accounts for the fact that measurements performed on chambers of different design give a relation between G and B which differs from that of Bevan.[8]

5. LOW-PRESSURE CHAMBERS

Low-pressure chambers are described in references 20 and 23. The temperature distribution in in the gas of a low-pressure chamber exhibits very little dependence on the temperature distribution along the walls[9] and thus cannot be regulated as in high-pressure chambers. When pressure is reduced the temperature in the lower part of an operating chamber can either increase or decrease, depending on the character of the temperature distribution at the higher pressure. Pressure reduction in a chamber with a steep non-linear temperature distribution (and thus with a thin sensitive layer) reduces the temperature in the volume. On the other hand, in a chamber with a nearly linear temperature distribution pressure reduction raises the temperature in the condensation zone. In both cases at reduced gas pressure the sensitive zone is observed to be of lesser height. This effect is evidently associated with reduced partial pressure in the chamber volume.[9]

In chambers with a thick sensitive zone (> 5 cm) reduction of the zone at lowered pressure results to a considerable extent from a higher temperature of the chamber volume. It is shown in reference 23 that at lower pressure the thickness of the sensitive zone is reduced from 100 mm at atmospheric pressure to 20 mm at 30 mm Hg.

At pressures below 30 mm Hg periodic fluctuations of the background density occur.[24] The sensitive zone breaks up into cells. Fig. 13 is a typical photograph of the sensitive layer. The fog alternately clears and is restored (pulsations of the fog background) and the shapes and arrangement of the cells can vary. Cell size and pulsation frequency depend on chamber pressure and on the nature of the gas and vapor. Pulsation frequency increases with reduced vapor flow and reduced gas pressure. The smaller the latent heat of condensation and the smaller the molecular weight of the gas, the higher the pulsation frequency. Fluctuations of the fog background density are evidently associated with the liberation of heat through condensation.

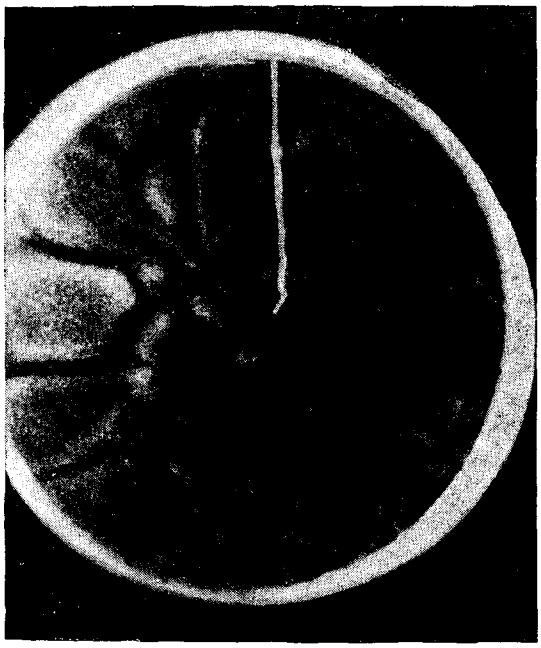

FIG. 13. Photograph of a sensitive zone in a low-pressure chamber ($p = 40$ mm Hg) filled with air and ethyl-alcohol vapor.

It is important to note that the track of an alpha particle passing through a few cells is continuous. Under certain conditions of illumination, a photograph may not show the cells at the same time that the alpha-particle track is clearly visible.

As already mentioned, fluctuations of the droplet background also occur in high-pressure chambers for a given temperature distribution. But unlike the case of high-pressure chambers, where this effect can be avoided, time fluctuations of the droplet background density cannot be eliminated in a low-pressure chamber since the temperature distribution in the chamber cannot be regulated.

6. CHAMBER CONTROL

A diffusion chamber can be controlled by either external or internal 25 counters. In work with accelerators the chamber is usually controlled by the accelerator itself.[26] The sequence of operations and typical time intervals between them are shown in Fig. 4, which was taken from reference 26.

In a diffusion chamber droplets begin to grow on ions immediately following the passage of a particle, whereas in a conventional cloud chamber some time elapses between the passage of the particle and the production of the required supersaturation; during this time ions diffuse from the places where they were generated. As a result particle tracks in a diffusion chamber are clearer than in

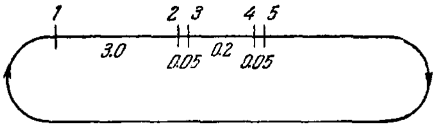

FIG. 14. Operating cycle of a diffusion chamber. Times are given in seconds. 1) Switching off of electric sweeping field; 2, 3) Entrance of particles; 4) Illumination pulse; 5) Switching on of electric sweeping field and film-moving mechanism. Total duration of cycle is 6 to 12 sec.

a conventional cloud chamber controlled by counters. It must also be remembered that in a diffusion chamber the tracks are not distorted by the motion of the expanding gas. The control system of a diffusion chamber is considerably simpler than that of a chamber involving expansion.

Because of its continuous operation, a diffusion chamber can be controlled by means of a photomultiplier "scanning" the working volume. Light scattered by the particle track enters the photomultiplier, the output pulse of which then triggers the control system. This control is subject to the condition that light scattered by the droplet background is considerably weaker than the light pulse from the particle track. This condition is easily fulfilled in the recording of strongly ionizing particles such as alpha particles or of showers generated by high-energy particles.

Reference 27 reports briefly on the possibility of controlling a diffusion chamber by means of a photocell. Control of the chamber by means of a photomultiplier is very promising, for example, for the recording of extensive air showers or events accompanied by the appearance of strongly ionizing particles in the volume of the diffusion chamber itself.

7. DESIGN OF DIFFUSION CLOUD CHAMBERS

a) Cooling of Chamber Bottom

The bottom temperature required for satisfactory operation of the chamber depends to a considerable extent on the nature of the vapor. It is customary to use methyl or ethyl alcohol vapor, for which the bottom temperature must be below −40°C. The bottom can be cooled most simply by direct contact with dry ice pressed against the bottom by a spring. This method gives very satisfactory results when the chamber walls are poor conductors. In metal chambers there is large heat flow along the walls. For example, in a chamber with a steel wall 6 mm thick and 430 mm in diameter and with a temperature gradient of 6°C per centimeter, the required heat flow is 50 cal/sec.[28] The evaporation rate of the dry ice then reaches 1 l/sec, which leads to the formation of a heat-insulating layer of gas. This in turn causes nonuniform cooling of the bottom.

Somewhat better results can be obtained by cooling the bottom with a mixture of dry ice and acetone or alcohol.[29,14] A container welded to the bottom is filled with the cooling mixture, which is in contact with the undersurface of the bottom plate, thus insuring more uniform cooling. In this case, however, the liberation of a large amount of gas with large heat flow reduces the total surface of contact with the cooling mixture, thus preventing the achievement of low temperatures.

Much lower temperatures are achieved by the use of liquid nitrogen. The bottom is then cooled either by means of a heat conductor within a Dewar vessel[20] or by passage of the liquid nitrogen through a coil of pipe fastened to the bottom.[8,12]

In diffusion chambers that are operated in conjunction with accelerators the cooling system usually consists of a heat exhanger (or refrigerator) and coil fastened directly to the bottom of the chamber. The cooling liquid is pumped through the heat exchanger, which is usually a tank filled with a mixture of dry ice and acetone, and then through the coil fastened to the bottom. The temperature can be regulated by varying the vapor pressure above the mixture; in this way the bottom can be cooled to about −100°C.[28] Reference 28 gives calculations which can be useful for the designing of a chamber-cooling circulating system. The cooling of a chamber with a transparent bottom, such as is described in reference 30, presents certain specific difficulties.

b) Chamber Walls

The walls of a diffusion chamber serve two different purposes. They form a portion of the container, which when the chamber is filled with gases at different pressures must be gastight and sufficiently strong. Secondly, the walls provide the boundary temperatures, which strongly affect the temperature distribution within the chamber.

To prevent local convection currents, which would disturb normal operation, the wall temperature in each horizontal cross section must be constant. This condition is easily fulfilled in the case of transparent walls, where no window is required for illumination. Metal walls require windows for illumination and for the admission of particles. In this case the flow of heat along the wall from the top to the bottom encounters different resistance in different cross sections. The vertical temperature distribution along the wall therefore varies and the existence of a horizontal component of the temperature gradient results in convection currents, which are easily detected through the formation of fog curtains that remain motionless for a long period. Convection establishes an internal temperature distribution in the chamber volume which is different from that along the walls.

Temperature differences in any horizontal cross section can be obviated through the use of sources of cold and heat sources disposed on the outside of the walls, but it is considerably simpler to create a temperature field by placing a special container inside the chamber.[8, 14, 31] A plexiglas cylinder with a pure copper bottom is placed inside the metal diffusion chamber. The bottom temperature of this cylinder is that of the copper disk, while its upper temperature is that of a copper trough containing evaporating liquid. The outside of the cylinder is surrounded by gas, which transfers heat between the different elements in the chamber. Measurements with a thermocouple sliding along the cylinder wall[8] have shown that the horizontal component of the temperature gradient does not exceed 1 or 2°C.

Difficulties associated with the need for equalizing the wall temperature of a metal chamber containing windows can be overcome to a considerable extent if illumination is achieved through the use of a window in the top cover and mirrors inside the chamber.[8] There are then no windows in the side walls. Side windows are also undesirable from considerations of strength. Large temperature gradients cause internal stresses in connected parts made of materials with different expansion coefficients. This is especially dangerous in high-pressure chambers, where leaks can occur as a result of repeated strains during cooling and heating. Methods and devices used to prevent leaks in window chambers complicate the operation of the entire instrument.[14]

c) Vapor Source

The vapor source in downward-diffusion chambers is usually a trough, fastened to the top plate, containing the working liquid. Near the top the vapor pressure decreases with increasing distance from the vapor source. To produce uniform supersaturation equal to unity near the top plate, the vapor source can be a liquid maintained at constant temperature[8] and evaporating from the lower surface of the lid. The cover then takes the form of a vessel with gastight walls and a porous bottom. A simpler vaporizer was described in reference 17. A very damp cloth was fastened to the lower surface of the metal lid, the moisture being maintained at a constant level by means of tubes.

Vapor sources in the form of troughs possess two serious disadvantages. They require periodic replenishing of the working liquid, which in the case of high or low gas pressures necessitates special devices,[14] thus complicating the design and operation of the chamber. Secondly, when a mixture of different liquids is used as a vapor source the composition of the mixture changes during operation, thus varying the operating conditions of the chamber. Consequently pure alcohol is usually used in diffusion chambers, although it is known that mixtures give better results. Unconnected troughs containing different pure liquids can be used to provide a vapor mixture, but this intensifies the disadvantage resulting from the fact that special devices are needed to replenish the working liquids.

A diffusion chamber with a continuously operating vapor source[32] and without the aforementioned shortcomings was proposed in 1952. A liquid poured on the chamber bottom rises through capillary action in porous plates located close to the walls; it then evaporates and diffuses into the chamber. This process is continuous so long as the required temperature distribution is maintained between the top and bottom. The composition of the mixture remains constant. Investigation of the structure of the sensitive zone by means of a gas discharge[8] and by means of expansion[12] in a chamber with a continuously operating vapor source[33] shows that supersaturation in the sensitive zone is practically independent of the horizontal coordinate. Partial pressure distribution within such a chamber is of the same character as in a chamber with the usual vapor source in a trough. Windows cut through the porous plates for illumination of the chamber do not cause inhomogeneity of the sensitive zone.

In a chamber with a continuous vapor source the droplet background is usually less dense and more uniform than in a chamber with a trough source close to the lid. This apparently results from the fact that under certain conditions a large number of condensation nuclei can be formed close to a vapor source provided by a trough fastened to the lid.

In chambers with a trough the vapor source temperature is usually a few degrees above the temperature of the ambient gas. This temperature difference is especially great in chambers where auxiliary heating of the vapor source is provided; see reference 22, for example. When gas from below comes into contact with such a source the condensation nuclei that are created migrate into the sensitive zone forming a fog background.

With nonuniform heating of the lid or walls, local convection currents arise and create a corresponding configuration in the droplet background. Downward currents of cooled gas enter the sensitive zone and form fog curtain that remain almost unchanged in shape and position for long periods. Such fog curtains have been noted by many investigators.[28] When the vapor source has a lower temperature than the gas near the lid (as with a continuously operating source) this effect is much less pronounced.

A continuous vapor source can be used in large chambers; for example, a chamber with a 60 × 90 cm bottom was demonstrated at the All-Union Industrial Exposition of 1956.

It has already been noted that the number of neutral centers and thus the droplet background will grow with rising vapor source temperature. At an interior temperature of 60°C a chamber cannot furnish good tracks of ionizing particles, and at about 80°C all registration ceases.

d) Illumination of Chamber

A diffusion chamber is usually illuminated from the side through transparent walls or through windows in the walls of a metal chamber. A heat-insulating air gap is used to prevent frosting or fogging of the outside surfaces of windows.[34, 35] The temperature of the surface exposed to the outside air is then usually above the dew point. The outside walls are sometimes heated to prevent condensation. To prevent fogging of the outside surface of windows in metal chambers special jackets are usually used to insulate the windows from the outside air.[14] The illuminating lamp and lens system are mounted inside the jacket, which contains dried air.

The light beam generally interacts with the gas and vapor mixture in the chamber; in some instances this increases the droplet background, worsens track quality, and reduces the ion-load limit. When a chamber is illuminated by means of a gas-discharge lamp, neutral condensation nuclei may appear.[14] Because of their long lifetimes the neutral nuclei can accumulate in the chamber; the droplet background then gradually grows and in the case of prolonged operation of the chamber can become so large that the recording of ionizing particles is impeded. Unfiltered pulsed illumination of a chamber can sometimes prevent normal operation for a long period or lead to total loss of sensitivity.

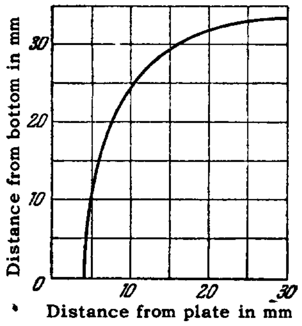

FIG. 15. Profile of sensitive layer close to a plate inside a diffusion chamber.

Light also heats the chamber walls, thus changing the temperature distribution. When the chamber volume is illuminated uniformly and heating of the walls is prevented, prolonged continuous illumination by means of an incandescent lamp does not appreciably affect normal operation. For example, a chamber used to project ionizing particle tracks on a screen functions continuously with a light flux of 2000 lumens.[30]

e) Particle-absorbing Plates in Diffusion Chambers

For the purpose of investigating interactions between high-energy particles and matter it is sometimes desirable to place absorbing plates inside a diffusion chamber. The presence of a solid body inside the chamber and the resulting changed conditions for the transfer of heat and matter can seriously affect the operation of the chamber. A thin plate which is a poor heat conductor has little effect on the temperature distribution in the chamber volume. The temperature distribution on the plate will be that of the chamber gas. Similar conditions exist when composite plates are used whose layers are thermally insulated from each other. In reference 36 it is shown that a lead absorber constructed in this manner does not disturb the thermal regime of a chamber.

When simple plates are used, made of materials that are good heat conductors, the temperature distribution on the plates is necessarily determined by the location of the sources of heat and cold. The plates then have a significant effect on the volume temperature distribution.

Supersaturation cannot exceed unity on the surface of a solid body; an insensitive zone is thus produced close to the plate. This is the principal obstacle which limits the use of plates inside diffusion chambers.

In reference 37 different ways of positioning plates were studied as well as the factors that affect the size of the insensitive zone close to a plate. The size of the insensitive zone was determined by means of alpha and beta-particle sources. An analysis of a track photograph obtained in this work shows that the insensitive zone has the shape represented in Fig. 15. The profile of the sensitive region can be obtained by photographing the chamber volume immediately following expansion or a gas discharge.[8] When the chamber is illuminated by a narrow light beam the photograph clearly shows an insensitive zone close to the walls because of the absence of fog.

The size of the insensitive zone is determined by the vapor flux. With increase of the latter the height of the sensitive zone increases and the insensitive zone is reduced. The character of gas movement within the chamber has a significant influence on the size of the insensitive zone, which can be greatly reduced (to 1 or 2 mm) near the surface of a solid through the flow of gas containing a large amount of vapor at a higher temperature than the surface. This is easily accomplished in a diffusion chamber with a large horizontal component of the temperature gradient.

8. CONCLUSION

Diffusion chambers possess a number of advantages over conventional cloud chambers and are thus replacing the latter at present for some purposes such as work with particle accelerators. Diffusion chambers permit great extension of this method of recording particles. For example, a diffusion chamber can record all ionization events occurring in its sensitive zone and can thus be used for absolute measurements of alpha and beta activities of the order of 10^{-12} Curie.[38] The continuous operation of diffusion chambers makes it easy to record very rare events that are accompanied by the production of strongly ionizing particles.

Diffusion chambers can be used successfully to study gas discharges, the behavior of charged droplets in electric and gravitational fields, as well as the formation and growth of droplets and of ice crystals on different kinds of condensation nuclei. They can also be used to investigate light scattering on droplets[39] and the behavior of a fog or mist-filled region in gravitational and electric fields.[40]

The simple construction and reliable operation of diffusion chambers has also lead to their widespread use for instructional purposes as a demonstration instrument that permits continuous observation of ionizing particle tracks.[30, 41] Diffusion chambers are being used extensively at present to investigate interactions between accelerated particles and matter.[14, 26] They will continue to be important despite the development of such promising instruments as scintillation detectors and bubble chambers.

[1] R. E. Vollrath, Rev. Sci. Instr. **7**, 409 (1936).

[2] A. Langsdorf, Phys. Rev. **49**, 422 (1936).

[3] A. G. Amelin, Теоретические основы образования тумана в химических производствах (Theoretical Foundations of Fog Production in Chemical Manufacturing). 1951.

[4] A. Langsdorf, Rev. Sci. Instr. **10**, 91 (1939).

[5] C. Succi and G. Tagliaferri, Nuovo cimento **9**, 1092 (1952).

[6] Argan, Angelo, and Gigli, Nuovo cimento **1**, 761 (1955).

[7] V. K. Lyapidevskii and Yu. A. Shcherbakov, J. Exptl. Theoret. Phys. (U.S.S.R.) **27**, 103 (1954).

[8] V. K. Lyapidevskii, Dissertation, Moscow Physics and Engineering Institute, 1956.

[9] V. K. Lyapidevskii and O. P. Astakhov, Приборы и техника эксперимента (Instruments and Measurement Engineering) No. 1, 43 (1957).

[10] H. L. Morrison and G. J. Plain, Rev. Sci. Instr. **23**, 607 (1952).

[11] V. K. Lyapidevskii and V. M. Martishin, Приборы и техника эксперимента (Instruments and Measurement Engineering) No. 1, 48 (1957).

[12] V. K. Lyapidevskii J. Exptl. Theoret. Phys. (U.S.S.R.) **29**, 263 (1955), Soviet Phys. JETP **2**, 346 (1956).

[13] V. K. Lyapidevskii, Report to the All-Union Scientific and Engineering Conference on the Use of Radioactive and Stable Isotopes and of Radiation in the National Economy and Science, 1957.

[14] R. M. Sulyaev, Dissertation, Moscow Physics and Engineering Institute, 1956.

[15] O. H. Weddle and C. E. Nielsen, Phys. Rev. **81**, 324 (1951).

[16] Nielsen, Needels and Weddle, Rev. Sci. Instr. **22**, 673 (1951).

[17] P. Harteck and G. Hertz, Naturwissenschaften **39**, 206 (1952).

[18] V. K. Lyapidevskii and O. P. Astakhov, Приборы и техника эксперимента (Instruments and Measurement Engineering) No. 3, 39 (1956).

[19] Miller, Fowler, and Shutt, Rev. Sci. Instr. **22**, 280 (1951).

[20] W. J. Choyke and C. E. Nielsen, Rev. Sci. Instr. **23**, 6, 307 (1952).

[21] R. P. Shutt, Rev. Sci. Instr. **22**, 730 (1951).

[22] A. R. Bevan, J. Sci. Instr. **31**, 45 (1954).

[23] Komar, Stabnikov, and Yashin, Dokl. Akad. Nauk SSSR **108**, 1, 66 (1956), Soviet Phys. "Doklady" **1**, 260 (1956).

[24] V. K. Lyapidevskii, Приборы и техника эксперимента (in press).

[25] Block, Broun, and Slaughter, Phys. Rev. **86**, 583 (1952).

[26] E. C. Fowler, W. B. Fowler, Shutt, Thorndike and Whittemore, Phys. Rev. **91**, 135 (1953).

[27] D. C. Marshall and D. Broun, Rev. Sci. Instr. **24**, 9, 881 (1953).

[28] Alston, Crewe and Evans, Rev. Sci. Instr. **25**, 6, 547 (1954).

[29] Miller, Fowler and Shutt, Rev. Sci. Instr. **22**, 280 (1951).

[30] V. K. Lyapidevskii, **Приборы и техника эксперимента** (Instruments and Measurement Engineering) No. 3, 103 (1957).

[31] Kozodaev, Sulyaev, Filippov, and Shcherbakov, Dokl. Akad. Nauk SSSR **107**, 236 (1956), Soviet Phys. "Doklady" **1**, 171 (1956).

[32] V. K. Lyapidevskii, Author's Cert. (Patent) No. 100, 754 (1952).

[33] V. K. Lyapidevskii, **Приборы и техника эксперимента** (Instruments and Measurement Engineering) No. 3, 40 (1956).

[34] E. M. Munyon and J. D. Kurbatov, Rev. Sci. Instr. **23**, 380 (1952).

[35] W. J. Choyke and C. E. Nielsen, Rev. Sci. Instr. **23**, 307 (1952).

[36] A. Rogozinski, J. phys. et radium **16**, No. 2, 166 (1955).

[37] O. Gordeev, Thesis, Moscow Physics and Engineering Institute, 1955.

[38] V. K. Lyapidevskii, **Приборы и техника эксперимента** (Instruments and Measurement Engineering) No. 2, 37 (1957).

[39] R. L. Lander and C. E. Nielsen, Rev. Sci. Instr. **24**, 1, 20 (1953).

[40] V. K. Lyapidevskii, J. Exptl. Theoret. Phys. (U.S.S.R.) **30**, 399 (1956), Soviet Phys. JETP **3**, 287 (1956).

[41] V. K. Lyapidevskii, **Физика в школе** (School Physics) No. 1, 47 (1953).

Translated by I. Emin