Optimum and limiting operating conditions for downward diffusion cloud chambers

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Measurements on a diffusion cloud chamber operated with fillings up to pressures of 11 atm are interpreted according to a theoretical treatment by Shutt. The results can be used to determine temperature conditions required for good operation with any permanent gas at all useful pressures and for any given mean radiation intensity. Factors which interfere with normal operating conditions are considered.

The continuous sensitivity of diffusion cloud chambers is achieved by vertical diffusion of vapour through a gas from a warm to a cold part of the chamber, so that an intermediate region is kept sufficiently supersaturated for droplet formation upon ions. This type of cloud chamber was demonstrated by Langsdorf in 1936[1] and has more recently been developed for use in various investigations.[2,3,4] Langsdorf has given a simplified theory[5] which has been extended by Succi and Tagliaferri to explain their results with air at atmospheric pressure.[6] The following results have been interpreted according to a more detailed treatment by Shutt.[7]

CHAMBER CONSTRUCTION

The 9 in. chamber already described[8] has been employed to determine the factors affecting its operation with various gases up to a pressure of 11 atm. To be safe at these pressures the original chamber required some modifications.

The side ports (through which the chamber is illuminated) were strengthened, steel bolts substituted for the brass bolts previously employed to clamp the chamber assembly together, and the $\frac{3}{4}$ in. thick "armour-plate" glass top window was clamped between rubber gaskets so that its free diameter was reduced to 6 in.

The lower part of the chamber was cooled by acetone pumped through copper pipes soldered to the base and a heat exchanger immersed in a slush of solid carbon dioxide and methyl alcohol. Temperature gradients were controlled by three heater wires on the side of the chamber. Additional control of the trough temperature was achieved with another heater wire and by regulating a flow of warm air from the projector lamps to the top of the chamber. Temperature measurements were made with thermocouples in good thermal contact with the well lagged side of the chamber, care being taken to allow time for the chamber to attain its equilibrium condition[9] so that the temperature gradient existing up the steel side of the chamber differed little from that within the gas inside.

A split clearing field ring was employed so that a current could be passed through the wire. Thus excessive condensation on the wire could be prevented with small continuous currents, while larger currents applied for shorter periods enabled the evaporation of any drops formed on the wire.

A 7 μc ^{60}Co γ-source was used to increase the ion load as required, its effect at different distances from the chamber being known, in relation to the normal background, from measurements with a Geiger counter. The normal background was taken as giving rise to about 2 ions per cm^3 per sec in air at N.T.P.

Mixtures of liquids have been used successfully as vapour sources in downward diffusion cloud chambers, but methyl alcohol gives as good or better results than other liquids

so far used separately under working conditions similar to those employed here.[10,11] Also, since Shutt's theory applies to a pure liquid and as he makes special reference to methyl alcohol, this substance was employed for most of the investigation.

THEORY

Shutt has deduced that the vertical temperature distribution required for tracks to be formed in a gas at temperatures below 260° K depends with good approximation on a single parameter

$$\beta_a = \mu_0 D_0^{-\frac{1}{3}} P^{\frac{1}{3}} (n_0 \tau Z P)^{\frac{4}{3}} \quad (1)$$

where μ_0 = viscosity of the gas at 273° K,
   D_0 = diffusion coefficient of the vapour within the gas at 273° K and unit pressure,
   P = pressure (in atmospheres),
   n_0 = number of ions per cm^3 per sec which would be produced in air at N.T.P. by the mean radiation intensity within the chamber,
   τ = number of atoms per molecule of gas, and
   Z = atomic number of the gas.

Further, Shutt's numerical calculations indicate that for a given βa there exists a minimum temperature gradient which will give satisfactory operation.

This theory does not explicitly take account of the formation of neutral condensation nuclei,[12] but Shutt estimates—from an expression derived by Farkas[13]—that for every increase of temperature of 6° K the total number of uncharged nuclei upon which condensation will occur is doubled. He states that by applying an electric sweeping field one can show that at temperatures between 273 and 283° K at the vapour supply there is created of the order of one uncharged drop per cm^3 per sec. Taking this estimate of 1 drop per cm^3 per sec as the value at 273° K, the number of neutral condensation nuclei formed within the chamber per cm^3 per sec is exp $(0 \cdot 116t)$, where t° C is the highest temperature of vapour within the chamber (usually the trough temperature). Now the average number of ions formed per cm^3 per sec within the chamber is, to a fair approximation,

$$n_0 \tau Z P / 14 \cdot 5 \quad (2)$$

Thus the total number of condensation nuclei formed per cm^3 per sec can be taken as

$$(n_0 \tau Z P / 14 \cdot 5) + \exp (0 \cdot 116t) \quad (3)$$

so, to take account of neutral condensation nuclei, the term $(n_0 \tau Z P)^{\frac{4}{3}}$ in equation (1) should be replaced by

$$[n_0 \tau Z P + 14 \cdot 5 \exp (0 \cdot 116t)]^{\frac{4}{3}}$$

giving as the appropriate parameter

$$B_a = \mu_0 D_0^{-\frac{1}{3}} P^{\frac{1}{3}} [n_0 \tau Z P + 14 \cdot 5 \exp (0 \cdot 116t)]^{\frac{4}{3}} \quad (4)$$

Therefore a plot of the minimum temperature gradients

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required for track formation below 260° K(G_a) against the corresponding values of B_a should show points lying on a single curve for all gases, pressures, ion loads and trough temperatures.

EFFECTIVE ION LOAD

Some care is needed in assigning values to n_0 under various operating conditions. Condensation of methyl alcohol occurs preferentially upon positive ions.[14] Thus it is possible to have conditions for which, as can be shown by application of a clearing field, negative ions do not act as condensation nuclei. With the chamber operating with normal background radiation, if the temperature gradient was decreased a state was reached at which even condensation on positive ions occurred only when a clearing field was applied ($\gtrsim 30$ V/cm) so as to prevent positive ions diffusing down into the sensitive region. This condition was taken to correspond to $n_0 = 0 \cdot 5$ ion per cm^3 per sec. With no clearing field, condensation upon positive ions only took place at a higher gradient, while, with this same temperature condition and a clearing field, condensation occurred upon negative ions also. Either of these conditions was assigned the value $n_0 = 1$ ion per cm^3 per sec. Condensation upon negative ions with no field just occurred at a still higher gradient, corresponding to $n_0 = 2$ ions per cm^3 per sec. Similar relations held with ion loads above the normal background values, and again excessive vapour depletion of the sensitive region might occur without a clearing field but satisfactory operation result from the application of the field. Ion loads corresponding to values of n_0 up to $\simeq 50$ ions per cm^3 per sec were employed.

RESULTS

Minimum temperature gradients (G_a) plotted against corresponding critical values of B_a for hydrogen, helium, nitrogen, air and argon are shown in Fig. 1. The full curve shows the relation $G_a = 3 \cdot 3 \log_{10} B_a + 8 \cdot 2$ (° K/cm) with P in atmospheres and other quantities in C.G.S. units. This empirical relation was obtained by plotting G_a against $\log_{10} B_a$. The linear relation between G_a and $\log_{10} B_a$ fits the experimental points quite well and may be used to estimate gradients to within about $0 \cdot 5$° K/cm for operation with methyl alcohol under a wide variety of conditions. Two points shown by asterisks indicate values obtained by Shutt from his theoretical treatment. Four experimental points for n-propyl alcohol are also included on the graph, but further data is required to discover over what temperature ranges similar relations exist for this and other vapours. However, by using the correct values of D_0 for the particular vapour employed, Fig. 1 might serve as a rough guide for initial operation.

Application of Results. The results for methyl alcohol in Fig. 1 are only valid for temperatures below about 260° K. Furthermore, the sensitive region will only extend downwards from the 260° K level if the trough temperature is high enough to provide sufficient vapour for adequate supersaturation of lower regions. Shutt gives an expression for the required vapour density at the top of the chamber which enables the necessary trough temperature (T_1) to be found [see Ref. 7, equation (19)]. This temperature not only depends on the highest temperature at which tracks are required (T_0), but also on the minimum gradient (G_a), since the larger the value of G_a the larger the vapour flux required. Fig. 2 shows T_1 as a function of $G_a(h - x_0)$ where h and x_0 are the heights of the trough and the top of the sensitive region respectively above the base of the chamber. The particular

value $T_0 = 253$° K is chosen here as fairly representative of good operation.

Figs. 1 and 2 provide sufficient information for most requirements. For example, suppose that a sensitive depth $\geqslant 5$ cm is required and that the base temperature can be maintained at 213° K. Then $G \leqslant 8$° K/cm if the top of the sensitive region is to be at 253° K. Table 1 shows how values of the position of the trough and the maximum pressure, for which $x_0 = 5$ cm and $G = 8$° K/cm, vary with trough temperature and radiation intensity for hydrogen and argon.
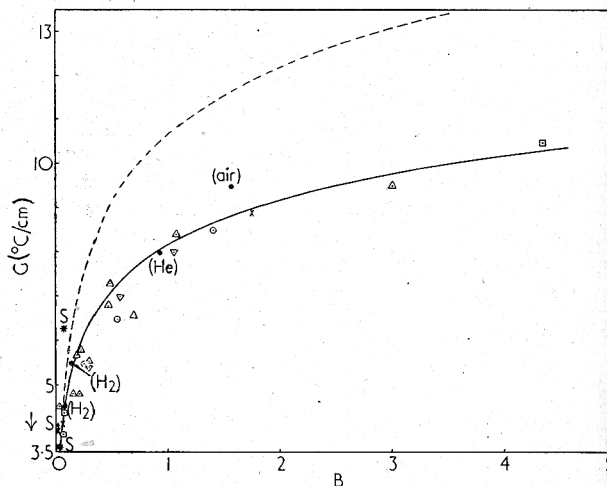

Fig. 1. Dependence of minimum gradients on the parameters B

Full curve: $G_a = 3 \cdot 3 \log_{10} B_a + 8 \cdot 2$
$B_a = \mu_0 D_0^{-\frac{1}{3}} P^{\frac{1}{3}} [n_0 \tau z P + 14 \cdot 5 \exp(0 \cdot 116 t)]^{\frac{1}{3}}$

Dashed curve: approximate $G_b - B_b$ relation
$B_b = \mu_0 D_0^{-\frac{2}{3}} P^{\frac{2}{3}} K_0^{\frac{1}{3}} [n_0 \tau z P + 14 \cdot 5 \exp(0 \cdot 116 t)]^{\frac{1}{3}}$

$\times$ = hydrogen with methyl alcohol. $T_0 < 260$° K
$\odot$ = helium with methyl alcohol
$\triangle$ = nitrogen with methyl alcohol
$\triangledown$ = air with methyl alcohol
$\boxdot$ = argon with methyl alcohol
$\bullet$ = n-propyl alcohol plus gas
*S = Shutt for methyl alcohol
$\downarrow$S = Shutt for methyl alcohol. $T_0 > 260$° K

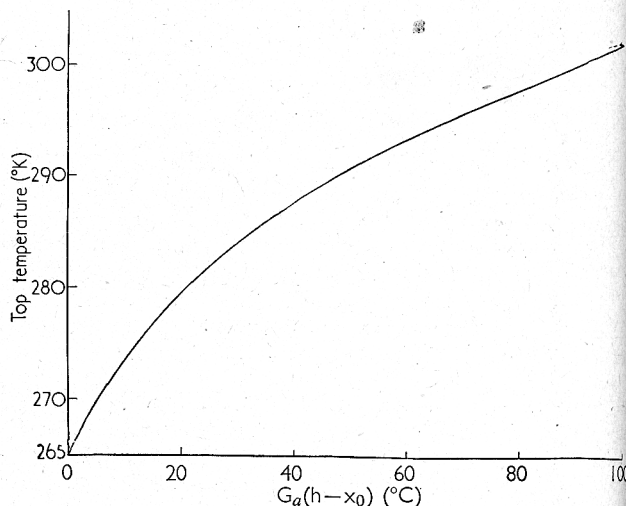
Fig. 2. Position and temperature of trough for track formation at $T_0 = 253$° K

The higher the trough temperature the more important it becomes as a controlling factor, and Table 1 illustrates the advantage of low trough temperatures with correspondingly shallow chambers, although with $h - x_0$ as small as 0·65 cm it is unlikely that a uniform vapour distribution at T_0 can be

Table 1. *Effects of trough temperature and ion load*

Trough temperature (°K)	$h - x_0$ (cm)	Radiation intensity n_0 (ions cm^{-3} sec^{-1})	Gas pressures (atm) hydrogen	argon
300	11·25	2	21	0·51
		1	28	0·56
270	0·65	2	73	5·2
		1	127	9·0

$G = 8°$ K/cm, $T_0 = 253°$ K, $x_0 = 5$ cm

achieved in practice. The pressures for hydrogen contrast with corresponding lower pressures for argon. Thus good results have been obtained by Wyckoff for hydrogen at 50 atm[15] whereas it is difficult to obtain good operation with argon at 10 atm.

Unstable conditions. With high trough temperatures and low gas densities an additional effect occurs. As the top temperature rises the vapour density increases until the total density of gas plus vapour at trough level (ρ_T) exceeds that existing at the top of the sensitive region (ρ_0). Thus warm saturated gas from the vicinity of the trough descends into the sensitive region. Here this gas cools, resulting in a high degree of supersaturation, so that condensation occurs readily upon ions and neutral vapour-molecule aggregates. The latent heat of condensation released during this drop formation is large compared with the heat removed initially from the descending gas before condensation occurs. Most of this latent heat is either conducted away from the drops by the gas or carried down with the drops to the pool of cold liquid covering the base of the chamber.

With hydrogen or helium this unstable condition is revealed by the non-uniform appearance of the sensitive region.[16] Rainy patches in which track formation occurs extend vertically through the sensitive region. They are separated by clear track-free channels. These rainy areas resist saturation by quite large ion loads. They are fairly stable, moving slowly from the side of the chamber, where they usually first appear, towards the centre of the chamber. Here they finally shrink and fade to give way to newer rainy patches moving inwards.

Shutt has considered the normal convection occurring in diffusion cloud chambers. With a uniform temperature gradient gas will rise in the centre and return down the walls of the chamber. No evidence of instability was obtained here except when $\rho_T \geqslant \rho_0$, indicating that the normal convection does not alone result in turbulence. Total gas plus vapour densities were obtained from the relations

$$\left.\begin{array}{l} \rho_T = \left[E \exp \left(B - \dfrac{E}{T_1} \right) \Big/ L T_1 \right] + [MP_g/RT_1] \\[2ex] \rho_0 = \left[E \exp \left(B - \dfrac{E}{T_0} + S \right) \Big/ L T_0 \right] + [MP_g/RT_0] \end{array}\right\} \quad (5)$$

where $\exp [B - (E/T)]$ is the saturated vapour pressure at temperature T, B and E being constants for a particular vapour, L is the latent heat of vaporization of the liquid, M the molecular weight of the gas, P_g the gas pressure and

R the gas constant. In the second of these relations

$$S = \frac{M_v}{RT_0\rho_d} \frac{3}{2} \left(\frac{4\pi\sigma^4}{e^2} \right)^{\frac{1}{3}};$$ σ, ρ_d and M_v being the surface tension, density and molecular weight respectively of the liquid and e the electronic charge. S is introduced into the exponential so that it represents the vapour pressure existing when the supersaturation is that necessary for drop-wise condensation upon ions.

If, just after or at the onset of patchiness for hydrogen or helium, the ion load was suddenly increased, either by bringing a source near the chamber or by setting the clearing field so as to direct positive ions into the sensitive region, the markedly non-uniform droplet distribution thus produced also gave rise to rainy track-forming regions which persisted after the ion load had been reduced again. Thus, while the relatively slow convective movement of vapour-saturated gas down the side of the chamber is normally responsible for the initiation of these circulating regions as the unstable condition is reached, other localized disturbances, such as the uprising of warmer gas from the edge of a droplet cloud and entrainment of gas from above by the densely packed droplets, can have a similar effect.

With nitrogen, air and argon no break-up of the sensitive region occurred even below atmospheric pressure with trough temperatures such that the vapour density at the trough was greater than the gas density. However, the performance of the chamber now appeared to depend on the trough temperature rather than on the temperature gradient at the walls of the chamber. Much background rain was present and relatively large ion loads failed to overload the chamber.

Thus large convection currents are set up when $\rho_T > \rho_0$ but the observed effects depend on the gases. This difference in behaviour is probably connected with the higher thermal conductivity of the lighter gases. The temperature drop between droplets and the gas in which they are formed is least for hydrogen and helium (e.g. Ref. 17), and much more of the latent heat of condensation will be removed by these gases. This rapid heat transfer results in small circulating regions in hydrogen and helium, while the dimensions of the chamber control the extent of circulation in the heavier gases.

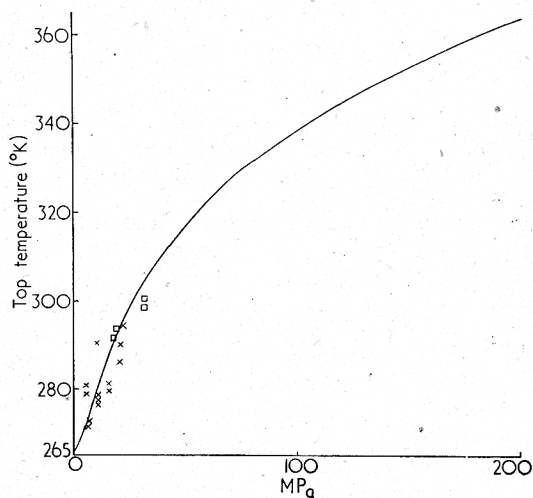Whatever the gas it is therefore necessary, for normal

Fig. 3. Trough temperatures above which normal operation ceases. ($T_0 = 253°$ K)

□ = helium; × = hydrogen

47

operation, that $\rho_T < \rho_0$. The relations (5) then lead to the limiting condition

$$\frac{E}{LT_1}\exp\left(B - \frac{E}{T_1}\right) + \frac{MP_g}{RT_1} = \frac{E}{LT_0}\exp\left(B - \frac{E}{T_0} + S\right) + \frac{MP_g}{RT_0} \tag{6}$$

This gives for methyl alcohol with $T_0 = 253°$ K the relation between T_1 and MP_g shown in Fig. 3. Experimental values of trough temperatures at the onset of patchiness for hydrogen and helium are shown in this figure. These observations can only be expected to agree approximately with the curve, since equation (6) is itself approximate and in practice T_0 was not constant at $253°$ K.

Further Examples. Since it is advisable to employ the lowest trough temperature consistent with other conditions, the limiting temperature above which normal operation ceases is usually important only for the lighter gases below 10 atm or the heavier gases below 1 atm. Table 2 shows

boiled off the wire. After the current was switched off it took several minutes for the chamber to regain its original sensitive state. A clearing field was of no help in dispersing this fog.

Condensation above $260°$ K. For temperatures above $260°$ K Shutt finds that the parameter upon which minimum gradients will depend is

$$\beta_b = \mu_0 P^2 (n_0 \tau Z)^{\frac{4}{3}} D_0^{-\frac{2}{3}} K_0^{\frac{1}{3}} \tag{7}$$

where K_0 is the thermal conductivity of the gas at $273°$ K in cal. cm^{-1} sec^{-1}/° K.

Again, by replacing $(n_0 \tau ZP/14 \cdot 5)$ by $(n_0 \tau ZP/14 \cdot 5) + \exp(0 \cdot 116t)$ as in equation (3) a new parameter

$$B_b = \mu_0 D_0^{-\frac{2}{3}} P^{\frac{2}{3}} K_0^{\frac{1}{3}}[n_0 \tau ZP + 14 \cdot 5 \exp(0 \cdot 116t)]^{\frac{4}{3}} \tag{8}$$

is obtained which should now include the effect of the trough temperature $t°$ C. Only a few results were obtained for this temperature domain. An approximate $G_b - B_b$ relation is shown by the dashed curve in Fig. 1 and a value obtained by

Table 2. *Some critical conditions at limiting top temperatures*

Gas filling		Gas pressure(s) (atm)	Maximum trough temperature (°K)	Radiation intensity n_0 (ions cm^{-3} sec^{-1})	Temperature gradient G_a (°K cm^{-1})	$h - x_0$ (cm)	x_0 (cm) (base at 213°K)
hydrogen	{	3	272	2	3·6	2·2	11
	{	1	268	2	3·5	0·9	11
air		0·5	286	100	9·2	4·0	4
argon		0·25	280	2	3·9	5·4	10
argon + hydrogen		0·25, 1 (respectively)	283	2	about 4·2	6·7	9·(5)

some limiting temperatures indicated by Fig. 3. As further examples of the use of Figs. 1 and 2, gradients and trough positions necessary for good operation at ion loads indicated in the fourth column are also included, together with sensitive depths to be expected with the base at $213°$ K. An example for a mixture of argon and hydrogen illustrates how the addition of a small amount of heavy gas to a light gas enables higher trough temperatures to be employed.[18] Other workers have used trough temperatures down to $253°$ K to avoid instability at low pressures.[19]

Boiling effect. If the temperature of methyl alcohol in the trough is raised to its boiling point (at the particular pressure within the chamber) fine streamers of descending rain are produced within the sensitive region—usually first appearing near the side of the chamber (see also Ref. 10). As the trough temperature is raised further the streamers develop into curtains of rain. No tracks occur in these excessively rainy regions and at still higher trough temperatures the whole chamber is rendered insensitive.

This effect is probably due to the evolution of large numbers of neutral condensation nuclei as the liquid in the trough starts to boil—the streamers arising from a few separate streams of tiny bubbles. Due to the convective movement of gas within the chamber these nuclei will still be concentrated in fairly localized regions after they have been swept down the side of the chamber into the sensitive region. Slightly higher trough temperatures cause more general and vigorous bubbling with an accompanying increase in the spread and amount of rain.

Another demonstration of this effect was made by heating the clearing field ring with fairly large currents after alcohol had condensed upon it. A rain streamer appeared below each drop, while with no visible drops the whole sensitive region rapidly became foggy as small amounts of liquid

Shutt is also indicated (all units as before). For a given gas at a pressure P (atm) with the same top temperature and ion load $B_b/B_a = (K_0 P/D_0)^{\frac{1}{3}}$. With $P < 20$, $B_b/B_a < 0 \cdot 27$ for the light gases and $B_b/B_a < 0 \cdot 20$ for the other gases.

Thus the curves in Fig. 1 show that, for $B_a < 2$ and $B_a < 4$ for the light and heavy gases respectively, with $P < 20$, tracks will be formed above $260°$ K with a lower gradient than is required below this temperature under otherwise similar conditions. However, a large background rain due to neutral nuclei originating from the warm trough will tend to cancel out any advantage arising from a greater sensitive depth. Also, condensation on ions above the $260°$ K level will render ineffective a clearing field operating just above this level which could otherwise be used to prevent charged condensation nuclei entering the lower region from above. After an initial descent of about 1 cm each droplet removes nearly the same mass of vapour per unit distance of fall (Ref. 7, equation (16) and also Ref. 17), so that droplets from the upper region can be allowed for in calculations, by assigning to n_0 for the lower region a value larger than that with an effective clearing field throughout the whole region above $260°$ K.

Two sensitive regions. Consider a uniform temperature gradient extending above $260°$ K. As the ion load or trough temperature is increased, the region below $260°$ K may therefore become overloaded before that at the higher temperatures. This vapour depletion will first show itself at the top of the lower region, since the gradient above $260°$ K, although enabling enough vapour to reach the top of the colder region if the space above is sufficiently supersaturated, may be inadequate once this degree of supersaturation is lowered by dropwise condensation. Therefore, above a certain ion load (and background rain due to the trough temperature), the sensitive region will divide into two parts,

and with further increases in condensation nuclei production the top of the lower region will recede downwards. This splitting of the sensitive region has been observed by Cowan[10] as well as during this investigation.

CONCLUSION

It is thought that the results as presented above for a 9 in. chamber will not differ greatly from those for other downward diffusion cloud chambers operated with methyl alcohol, so that the data and information given should enable the best results to be obtained from existing chambers and assist in the design of others for particular applications.

ACKNOWLEDGEMENT

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