AN APPARATUS FOR THE MAINTENANCE OF A CARBON DUST CLOUD OF CONSTANT CONCENTRATION

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During the course of an investigation of the health risk due to charcoal dust, it became necessary in connection with animal experiments to produce and maintain a cloud of charcoal containing a trace element of concentration and particle-size corresponding to that found under factory conditions. Animals were to be placed in the cloud for a considerable daily period extending over some months, and in order to estimate the dosage applied it was necessary to control the cloud concentration automatically. An apparatus was developed to fulfil these conditions, and as it may have a wider application for the purpose of maintaining a constant concentration of many other types of particulate cloud over a long period, it is described in detail. The physiological work has been completed and is the subject of an internal report of the Ministry of Supply.

Considerations of Cloud Production Method

The accurate determination of the optical size distribution of a cloud of carbon particles in which a considerable degree of aggregation exists is a matter of extreme difficulty and uncertainty. The cascade impactor was used as a comparative instrument, samples being taken of the factory cloud, the relative densities of the deposits on the four graded plates being used as standards. Samples of the experimental cloud could then be taken and compared with the standards, and the particle-size of the cloud adjusted in the appropriate manner. The apparatus used, therefore, had to fulfil the following conditions :

- (a) to simulate the factory cloud the particle-size range must be such that when the cloud is sampled with the cascade impactor, at a flow-rate of 17.5 litres per minute, almost all the deposit is found on the third and fourth plates.
- (b) sufficient cloud must be produced to maintain a concentration of 250 mgm. per cu. m. of carbon in a chamber of 7.8 cu. m.
- (c) the apparatus should be capable of maintaining the cloud for at least 7 hours before recharging with charcoal is necessary.
- (d) The apparatus should be simply controllable in order to facilitate the application of a suitable regulating device to ensure constancy of cloud concentration.

- (e) In order to ensure the continuity of the experiment from the physiological viewpoint the apparatus must be comparatively trouble-free over a period of 700 hours at 7 hours per day on a 6-day week basis.

Method of Cloud Production

The apparatus finally developed is shown in fig. 1. The cloud is produced by the attrition of charcoal in the rotating drum, which is enclosed by the hood, and is then blown into the cloud chamber as shown by the arrows on the figure. The drum consists of a cylinder of 8 inches diameter and 10 inches length, the side being made of 22 mesh 26 S.W.G. copper gauze, and the end plates of $\frac{1}{8}$ inch thick sheet iron. Inside the drum the three radial vanes pour the charcoal and produce attrition as the drum rotates. The drum rests upon rubber-covered rollers, one of which is rotated by means of an electric motor. The second roller is merely an idle rotating support. The enclosing hood is fitted with an air intake and exit, the former being connected to the centrifugal blower drawing its supply of air from the cloud chamber. The exit rises vertically for 9 inches and is then led horizontally into the cloud chamber. This vertical rise is designed to remove the larger particles by elutriation, and the horizontal section performs the same function by sedimentation. Since the air supplied to the drum is derived from the cloud chamber and therefore contains considerable carbon cloud, the drum mechanism is enabled to maintain higher concentrations in the cloud chamber than would otherwise be possible, i.e., the system is regenerative. The drum is taken out through one side of the hood, which is detachable, and charged with charcoal after the removal of one end plate. The normal charging of granules is approximately one-third of the volume of the drum, the granules being of the order of 1.84 mm. in diameter. Debris from the ground charcoal is sieved through the side of the drum and accumulates on the floor of the hood ; this has to be removed at about 20-hour intervals.

Particle-size Distribution. As described in the previous paragraph, favourable conditions are obtained for the removal of the larger particles in the cloud by elutriation and sedimentation. A comparatively sharp cut-off is obtained on the maximum particle-size by control of the air stream

FIG. 1.—Diagram showing drum and roller. (Hood shown in dotted lines.)

velocity, varied by adjustment of a series resistance in the centrifugal blower circuit. This was adjusted until an accurate simulation of the size distribution of the factory cloud was obtained.

Control of Output. Since for the purpose of animal experiments the required cloud concentration was about three times the factory peak conditions, and since it was also desired to use only one drum for economy and simplicity, it was essential to achieve the maximum output. As the speed of rotation of the drum increases there is a progressive rise in output due to increasingly violent pouring and churning of the charcoal granules. On reaching some critical speed, centrifugal forces begin to take control and prevent the pouring from taking place, the system tending to rotate as a rigid whole, and causing a rapid diminution in output. Fortunately, the onset of the centrifugal effect is made apparent by a change in the sound emitted

by the drum. It was therefore a simple matter to adjust a series resistance in the motor circuit to give to optimum speed of rotation for maximum output. A difficulty arose due to the drum motor being unable to start unaided from rest with the resistance adjusted as described above. Since regulation of cloud concentration was achieved by automatic switching of the drum motor at frequent intervals, this difficulty had to be overcome, and was obviated by temporarily short-circuiting the control resistance on starting. The device used is shown in fig. 2. When the regulator closes S_1 , current flows directly to the motor through the closed mercury switch S_2 . At the same time the solenoid is energized and withdraws the iron plunger from the mercury, and immediately mercury begins to flow from the reservoir, through the capillary, equalizing the level in the two arms. Conditions can be arranged so that after 10 to 12 seconds the level falls below the upper contact S_2 , thus breaking the circuit.

FIG. 2.—Motor starting switch.

The motor then receives its supply through the control resistance R , and this state continues so long as S_1 remains closed. On S_1 opening, the plunger falls, closing S_2 , and the device is reset for a fresh cycle of operation.

The Requirements for the Regulator

For the purpose of physiological experiments,

and having due regard for the probable accuracy of routine chemical estimation, it was decided that stabilization of cloud concentration to within ± 5 per cent. of the required value would be sufficient. The simplest method of achieving this result is to switch the drum motor on and off at suitable intervals in the manner of a thermostat heater. The controlling element chosen was a photocell in conjunction with a source of constant illumination, arranged so that the cloud obscured some of the light from the lamp before reaching the photocell. The photocell current then depends on the optical density of the cloud. The limitations of this controlling element depend principally on the degree of constancy obtainable in the light source; experiment shows that a 75-watt lamp bulb driven by a 150-watt 'Advance' constant voltage transformer exhibits maximum fluctuations of about ± 3 per cent. in candle-power with normal A.C. supply mains fluctuations. The equivalent change in cloud concentration to produce the same change at the photocell is approximately ± 3 per cent., and so for the differential cloud concentration to be not greater than ± 5 per cent. the drum motor should be switched with about 2 per cent. change in illumination of the photocell. In practice this necessitates considerable amplification between the photocell and the relay controlling the drum motor. These considerations led to the design of the photocell relay described in the next section.

The Regulator. The optical system of the regulator is very simple, consisting only of a 75-watt lamp

FIG. 3.—The Regulator.

V_1 = MADZA P.E.8.	R_1 = 10 M Ω .	R_{10} = 2215 Ω .
V_2 = OSRAM H.63. OR Am. 6F5G.	R_2 = 50,000 Ω .	C_1 = 0.1 μ F.
V_3 = OSRAM GTIC	R_3 = 1 M Ω .	C_2 = 1.0 μ F.
S_1 = SUNVIC VACUUM SWITCH.	R_4 = 20,000 Ω .	
TDS = THERMAL DELAY SWITCH (BULGIN).	R_5 = 5,000 Ω .	
T_1 = 'ADVANCE' CONSTANT VOLTAGE TRANSFORMER 230 V 150 WATT.	R_6 = 250 Ω .	
T_2 = 0/230. 4V. 1.5A. AND 6.3V. 1.5A.	R_7 = 6,000 Ω .	
L = 75 WATT. 230V. LAMP BULB.	R_8 = 0.25 M Ω .	
	R_9 = 0.25 M Ω .	

bulb, a portion of whose filament is focused with a single condenser lens on to the photocell, about $1\frac{1}{2}$ metres distant. The circuit diagram of the complete regulator is shown in fig. 3. T_1 is an 'Advance' 150-watt constant voltage transformer of 230 volts output, V_1 is the photocell, V_2 the amplifier, V_3 a thyratron, and S_1 a hot wire vacuum relay whose contacts control the drum motor through the starting switch S_2 . The operation of the circuit can best be described by assuming some light to fall on V_1 , and considering the state of affairs at successive A.C. half-cycles. Take first the half-cycle when B is positive and A negative. V_1 passes current producing a voltage drop across R_1 so that the top plate of C_1 is negative with respect to the bottom plate. The time constant R_1C_1 is long compared with $1/50$ th second, so that the voltage across C_1 remains practically constant over one cycle.

Now consider the next half-cycle when A is positive with respect to B. V_2 now conducts, and its grid bias is controlled from three sources, and hence its anode current depends on three factors. Negative A.C. bias is derived from R_7 , R_6 ; positive A.C. bias is derived from R_3 , $(R_2 + R_4 + R_5)$, and this is variable; negative D.C. bias is derived from R_1C_1 controlled by V_1 as described above. The two A.C. biases partially counter-balance one another and are used so that R_1 may be made large to obtain a large voltage output from V_1 . The anode current of V_2 produces a voltage drop across R_8 charging C_2 with the polarity shown in fig. 3, and the time constant of R_8C_2 is again large compared with $1/50$ th second.

Now consider the next half-cycle when B is again positive with respect to A. V_3 now conducts over part of the half-cycle—as controlled by the voltage across C_2 —and the resulting anode current will flow through the hot wire control of S_1 . Obviously at some value of anode current through V_3 the switch S_1 will close, thus turning the drum motor on, and this point is controlled by the grid bias of V_2 . Thus by adjustment of R_4 and R_5 , 'fine' and 'coarse' respectively, the additional D.C. bias required from V_1 to close S_1 can be varied, and hence the cloud concentration at which S_1 opens and closes can be varied at will. In other words the cloud concentration can be varied by adjustment of R_4 and/or R_5 after which it will be stabilized at the new concentration without further adjustment of the apparatus.

On striking, V_3 takes appreciable grid current which tends to charge C_2 with polarity the reverse of that shown in fig. 3. If $R_9 = 0$, then at the firing point the grid current of V_3 is more than the anode current of V_2 , so that the latter current must be increased to a greater value than V_3 's grid current before S_1 can open. In practice this means that there is some 'backlash,' i.e. the opening and closing illuminations are somewhat different. This 'backlash' or differential can be reduced or eliminated by making R_9 large. In practice it was found desirable to make R_9 variable so that the

on/off period could be partially controlled. With no 'backlash' (i.e. R_9 very high) a change of illumination of about 0.2 per cent. was required to operate S_1 , and since there were continual small fluctuations in the illumination, S_1 was opened and closed as often as once in two or three seconds, which was inconveniently frequent. The operator must strike a balance between too little 'backlash,'

FIG. 4.—Block Diagram of Automatic Control.

unduly frequent operation, and too much poor regulation. In use this presents no difficulty.

One or two further points should be noted. The values of the resistances controlling the bias of V_2 will depend on the amplifier valve type chosen, the type of photocell used, and the illumination available. The values shown in fig. 3 were those used with the components shown and the illumination available at a cloud concentration of 250 mg. per cu. m. The thermal delay switch (T.D.S.) is used to allow V_3 to heat up for $\frac{1}{2}$ minute before applying anode potential. This is the manufacturer's recommendation for cathode preservation and T.D.S. also provides some protection against temporary supply failure. T_2 is a small transformer used to supply the heaters of V_2 , V_3 , and T.D.S.—two separate windings are required. R_{10} is adjusted to prevent overload of the hot wire section of S_1 . It may be mentioned in passing that this regulator or photocell relay may be used for other purposes than that described herein, to operate stably with changes of 0.5 per cent. upwards. It would be of especial use when considerable illumination is available, heavy loads must be switched, and a time lag (due to S_1) of one or two seconds is not objectionable.

V_4 = 6J7G. (TRIODE CONNECTED) A.m.
 V_5 = 6J7G. (TRIODE CONNECTED) A.m.
 V_6 = OSRAM H.63. OR A.m. 6F5G.
 V_7 = MULLARD 7475.
 V_8 = MAZDA P.E.8.

R_{11} = 5 M Ω .
 R_{12} = 0.03 M Ω .
 R_{13} = 0.03 M Ω .
 R_{14} = 0.075 M Ω .
 R_{15} = 0.025 M Ω .
 R_{16} = 0.015 M Ω .
 R_{17} = 0.01 M Ω .
 R_{18} = 0.03 M Ω .

FIG. 5.—Check Photometer.

The regulator has been in continual use for four months and has performed for about 700 hours. In that time one switch (S_1) has failed (it was in poor condition initially), one lamp has failed, one thyatron (V_3) has failed, and one resistance (probably initially faulty) has failed. Apart from these failures the only attention the regulator has required has been periodical cleaning of the lamp bulb. In use this became sooted over with charcoal, reducing the illumination, and hence the cloud concentration. No really satisfactory static self-cleaning device was developed, but something in the nature of a motor car wind-screen wiper would have been convenient. For the major portion of the running period the regulator was unattended.

Fig. 4 shows the general layout of the apparatus in diagram form. Details of the drum are shown in fig. 1, the starter switch in fig. 2, and the photocell amplifier and relay in fig. 3. The rest of the diagram is self-explanatory. A perspective view of the complete apparatus is shown in fig. 6. Fig. 7

shows a view of the cloud chamber, the animals being placed on wire netting shelves.

A Simple Check Photometer

It was thought desirable to have a check upon the absolute cloud concentration which might change due to the relative movement of the lamp and photocell on cleaning. In a more rigid optical arrangement this could perhaps have been avoided. To provide such a check a simple linear photometer was designed and constructed, the circuit diagram of which is shown in fig. 5. Additionally, the check photometer could be used to maintain the cloud with manual switching of the drum motor in the event of regulator breakdown.

V_8 is a photocell identical with V_1 and viewing the same lamp (fig. 3) through a portion of the cloud. Before starting the regulator each morning the meter M (50 μ A. 1500 Ω) was adjusted to zero with R_{15} (i.e. with no cloud). Then on production of cloud the illumination on V_8 fell, producing a

change of voltage at V_4 's cathode, and hence an arbitrary reading on M. The cloud was adjusted by alteration (if required) of R_4/R_5 (fig. 3) until the regulator stabilized the cloud at a fixed but arbitrary reading of M. V_6 and V_7 provided a stabilized high tension voltage derived from the D.C. mains supply, which is further stabilized by the cathode follower connection of V_4 and V_6 so that variations in the supply input voltage are reduced by a factor of about 2000 before being applied to the meter.

Performance

Samples of the cloud were taken on filter paper and the concentration found by estimation of the trace element. In separate experiments the trace element/charcoal ratio was determined for (a) supply, (b) the sieved debris and (c) the sedimented cloud. The ratio was found to be sensibly constant within the limits of estimation error, showing that no alteration of the trace element/carbon ratio had taken place. In practice a sample was taken on each day's run as a check on the absolute concentration. In addition, pairs of samples were taken at hourly intervals on each of three days to check the performance of the regulator. A statistical analysis of the results showed that the required aim of

± 5 per cent. in the cloud concentration was achieved.

In addition to the regulator failures mentioned previously, in 700 hours one drum side was worn out and replaced by a spare, and the rubber of the rollers was renewed once. None of the failures was serious, the only fault causing a delay of more than a few minutes running time was the breakdown of the rubber rollers. Subsequently it was found that insulation tape was more durable, gave a better drive than rubber and was very much easier to replace. This fault caused a loss of one day (7 hours) in running time, and afforded an opportunity for a general overhaul. Care should be taken to prevent carbon from depositing on the electrical circuits and all apparatus should be earthed and circuits adequately supplied with fuses.

Results

The standard deviation σ_c of the chemical estimation and sampling errors was estimated by taking all samples in duplicate. The standard deviation of the overall variation of the results σ_r was calculated and hence the standard deviation of the regulator σ_R obtained. The calculated value of σ_R was 2.27. If the normal error curve is assumed, the apparatus

FIG. 6.—Control Chamber.

FIG. 7.—Cloud Chamber.

will be within ± 2.27 per cent. of its adjusted value for 68 per cent. of the running time, and within ± 4.45 per cent. during 98 per cent. of the running time. As large departures from the mean (except for breakdowns) are impossible, the figure of ± 5 per cent. can be regarded as the outside limit of error.

Summary

An apparatus has been developed for the production of a carbon dust cloud in connection with physiological research on health hazard in charcoal filling factories. The cloud was produced by the attrition of charcoal in a rotating drum, and the maximum particle-size adjusted by elutriation. The drum was driven by a motor switched in the manner of a thermostat heater by a

photoelectric relay controlled by the optical density of the cloud. The whole system provided a cloud of concentration $250 \text{ mg./m.}^3 \pm 5$ per cent. in a specially constructed chamber of 7.8 cu. m. for a period of 700 hours (7 hours/day). The apparatus was largely unattended except for a short daily period of standardization at the beginning of each run, and a second period of a few minutes at midday.

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