METHOD AND APPARATUS FOR PRODUCING AEROSOLS

Filed March 24, 1943 2 Sheets-Sheet 1

Fig.1.

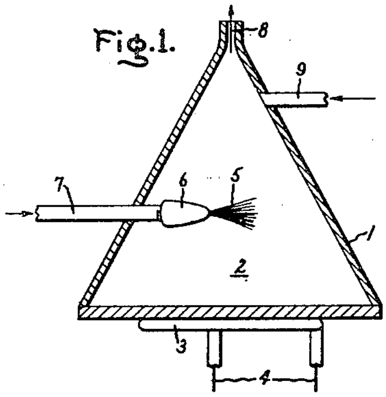


Fig.2.

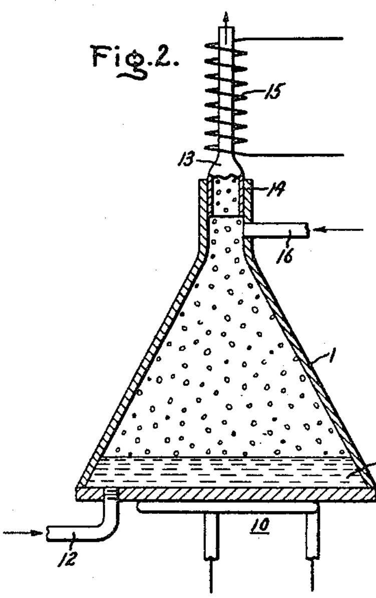


Fig.3.

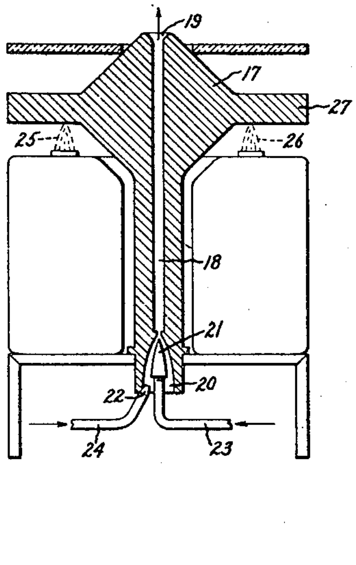


Fig.4.

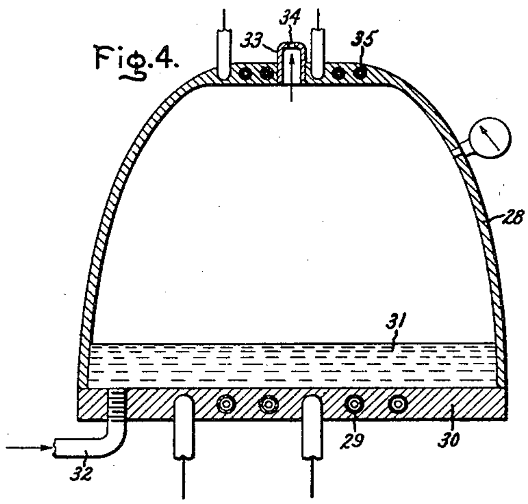
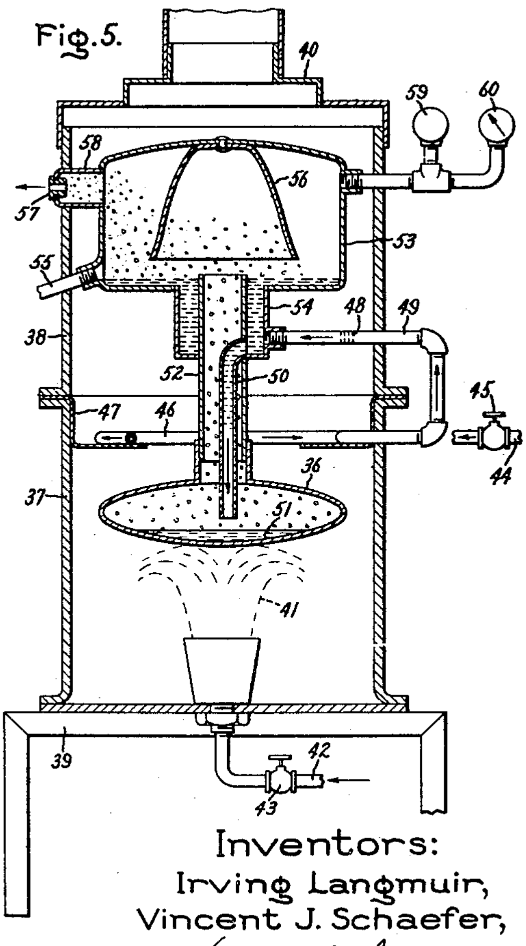


Fig.5.



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March 16, 1948. I. LANGMUIR ET AL 2,437,963

METHOD AND APPARATUS FOR PRODUCING AEROSOLS

Filed March 24, 1943 2 Sheets-Sheet 2

Fig.6.

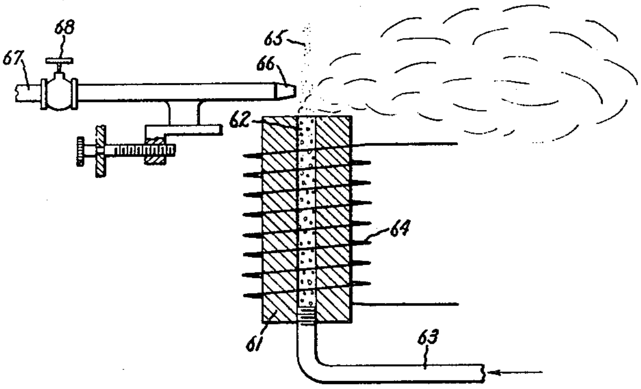
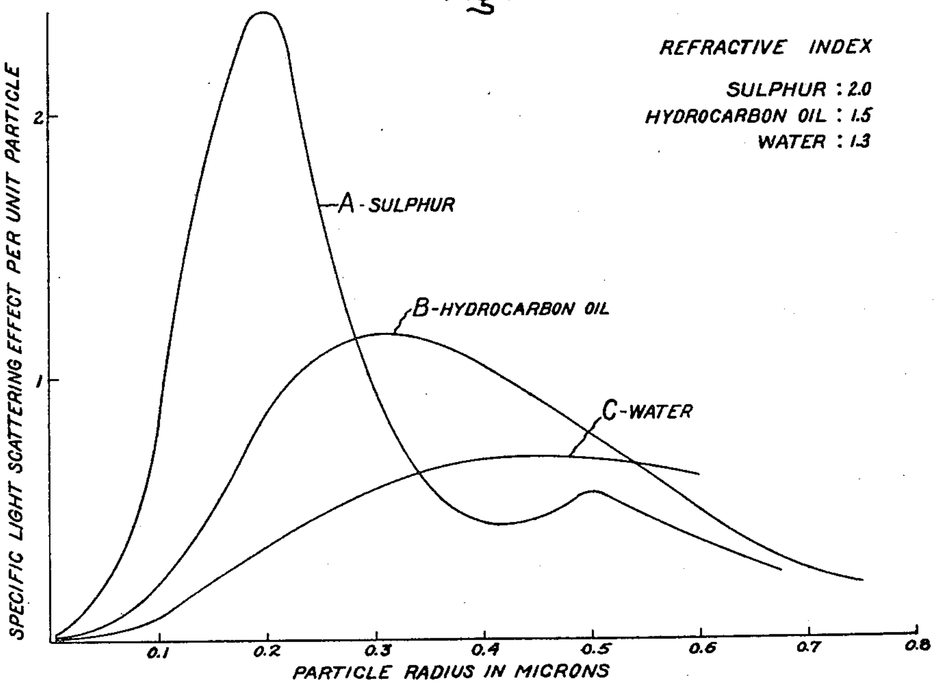


Fig.7.



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UNITED STATES PATENT OFFICE

2,437,963

METHOD AND APPARATUS FOR PRODUCING AEROSOLS

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Application March 24, 1943, Serial No. 480,302

6 Claims. (Cl. 252—359)

1

Our invention relates to methods and apparatus for producing suspensions of solids or liquids in an atmosphere such as air, and more particularly to methods and apparatus for producing aerosols of controllable character.

Heretofore, apparatus and methods used for the production of suspended liquids or particles in gas or an atmosphere such as air, have been characterized by the lack of uniformity in the aerosols so produced and by difficulty in obtaining reasonable efficiencies and effectiveness. For example, in the prior art arrangements used for the production of smoke-screens of visually opaque fogs, the generators have not been able to produce appreciable quantities of the smoke without using an inordinate amount of material or fluid and consequently have entailed the use of an excessively large number of units or generators to produce an appreciable screening effect. Even when large numbers of such prior art units have been used in an attempt to blanket an appreciable area, these arrangements have not been satisfactory due to the inability of the generators to produce striation-free screens and the further inability to effect a reasonable scattering or dispersion of light required to attain satisfactory screening.

It is an object of our invention to provide new and improved methods and apparatus for the production of aerosols or suspensions of matter such as fluids in an atmosphere.

It is another object of our invention to provide new and improved methods and apparatus for controlling the size of particles or droplets constituting an aerosol.

It is a further object of our invention to provide new and improved methods and apparatus for obtaining the maximum obscuring power of an aerosol by controlling the droplet size whereby it is made possible to use a variety of available substances or materials.

It is a still further object of our invention to provide new and improved methods and apparatus for the utilization of hydrocarbon fluids in the production of visually opaque aerosols.

Briefly stated, in accordance with our invention we provide methods and apparatus for the production of suspended matter, such as vaporized liquids, in an atmosphere which may be air, and in which the average size of the suspended particles or droplets of the suspended matter is readily determinable and controllable. Although not limited thereto, one example of a use of our invention is the production of visually opaque smoke screens or fogs for naval or military purposes.

Considering more particularly one aspect of the methods which we provide, it may be stated generally that the light scattering effect of an aerosol may be controlled by controlling the size or

2

diameter of the particles or droplets constituting the aerosol. The maximum obscuring power or opacity to visual light may be obtained by controlling the particle size to have that value which for the particular material employed will produce the maximum specific light-scattering effect per unit particle or mass. Furthermore, the particle sizes of an aerosol may be controlled to render the aerosol discriminatory or selectively pervious to radiations of predetermined wave lengths, such as infra-red radiation, while maintaining a substantial visual opacity.

In accordance with one feature of the illustrated embodiments of our invention, we provide apparatus to produce aerosols of which the average particle or droplet size is readily controllable. In illustrated embodiments of our invention, a relatively high velocity is imparted to a vaporizable material such as a hydrocarbon liquid, in vaporized state, whereby the vapor is rapidly cooled or chilled to control the rate at which the smaller droplets condense or coalesce on the larger droplets and hence limit the time during which coagulation occurs, thereby limiting the average size of the droplets constituting the aerosol, the characteristics of which it is desired to control or determine.

One way in which the production of an aerosol comprising suspended particles of optimum size may be produced in accordance with our invention is to vaporize a material, such as a hydrocarbon liquid, in a substantially enclosed chamber and to eject the gas or vapor through an aperture or nozzle at high velocity into an atmosphere of lower temperature such as air which effects rapid cooling of the vapor and, hence, limits the average size of the droplets. We have found that for a given vaporized material ejected into the atmosphere through an orifice or a nozzle, a minimum optimum value of average droplet radius is produced, when the velocity of ejection is equal to the acoustic velocity for that material which is established for a particular nozzle or orifice operating at pressures equal to or greater than the critical orifice or nozzle pressure.

The vaporized material may be ejected into an atmosphere either by pressure of the vaporized material itself within an enclosed chamber or by vaporization in conjunction with the application of auxiliary fluid pressure, such as air pressure, acting on the vapor or gas within the chamber. Optionally, the material may be vaporized at low pressure, such as under atmospheric conditions, and the high velocity of the vaporized droplets attained by causing a jet of a high velocity fluid or gas, such as air, to move the vapor rapidly thereby causing appreciable turbulence to control or limit the extent of droplet growth.

Alternatively, the aerosols produced in accordance with our invention may be made by atomizing a liquid within a chamber, and applying heat thereto thereby causing vaporization of the liquid which is then ejected through an orifice or nozzle into the atmosphere.

For a better understanding of our invention, reference may be had to the following description taken in connection with the accompanying drawings, and its scope will be pointed out in the appended claims. Fig. 1 of the accompanying drawings diagrammatically illustrates an embodiment of our invention wherein a vaporizable material or substance, such as a hydrocarbon liquid, is atomized in a heated chamber and wherein the vaporized material is ejected into an atmosphere, such as air, at sufficient velocity in order to produce an aerosol of predeterminable character, that is, one in which the particles or droplets have determinable or controllable diameters. Fig. 2 diagrammatically illustrates another embodiment wherein a vaporizable liquid is boiled within a substantially enclosed chamber and in which the vaporized liquid is ejected into an atmosphere through a heated tube at high velocity to produce an aerosol. Fig. 3 is a modification of the arrangement shown in Fig. 1 wherein a jet of vaporizable material mixed with a compressed gas, such as air, is heated within an elongated heating tubular structure and ejected into an atmosphere, such as air, at sufficient velocity to produce an aerosol. Fig. 4 is a still further embodiment which is a modification of the arrangement shown in Fig. 2. Fig. 5 diagrammatically illustrates a still further modification of our invention wherein a vaporized liquid is ejected into an atmosphere to produce an aerosol and wherein the apparatus comprises a boiler, preheat means for the liquid and a vapor chamber or pressure chamber provided with a nozzle. Fig. 6 is a further simplified modification of our invention wherein a vaporizable fluid is vaporized at relatively low pressures and ejected into an atmosphere, such as air, and wherein a high velocity is imparted to the vapor by means of an external positionable source of compressed gas, such as air, and wherein the size of the droplets constituting the aerosol is controllable or determinable by controlling the position of the jets of compressed gas with respect to the column of gas emanating from the heating structure. Fig. 7 generally illustrates the relationship which exists between the light scattering effect of exemplary suspended particles as a function of the radii of the particles.

In the development of our invention, certain theoretical considerations as to the growth of particles or droplets in an aerosol have evolved, and prior to a detailed consideration of the various embodiments of our invention it is believed appropriate to review generally these fundamental considerations.

In an aerosol, smoke, or fog, the particles or droplets of such suspensions have non-uniform sizes; that is, there will be a variety of sizes, the small droplets having a higher vapor pressure than the larger droplets. Thus, in an aerosol or smoke consisting of particles of different sizes, the small droplets tend to evaporate and produce supersaturated vapor which condenses or coalesces on the larger particles. Therefore, the small droplets disappear and the material from them is delivered to the larger drops. As a result, in any aerosol or smoke with particles of non-uniform size, the number of particles continually decreases if the vapor pressure is sufficiently high and the average size thereof increases.

In aerosols used as smoke-screens, it is essential in order to obtain the maximum opacity to light that the particles of the aerosol should have an average size properly correlated with respect to the light-scattering effect as a function of droplet size or diameter. Of course, each suspension, by virtue of its refractive index, has a particular relationship between the scattering effect and the average particle size. A curve for each such material or fluid representing relationship between the scattering effect and the particle size indicates values at which the maximum obscuring power or scattering effect is obtained. As a general matter, Fig. 7 may be referred to wherein the curves A, B and C represent the relationship between the specific light scattering effect per unit mass or particle and the particle radius for suspensions of materials having different refractive indexes. Curves A, B and C represent, respectively, the light-scattering effects of sulphur, an hydrocarbon liquid and water as a function of particle or droplet size. It will be observed that the maximum obscuring power, that is the maximum specific light-scattering effect, occurs at different particle sizes for the respective materials.

In view of the above, in the determination and control of the particle size, it is of importance to have knowledge of the rate at which the growth of the particles occurs. Considering a single small particle or droplet of radius r in the presence of a large number of relatively large drops, the total force of surface tension acting on the perimeter of a circle (equator) having its center at the center of the drop is $2\pi r\gamma$, where γ is the surface tension of the liquid constituting the drops. This force must be compensated by an internal pressure p_1, inside the drop. Consequently,

$$p_1\pi r^2=2\pi r\gamma$$

or

$$p_1=\frac{2\gamma}{r} \qquad (1)$$

For the purpose of lending particularity to the discussion, without limiting the applicability of the theoretical and practical considerations, let it be assumed that the droplets under consideration are constituted of a hydrocarbon fluid or oil of a radius equal to 0.3 micron (3×10^{-5} cm.). The surface tension at room temperature may be taken to be 31 dynes per sq. cm. Thus, the pressure within the droplet is 2.07×10^6 dynes per sq. cm., or about two atmospheres above atmospheric pressure.

One effect of this internal pressure is to increase the tendency of the liquid to escape from the droplet, resulting in an increase of the vapor pressure because such action allows the escape of the liquid from the droplet. The free-energy change per molecule due to the internal pressure is p_1 times the volume per molecule which is

$$\frac{p_1M}{N\rho}$$

where M is the molecular weight (about 304 for an assumed hydrocarbon fluid under consideration), ρ is the density (0.896) thereof and N is the Avogadro constant 6.06×10^{23}. The increase in free-energy is also equal to:

$$kT\ln\left[\frac{(p_0+\Delta p)}{p_0}\right]$$

where k is the Boltzmann constant 1.37×10^{-16}, T is the absolute temperature, p_0 is the normal vapor pressure at this temperature, Δp is the increase in vapor pressure resulting from the internal pressure, and $1n$ is the natural logarithm.

By equating the above two energy changes, there is obtained:

$$KT1n\left[\frac{(p_0+\Delta p)}{p_0}\right]=\frac{2\gamma M}{rNp} \qquad (2)$$

For a droplet of a hydrocarbon fluid such as that considered above having a radius of 0.3 micron, it is found from Equation 2 that a room temperature (293° K.) the value of

$$\frac{\Delta p}{p_0}$$

is 0.0306. Thus, the vapor pressure of a droplet of this size is increased 3.06 per cent because of internal pressure. Since in general under the conditions of interest in this problem,

$$\frac{\Delta p}{p_0}$$

is always far less than unity we can reasonably state that

$$1n\left[\frac{(p_0+\Delta p)}{p_0}\right]$$

is equal to

$$\frac{\Delta p}{p_0}$$

and Equation 2 above becomes:

$$\Delta p=\frac{2M\gamma p_0}{N\rho KTr} \qquad (3)$$

The increased vapor pressure Δp of the droplet in the presence of surrounding saturated vapor tends to cause the droplet to evaporate. The evaporation of small spheres is limited to the rate of diffusion of the vapor from the surface of the sphere (see Irving Langmuir, Physical Review No. 12,368 (1918). Thus the rate of change in the radius of the droplet is given by:

$$r\left(\frac{dr}{dt}\right)=-\frac{MD\Delta p}{N\rho KT} \qquad (4)$$

where D is the diffusion coefficient of the vapor in air which for the hydrocarbon liquid mentioned above at about 0.03 cm.^{2} per sec. at 20° C. or 0.08 cm.^{2} per sec. at 200° C. Combining Equations 3 and 4 there is then obtained:

$$r^2\left(\frac{dr}{dt}\right)=-2\left(\frac{M}{N\rho KT}\right)^2 D\gamma p_0 \qquad (5)$$

By integration of Equation 5 between the limits, $r=r_0$ and $r=0$, we can caluculate the time t needed for the complete evaporation of a droplet which has an initial radius r_0. The time for complete evaporation is given by:

$$t=\frac{\left(\frac{N\rho KT}{M}\right)^2 r_0^3}{6D\gamma p_0} \qquad (6)$$

Therefore, the life of a droplet in a saturated vapor varies in proportion to the initial volume of the droplet and varies approximately inversely as the normal vapor pressure p_0.

As a rough, but provisionally sufficiently good approximation, the vapor pressure p_0 of a hydrocarbon fluid at absolute temperature T may be stated as:

$$\log_{10} p_0=11.1-\frac{5.1T_B}{T} \qquad (7)$$

where T_B is the absolute mid-boiling point of the hydrocarbon fluid. For a particular hydrocarbon fluid heretofore considered in this discussion, T_B may be considered as 700° K. (427° C.) resulting in:

$$\log_{10} p_0=11.1-\frac{3570}{T} \qquad (8)$$

At 200° C. (473° K.), this indicates a p_0 of 3570 dynes per sq. cm. (2.7 mm. of mercury), but at 20° C. (293° K.) p_0 is only 0.08 dyne per sq. cm. (or 0.00006 mm. of mercury).

Inserting the above values of p_0 into Equation 6 together with

$$\gamma=20.2$$
$$D=0.08 \text{ at } 200° \text{ C}$$

and

$$\gamma=31$$
$$D=0.031 \text{ at } 20° \text{ C.}$$

we find that the life of a particle having a radius of 0.3 micron in saturated vapor would be only 0.0106 second at 200° C., but would be 300 seconds at 20° C. At higher temperatures, such as 300° C., the life of the particle or droplet would amount to only 0.00076 second. Consequently, the transfer of material from the small droplets to the larger particles can be made an extremely rapid process at temperatures of 200° to 300° C., where the vapor pressure is of the order of 0.003 to 0.07 atmosphere (or 2.7 to 56 mm. of mercury). It is thus apparent that to prevent the growth of particles to sizes greater than an optimum diameter such as 0.3 micron, which produces a maximum obscuring power or opacity to light for the above described hydrocarbon vapor, it is desirable to chill or cool the vapor from a boiling temperature of vaporized hydrocarbon extremely rapidly within a few milli-seconds.

We have found that one way to limit the growth of particles and to attain the optimum size or diameter thereof is to allow a vapor to escape from a small aperture, orifice, or nozzle under high pressure. Due to the intense turbulence incident to the presence of the high pressure jet, admixture with cold air occurs at very high speed, thereby satisfying the above described requirement as to time of cooling to prevent growth.

Another way of accomplishing the same results is to allow the vapor to issue at lower pressure from a nozzle but causing the impingement of an intense jet of compressed gas or air against the vapor jet immediately as it escapes from the aperture or nozzle. In this manner, a high velocity is imparted to the vapor jet, controlling the rate of cooling thereof and consequently controlling the particle size.

Other methods of producing an aerosol comprising particles or droplets of controllable size may also be employed. For example, a vaporized fluid may be atomized within a heated chamber and ejected into the atmosphere either with or without the use of additional means for exerting a pressure within the chamber.

Referring now to Fig. 1 of the accompanying drawing, our invention is there illustrated as applied to an arrangement for producing an aerosol which comprises a container or enclosing member 1 which may be constructed of metal defining a substantially enclosed chamber 2. The container 1 is heated by a suitable means which may comprise an electric heating element 3 energized from a suitable source of electric current 4. A jet 5 of vaporizable fluid in atomized form is injected into the chamber 2. This atomized jet 5 may be produced by means of a suitable nozzle 6 supplied with the fluid through a conduit 7. The temperature of the chamber 2 is sufficiently high to effect rapid vaporization of the fluid, and the vapor is ejected at high velocity through an aperture, orifice or nozzle 8 preferably located at the top of member 1.

Control of the velocity at which the jet of vapor emanates from the chamber 2 may be obtained by the use of an auxiliary source of compressed gas or air which is in communication with chamber 2 through a conduit 9. The use of such auxiliary means is optional and the desired pressure within the chamber 2 may be obtained by utilization of the pressure incident to the vaporization of the fluid. Of course, in order to assure a desired constant supply of the fluid in atomized form the fluid within conduit 7 should be subjected to a reasonable pressure.

Fig. 2 diagrammatically illustrates a further embodiment of our invention wherein an aerosol is produced by boiling a vaporizable fluid within a container 1 which is heated by suitable means such as an electric heating coil 10. A substantially constant level of the vaporizable fluid 11 is maintained in the bottom of the container and is supplied thereto through a conduit 12 in which the fluid is maintained preferably at a substantially constant pressure.

Increase in the temperature and pressure of the fluid emanating from the container is obtained by means of a metallic tubular member 13 joining an outlet 14 of the container. The temperature of the tubular member 13 and hence the temperature of the emanating vapor is controlled by suitable heating means such as an electric heating coil 15 which is preferably wound about the tubular member in order to effect substantially uniform spatial distribution of temperature.

The pressure acting within the tubular member 13 and hence the velocity at which the vapor jet emanates from the upper end of the tube is controllable by varying the amount of heat supplied to the container and to the tubular member 13. Consequently, the size of the droplets constituting the aerosol produced are readily controllable. Alternatively, the pressure may be controlled by provision of an auxiliary source of compressed gas or air which is in communication with the container, preferably within the vicinity of the outlet 14 through a conduit 16. Of course, the velocity of ejection of the vaporized fluid may be controlled by joint variation of the heat supplied and the pressure afforded by the auxiliary means.

A still further modification of our invention is illustrated in Fig. 3 wherein the structure may comprise a metallic heating member 17, preferably constructed of copper and which is provided with a chamber such as a central elongated channel 18 provided at its upper extremity with an orifice 19 and at its lower extremity with a mixing nozzle assembly 20 comprising a fluid injection nozzle 21 and a pressure nozzle 22, the former of which is, of course, supplied with a vaporizable fluid through a conduit or tube 23 and the latter of which may be supplied with compressed gas or air through a tube 24.

The member 17 is heated by a suitable means. One example of such heating means may comprise a plurality of gas flames 25 and 26 circumferentially positioned about the flanged part 27 of heating member 17. The treating means raises the temperature of the body of this member to a value sufficient to give to the vaporized fluid the desired state of vaporization. In this modification of our invention, the velocity at which the vaporized fluid emanates from the orifice 19 may be controlled principally by the pressure afforded by nozzle 22 to produce particles or droplets of controllable size.

Fig. 4 represents diagrammatically a further embodiment of our invention. In this device, a vaporizable fluid is heated within a substantially enclosed chamber defined by a metallic bell-shaped member 28 in which the heating means may comprise an electrical heating soil 29 embedded in a metallic base part 30 of substantial thickness. A vaporizable fluid 31 is maintained at a predetermined desired level in the bottom of the chamber, being supplied thereto by a tubular conduit 32 which is preferably maintained at a pressure greater than the pressure within the chamber in order to insure a constant flow of fluid to the chamber. A suitable constricted orifice or nozzle may be located at the top of member 28 and may comprise a cup-shaped part 33 provided with an aperture or orifice 34 through which the vapor emanates. In order to prevent appreciable condensation of the fluid within the vicinity of the orifice, we may employ a second heating means comprising an electrical heating coil 35 embedded in the top of member 28. The velocity at which the fluid is ejected into an atmosphere, such as air, and hence the size of the particles constituting the aerosol, is controllable by variation in the amount of heat supplied to the chamber.

Referring now to Fig. 5, we have there shown still another embodiment of our invention which may comprise a boiler 36 which may be of the flashing type enclosed within a heating structure or chamber. The heating structure may comprise a pair of metallic cylinders 37 and 38 supported upon a base structure 39. At the top of structure 39 we provide a suitable hood or chimney construction 40 to permit exhaust of the products of combustion present when a flame or jet of combustible fluid is employed for heating purposes. For example, we may employ for supplying heat to boiler 36 means for producing a jet of combustible fluid 41 supplied through a conduit or tube 42 through a pressure adjusting valve 43. As one example of a suitable heating fluid, we have found that propane gas is highly satisfactory.

The fluid which it is desired to vaporize is supplied to the boiler 36 from a tubular conduit 44 through a pressure adjusting valve 45 and through fluid preheating means which may comprise a single turn of metallic tubing 46 supported by a flanged annular member 47 held in the position illustrated by flanged parts of cylinders 37 and 38. The preheating means is preferably located in the position illustrated above the boiler 36 where it is heated by the products of combustion incident to jet 41. The preheater is employed principally for the purpose of attaining a substantially constant viscosity of the fluid supplied to boiler 36, thereby compensating for variations in temperature of the fluid supplied through tubular conduit 44. As a further means for assuring a substantially constant flow of the vaporizable fluid to the boiler 36, we provide suitable means such as a plurality of spaced diaphragms 48 provided with apertures and which are positioned in a tube 49 in communication with the preheating means comprising tube 46. After passage through the orifices of diaphragms 48, the fluid enters an inlet tube 50, the lower extremity thereof being located within boiler 36 to maintain a pool 51 of the vaporizable fluid. The inlet tube 50 is positioned within a vertical communicating vapor channel 52 which surrounds the inlet tube 50 and provides a path for the upward flow of the vapor to a pressure chamber or vapor chamber 53.

The vapor chamber 53 is provided with a structure 54, preferably annular in configuration, which serves as a sump for the condensate which collects within chamber 53 and which is also in communication with tube 49 and inlet tube 50. Chamber 53 is also provided with an overflow tube 55 to limit the amount of condensed fluid which collects in this chamber. A deflecting and condensing baffle 56 is also positioned within chamber 53 and serves to prevent the passage of large drops or particles of the vaporized fluid through an ejection nozzle 57 preferably positioned in lateral communication with chamber 53 through a tube 58. The nozzle 57 is preferably convergent outwardly. As a safety provision, a valve 59 may be employed to relieve the pressure within chamber 53 and a suitable pressure indicating gauge 60 is also employed.

In operation, upon supply of the vaporizable fluid to the boiler 36 the fluid may be considered as being flash heated to a vaporized state, the vapor rising to chamber 53 through the communicating tube or channel 52 whereupon it is ejected into the atmosphere through nozzle 57 at a relatively high velocity to produce an aerosol. We have found that in the operation of the device illustrated in Fig. 5, it is desirable to maintain an appreciable differential in pressure between the fluid in tube 44 and that supplied to the preheating means and the boiler 36 by adjustment of valve 45.

The fluid in vaporized form is ejected through nozzle 57, the jet thereby produced having a generally conical configuration. Briefly, the gas within a small distance immediately beyond the nozzle 57 is in a superheated condition and is invisible save for the slight difference in refractive index of the gaseous vapor compared with the cold air. Due to the high velocity of the jet of ejected gas or vapor, considerable turbulence of the surrounding cold air is caused, effecting a rather violent mixture of the gas with the air and consequently causing rapid cooling of the gas particles.

On the basis of the concepts developed hereinbefore, it is clear that the rate of growth of particles in the ejected vapor stream can be calculated between the time the vapor issues from the nozzle and the time that it has reached temperatures so low that the process of growth stops. The results of the above concepts may be expressed by the following equation:

$$r^3=\frac{4.8Zq^{1/2}}{(1+\mu_0)^{3/2}v^{3/2}} \qquad (9)$$

where

r is the radius in cm. of the particles or droplets formed by the generator,

q is the number of grams of fluid per sec. which are evaporated in the generator,

μ_0 is the number of grams of admixed air per gram of fluid,

v is the velocity in cm. per sec. of the gases in the jet at the moment of leaving the nozzle,

Z is a function of H, the heat content of the gas escaping from the nozzle per gram of fluid, as explained hereinafter.

Equation 9 is a general expression for all materials, for which the value of Z for each material under consideration is calculated from such factors as the vapor pressure of the material, surface tension, specific heat and the heat of condensation.

For the case where the liquid or gas is of the hydrocarbon type, such as that mentioned above, with a mid-boiling point of about 420° C., the smallest possible value of H of joules per gram is 1250, establishing a value of $Z=40.\times10^{-10}$. As H increases, Z decreases to a minimum of 32.5×10^{-10} at $H=1500$, and then it increases, slowly at first, giving a value of $Z=64\times10^{-10}$ at $H=3020$. For very much greater values of H, Z increases about in proportion to it. These conclusions are in quantitative agreement with actual tests and operation of apparatus built in accordance with our invention.

In apparatus built in accordance with our invention, such as that shown in Fig. 5, control of the particle or droplet size is readily attainable thereby making it possible to produce an aerosol of predetermined characteristics including control of the degree of opacity to visible light. One way in which the particle size may be readily controlled is by employment of a nozzle of constant size or cross-sectional area and by variation of the quantity q in Equation 9, that is, by variation of the quantity or weight of fluid evaporated per unit of time. Another way in which the particle size may be readily controlled is by effecting a substantially constant rate of evaporation of the fluid, that is, q is equal to a constant, and controlling the nozzle or orifice area. A more detailed explanation of these two methods of controlling particle size may be obtained by referring to the following Table I wherein effects on particle size are listed for a smoke generator of the type shown in Fig. 5 as functions of variations in the quantities q and nozzle diameter.

Table I

Gauge Pressure, lbs./in.²	Nozzle Velocity v cm./sec.	H Joules per gram	$10^{10}Z$	Constant Nozzle Sizes			Constant Flow Rate		
				Nozzle Diam. D, cm.	q g./sec. Approx., Gals./hr.	Particle radius r microns	Nozzle Diam. D, cm.	q g./sec. Approx., Gals./hr.	Particle radius r microns
0.1	1,615	1,345	34	0.424	1.19	0.652	1.228	10.0	0.935
0.5	3,580	1,350	34	0.424	2.64	0.500	0.825	10.0	0.623
1.0	5,030	1,358	35.5	0.424	3.67	0.442	0.699	10.0	0.523
2.0	7,030	1,372	33.0	0.424	5.15	0.395	0.591	10.0	0.440
4.0	9,720	1,390	33.0	0.424	7.06	0.354	0.504	10.0	0.374
9.4	14,300	1,448	32.5	0.424	10.00	0.308	0.424	10.0	0.308
12.0	14,340	1,481	32.5	0.424	11.03	0.312	0.404	10.0	0.307
15.0	14,420	1,507	32.5	0.424	12.17	0.317	0.384	10.0	0.307
20.0	14,510	1,546	33.0	0.424	14.18	0.326	0.356	10.0	0.307

The data appearing in Table I were calculated by means of Equation 9 for particle sizes obtained when a hydrocarbon vapor was ejected from the nozzle 57 into cold air. It is seen that within the range of pressure from 0.1 to 20.0 lbs. per sq. inch gauge pressure, that is, superatmospheric pressure, Z is nearly constant. The nozzle velocity at pressures above 9.4 lbs. per sq. inch is constant and equal to the velocity of sound in this vapor, but at lower pressures the nozzle velocity increases with pressure. This relationship is readily appreciated when it is considered that when the driving pressure acting upon a nozzle is greater than the nozzle critical pressure, maximum flow through the nozzle is obtained and the particles assume a velocity corresponding to the acoustic velocity or the velocity of sound in the material or fluid under consideration. With a nozzle of such size that 10 grams per second escape at 9.4 lbs. per sq. inch, q increases in proportion to the nozzle velocity. The seventh column of Table I shows that with a pressure of 0.1 lb. per sq. inch, the particle radius is more than twice as great as it is at 9.4 lbs. per sq. inch where the radius has a minimum value of 0.308 micron. As the pressure is raised above 9.4 which results in a nozzle velocity of about 143 meters per second, the particle radius increases slightly.

If for each pressure a nozzle is selected which will produce a flow of 10 grams per second, then we obtain the data for particle radii given in the last column of Table I. It will be noted that there is nearly a three-fold increase in radius if the pressure is lowered from 9.4 to 0.1, but the radius remains constant then the pressure is raised above 9.4 lbs. per sq. inch. It should be further noted that if the output q is increased by increasing the nozzle diameter (keeping the pressure constant) the particle radius r increases in proportion to $q^{1/6}$, that is ten-fold increase in q causes a 47% increase in radius. This increase in radius may be avoided by using multiple nozzles a foot or more apart.

Thus in a generator operating at 9.4 lbs. per sq. inch using 100 grams per sec. (approximately 106 gallons per hour) the particle radius would increase about 47%, and the nozzle would require an area ten times as great. In order to avoid this increase in particle size, we may employ ten nozzles in parallel, the size of each individual nozzle being kept the same and the particle size consequently remaining the same. It is of importance, however, to separate the nozzles sufficiently so that the jets do not merge until the gases have moved at least a distance of a couple of feet from the nozzle so that the particles have completed their intended growth.

The following Table II is a tabulation of data relative to the rate of growth of particles in a jet from a nozzle having a diameter of 0.425 cm. (0.167 inch) using a hydrocarbon fluid of the type referred to above, operating at 9.4 lbs. per sq. inch gauge pressure at 453° C. The flow of the hydrocarbon fluid is 100 grams per sec. (approximately 106 gallons per hour) and the escape velocity is 14,300 cm. per sec. In Table II the particle radius r is given as a function of x, the distance in cm. from the nozzle, and t the time in milliseconds.

Table II

Temp., °C.	x	t millisec.	λ fraction as vapor	r microns
275	9.4	1.1	0.944	0.121
250	11.9	1.7	0.620	0.227
225	14.7	2.6	0.364	0.265
200	17.8	3.8	0.229	0.285
175	21.3	5.4	0.091	0.296
150	25.6	7.9	0.039	0.301
125	31.6	12.0	0.0147	0.304
100	40.6	19.7	0.0050	0.306
75	56.1	37.6	0.0015	0.307
50	90.5	98.0	0.0004	0.308

At any given distance x from the nozzle, the average temperature across the jet is presented by the data in the first column; t is the time in milliseconds required for the vapor to travel from the nozzle to a point at a distance x from the nozzle. The fourth column presents the fraction of the hydrocarbon fluid which is still in the form of vapor, and r is the radii of the particles at the distance x from the nozzle. It will be observed that the particles have practically reached their full size when the temperature has fallen to 125° C. at a distance of 31.6 cm. from the nozzle. The particles will have reached the size corresponding to half their final volume when having traveled about 13 cm., which corresponds to about 2 milliseconds from the time the vapor leaves the nozzle.

Heretofore, prior investigators in this field have considered that the rate of growth of the particles was primarily dependent upon the concentration of the aerosol, that is, as a function of the square of the number of particles per unit of volume, and accordingly attempted to limit the rate of growth by limiting the concentration by diluting the aerosol with large volumes of hot air or steam before condensation was allowed to occur. Investigations with apparatus of the above described type, substantiated by the above presented calculations, have shown, however, that there is no appreciable amount of coagulation during the short time of a few milliseconds which elapses between the escape time of the vapor from the nozzle until its mixture with such a large volume of air that the rate of coagulation becomes negligible. This concept is a potent factor or reason for using jets of high velocity.

Fig. 6 represents an alternative or optional arrangement for utilizing our invention wherein a vaporizable fluid, such as a hydrocarbon fluid, is vaporized at relatively low pressure. The heating structure may comprise a metallic cylinder 61 provided with a vaporizing chamber, such as a longitudinal vertical channel 62 preferably having one end thereof open to the atmosphere to serve as an ejection aperture or orifice. A vaporizable fluid may be supplied to the channel 62 through a tubular conduit 63. The amount of heat supplied to the fluid and hence the temperature thereof may be controlled by an electric heating coil 64 which surrounds the cylinder 61. Upon vaporization, the fluid rises and the vapor may be in such state at this time that it is barely visible. In order to control the particle size and degree of obscuring power produced by the suspended vapor, we employ an externally positionable source of compressed gas, such as compressed air, to impart to the particles of the vapor jet 65 a relatively high velocity. This means may comprise a positionable nozzle 66 to direct a jet of air transversely across the vapor jet 65, thereby subjecting the jet to considerable turbulence to produce the desired rate of cooling of the particles thereof. Of course, control of the velocity imparted to the vapor particles may also be obtained by controlling the pressure within conduit 67 connected to nozzle 66 or by means of a valve 68. The effective pressure of the jet of gas produced by nozzle 66 on the jet of vapor 65 may be controlled by positioning the nozzle 66 with respect to the jet 65. As the nozzle 66 is moved away from the jet 65, the effective pressure is, of course, reduced, decreasing the velocity imparted to the particles or droplets constituting the stream of gas or vapor 65.

One advantage of directing a jet of compressed gas against the emitted vapor at a point external to the heating chamber or structure is the reduction in the amount of heat required to produce the desired state of vaporization of the fluid as compared with the arrangements where a compressed gas is injected in the chamber. In this manner, a gain in overall efficiency is obtained.

The apparatus described above in Figs. 1 to 6, inclusive, has been presented in simplified form for the purpose of clarity, and it is to be understood that in all of these arrangements the apparatus may be constructed in modified forms. Furthermore, the arrangements of Figs. 1 to 6, inclusive, may be provided with suitable thermal insulation which surrounds the various parts of the respective illustrated embodiments.

While in the description of the methods and apparatus which we provide for the production of aerosols mention has been made specifically of a hydrocarbon fluid of particular characteristics, our invention is in no way limited to the use of a particular matter or fluid, the above described methods and apparatus being applicable with equal facility to other fluids and materials with which it is desired to produce aerosols.

One type of vaporizable fluid which we have found to serve well in the production of visually impervious or opaque aerosols is hydrocarbon fluid of naphthenic base which undergoes the desired process of vaporization and ejection without causing appreciable sludging. In this connection we have found it desirable to use a hydrocarbon fluid having a relatively low viscosity, thereby assuring an adequate and substantially constant flow of the fluid to the generator employed.

Generally speaking, it may be stated that it is desirable to employ a vaporizable material or materials having a relatively high boiling point or range of boiling points, preferably greater than 350° C., that is, materials which do not tend to evaporate at ordinary room or atmospheric temperatures.

It will be readily appreciated that the above described methods and apparatus are susceptible of many uses other than for the production of visually opaque screens. For example, one other use of the above methods and apparatus is the production of evenly distributed and rapidly disseminated insecticides, where it is desired to distribute insecticides over a relatively large area. Another example of such other uses would be in the field of producing smoke smudges to protect vegetation from radical or severe changes in climatic or weather conditions.

As mentioned generally above, our described methods and apparatus may be employed to produce aerosols which are discriminatory to radiations of predetermined wave lengths. For example, the particle size may be chosen and controlled to transmit infra-red radiation while having a definite visual opacity, and consequently serving concurrently to afford a substantial obscuring power to visual observation. Under such conditions, the aerosol may be employed to obscure a given area while permitting the use of infra-red photographic technique.

While we have shown our invention as applied to specific apparatus of particular size and configuration, it will be obvious to those skilled in the art that changes and modifications may be made without departing from our invention, and we, therefore, aim in the appended claims to cover all such changes and modifications as fall within the true spirit and scope of our invention.

What we claim as new and desire to secure by Letters Patent of the United States is:

1. The method of producing an aerosol which comprises vaporizing a material which does not tend to evaporate at ordinary atmospheric temperatures in an enclosed space at a sufficiently high rate to result in a pressure in the range of about 9.4 to 20 pounds per square inch gauge pressure, and ejecting such vapor into the cooler atmosphere at a velocity of about 143 meters per second.

2. The method of producing an opaque aerosol which consists in vaporizing in an enclosed space a normally liquid hydrocarbon to result in a gauge pressure of about 9.4 to 12 pounds per square inch, and ejecting the compressed vapor into the atmosphere through an opening of about 0.167 inch, whereby the ejected vapor issues at substantially acoustic velocity and by rapid admixture with cooler atmospheric air condenses in a few milliseconds into minute suspended droplets.

3. The method of suspending in the atmosphere minute particles less than about a micron in diameter of a material which is substantially non-evaporating at ordinary atmospheric temperatures which consists in converting said material at an elevated temperature into vapor and projecting said heated vapor into the atmosphere at a high velocity approximating the velocity of sound in said vapor, whereby said vapor by admixture with the relatively cooler atmosphere will be condensed within a few milliseconds of time in the state of desired minute suspended particles.

4. The method of producing in the atmosphere a vision-obscuring fog consisting of particles which consists in vaporizing in a confined space a hydrocarbon having a boiling point of at least about 350° C., collecting the resulting vapor in said space and ejecting said heated vapor into cooler atmosphere at a high velocity approximating about 140 meters per second, thereby resulting in condensation of said vapor in a few milliseconds to form suspended particles less than about a micron in diameter.

5. The method of producing in the atmosphere a vision-obscuring fog which consists in vaporizing a hydrocarbon having a boiling point of at least about 350° C., collecting the resulting vapor in a confined space at a pressure approximating nine pounds above atmospheric pressure and ejecting said vapor into the atmosphere through a nozzle having an approximate diameter less than one-half centimeter whereby the ejected vapor by admixture with the cooler atmosphere will be condensed within a few milliseconds of time in the state of minute droplets.

6. In apparatus for producing an aerosol, the combination comprising a heating chamber, a boiler within said chamber, means for applying heat to said boiler, a source of vaporizable fluid, means connected between said source and said boiler comprising preheat means positioned within said chamber above said boiler, a vapor chamber positioned in said heating chamber above said boiler and preheat means, a vertical vapor conduit connecting said boiler and said vapor chamber, said vapor chamber being provided with a member serving as a sump for collection of condensed fluid therein, and an orifice in communication with said vapor chamber for ejection of said vapor.

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