

Oct. 6, 1942.

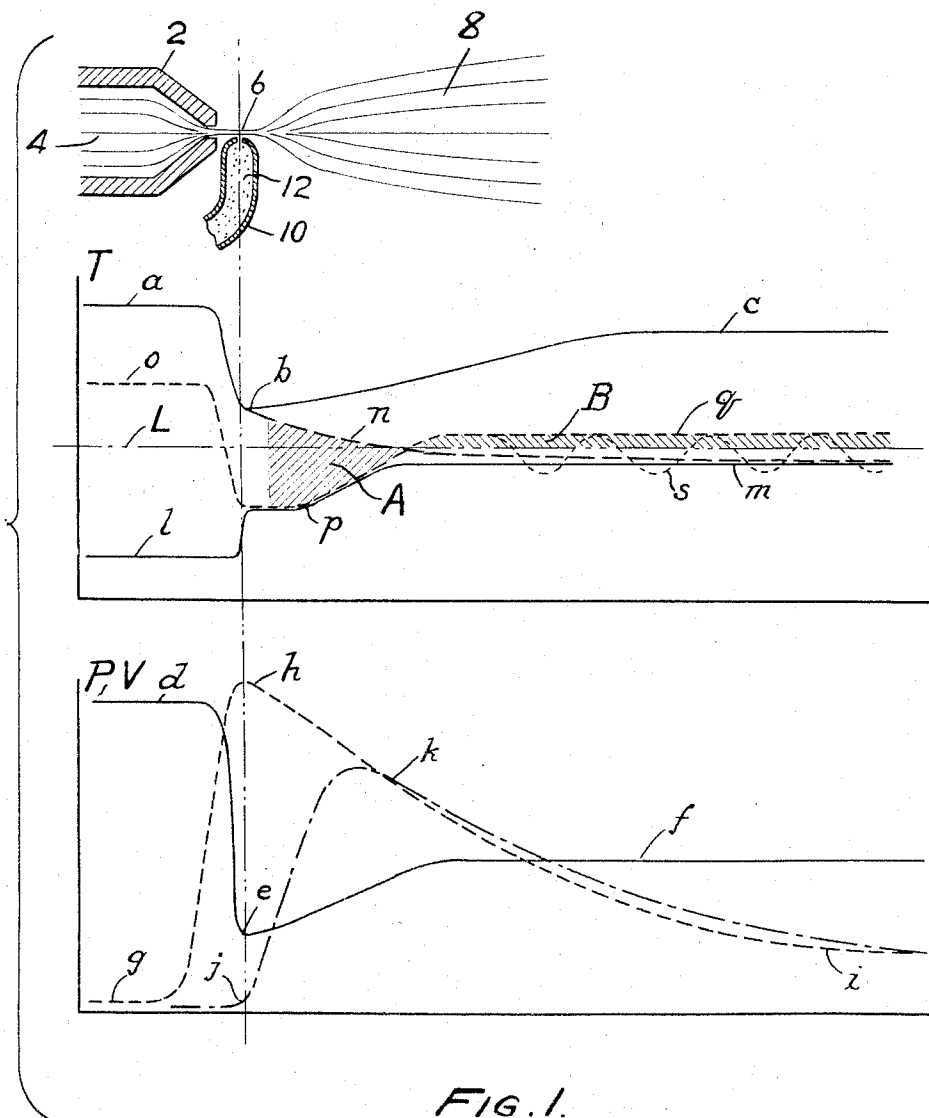
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2,297,726

METHOD AND APPARATUS FOR DRYING OR THE LIKE

Filed April 2, 1938

4 Sheets-Sheet 1



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METHOD AND APPARATUS FOR DRYING OR THE LIKE

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4 Sheets-Sheet 2

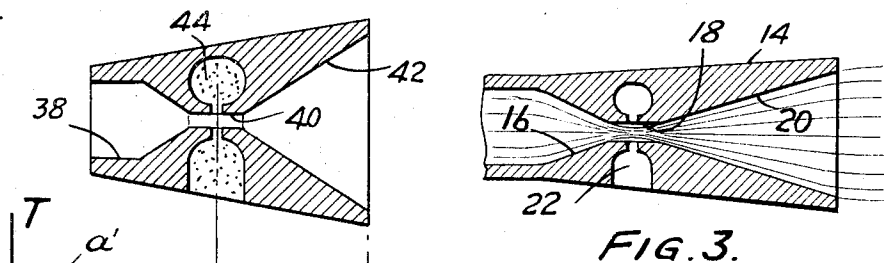


FIG. 3.

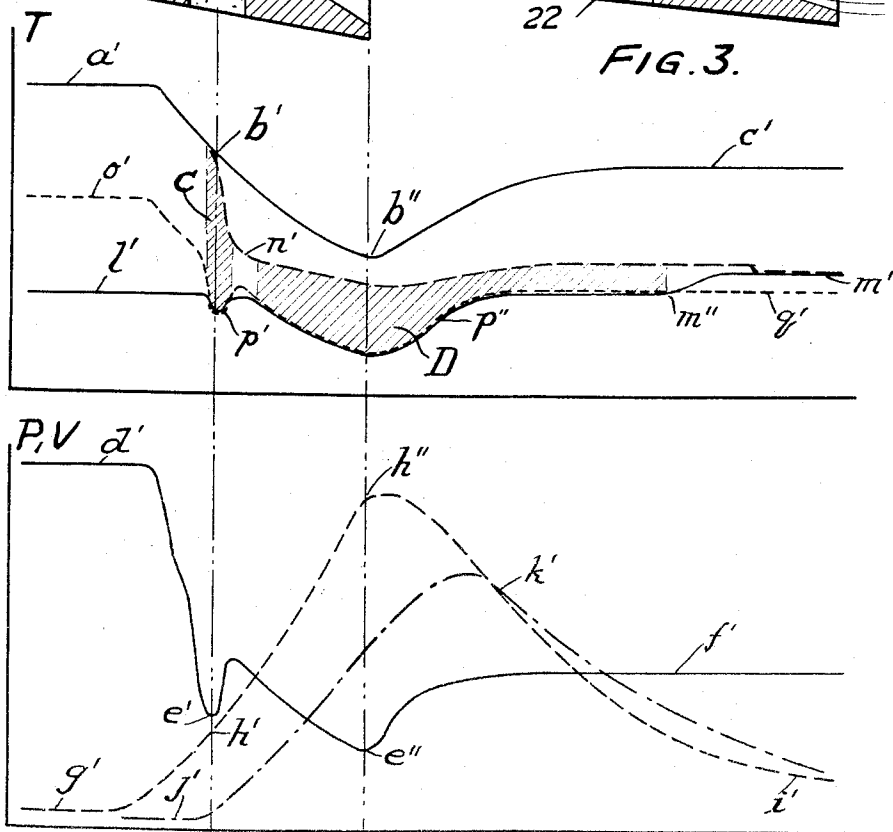


FIG. 2.

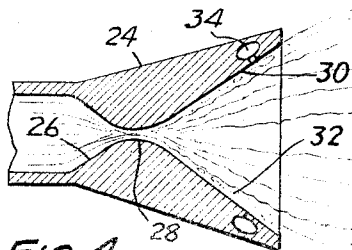


FIG. 4.

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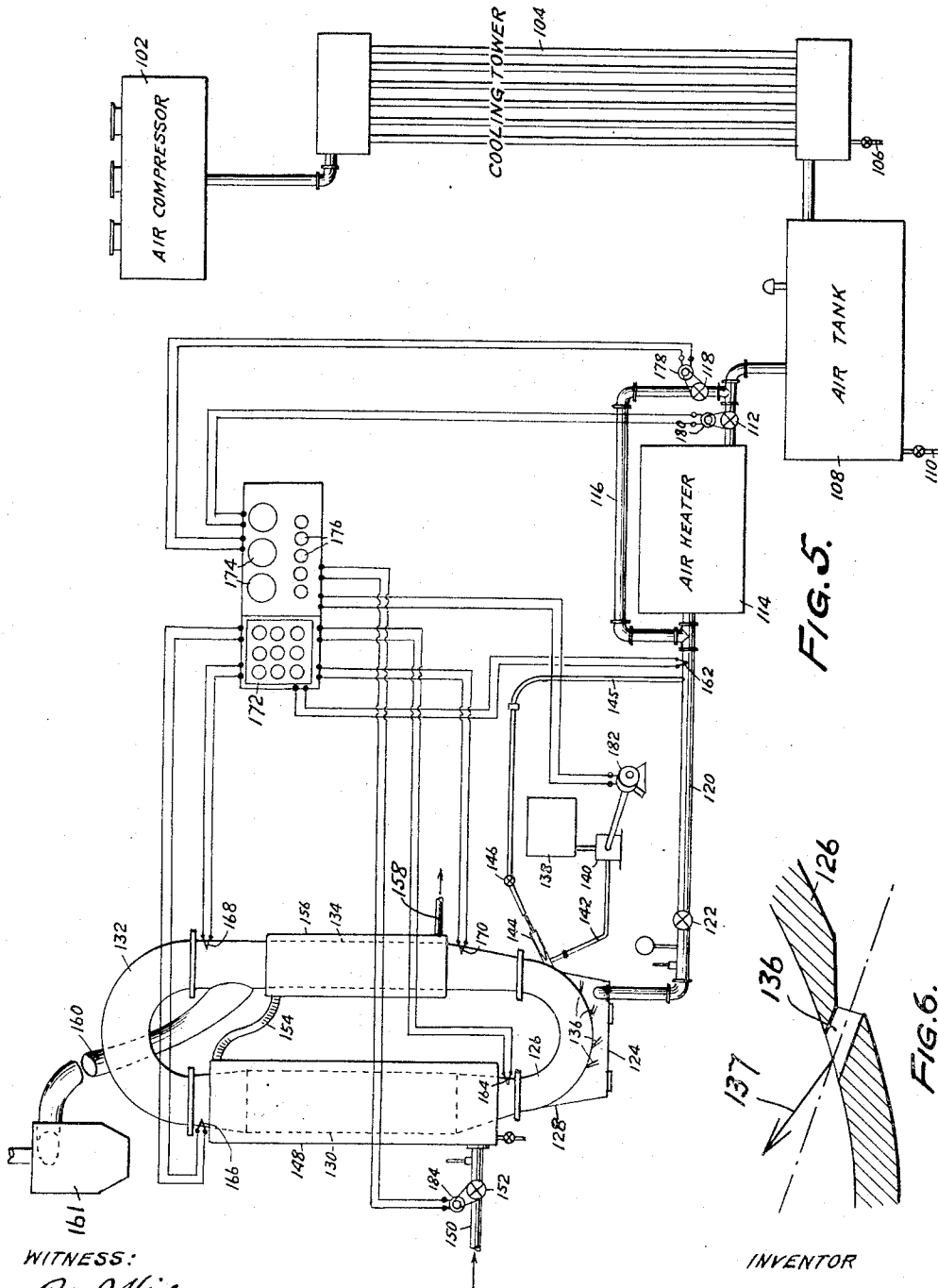
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4 Sheets-Sheet 3



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METHOD AND APPARATUS FOR DRYING OR THE LIKE

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4 Sheets-Sheet 4

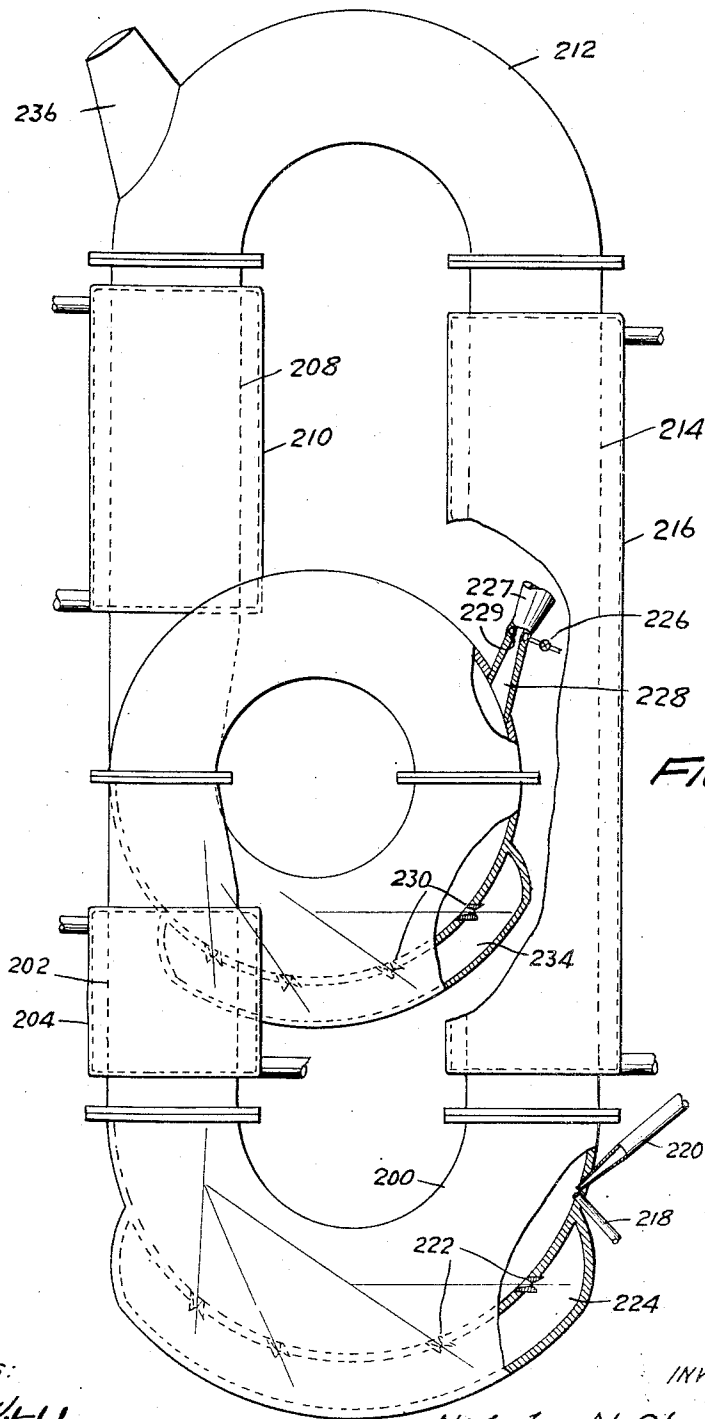


FIG. 7.

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UNITED STATES PATENT OFFICE

2,297,726

METHOD AND APPARATUS FOR DRYING OR
THE LIKE

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Application April 2, 1938, Serial No. 199,687

15 Claims. (Cl. 34—10)

This invention relates to a method and apparatus for drying, in a broad sense, material in the form of droplets or particles and, more particularly, to a method and apparatus for effecting such drying by the atomization of the material to be dried in a high velocity gas or vapor jet or jets.

There frequently occurs the necessity for securing solid materials in the finely dispersed form of particles of sizes ranging through only a few microns in diameter coupled with the preliminary necessity of securing such material from solution or from a wet or plastic raw material containing an evaporable liquid. If drying is accomplished in the usual fashion by ordinary evaporation, the material results in a massive form and must be subjected to pulverization. If the material is hygroscopic, it may be very difficult to dry in any event; and if it is likely to be injured by elevated temperatures, vacuum drying must be resorted to. If minute crystals rather than amorphous powder is required, they must be obtained generally in the form of ground up larger crystals. Numerous problems of other types, which need not be mentioned here also frequently arise.

In accordance with the present invention, dried materials may be obtained in the form of extremely minute particles in a single operation. The methods for accomplishing this, however, are also applicable for efficient and rapid drying even when the problems indicated above are not presented, and it has been found that the present invention is applicable generally to secure the following results: the complete or partial evaporation of volatile solvents from solutions of solids, sometimes with attendant crystallization, the complete or partial evaporation of volatile liquids from plastic materials or wet solids, the complete or partial removal of volatile liquids from emulsions of solids or liquids, and the complete or partial removal of volatile liquid from its solution or admixture with a relatively nonvolatile liquid.

The invention is, furthermore, adapted to the coating of minute particles with either liquid or solid material, with the attendant evaporation of volatile liquid. As will be obvious hereafter, so far as the present apparatus is concerned, the above results involve the same manipulative principles, and to avoid repetition and enumeration where that is not necessary hereafter, it will be understood that the term "drying" is to be considered generic to the removal by evaporation of volatile liquid from various raw materials, and it will also be understood that the term "dried

material" is used in a relative sense, since the products need not be dry in the usual sense in many instances. Not only may a certain percentage of liquid be present as a desirable constituent of a solid product, but the final product may be actually of a moist or pasty nature. In the latter case, advantage is taken of improved drying conditions but not of the comminuting function of the method.

Briefly stated, the invention comprises the drying of the material by introduction into a portion of a jet of elastic fluid wherein there exist conditions capable of producing evaporation while in that portion of the jet the fluid is moving with acoustic or superacoustic velocities as determined by the temperature and pressure conditions existing thereat. Under these conditions there occurs a distinct departure from the conditions existing in the case of the carrying of the droplets or particles in relatively slowly moving streams of elastic fluid. The kinetic energy of a particle is proportional to the square of its velocity and, comparing volumes of equal size, to its density. The density of any solid material existing in suspension in an elastic fluid is, of course, much greater than that of the fluid, and it is obvious that a particle introduced into a region of acoustic or superacoustic velocity of flow of an elastic fluid is going to resist greatly, by reason of its inertia, the imparting to it of the velocity of the fluid. The extremely high velocity of the fluid makes the fluid velocity even more difficult of attainment, with the result that the dispersed particles or droplets are subjected to an extremely high relative velocity of fluid flow. The force acting upon a particle to accelerate it is also enormous, being proportional to a power of the velocity considerably greater than the square. In the case of a droplet the forces exerted on it are immensely greater than its coherence, and consequently, it will be torn apart with the resultant production of particles of sizes of the order of no more than a few microns. In the cases of solid particles, it will be obvious that they also will be subjected to enormous forces and, being violently driven against each other, grinding will occur.

By "acoustic velocity" there is meant herein the velocity which sound would have in the fluid of the jet having the same pressure and temperature as the jet at the region under consideration. The velocity of sound is a function of the elasticity and density of the elastic fluid. The elasticity is a function of the pressure and ratio of the specific heats of the elastic fluid at con-

stant pressure and at constant volume. The density is a function of the pressure, temperature and composition of the elastic fluids. Thus the sound, or acoustic velocity depends on the nature of the fluid, and its pressure and temperature.

The fact that the particles or droplets themselves acquire the acoustic velocities only with difficulty because of their very high relative mass has two effects. First, an acoustic velocity implies inherently the impossibility of propagation of disturbances in the fluid contrary to the direction of motion. This means that on the downstream side of each particle or droplet there will exist a substantially perfect vacuum, with the result that irrespective of the existing temperature boiling on this side of the particle must occur. Of course, as the particle velocity rises, there may not be between it and the fluid a relative velocity as great as the acoustic velocity, but nevertheless, it will be apparent that an extremely high vacuum will nevertheless exist, effective to produce boiling if the temperatures are, as is desirable, as high as possible consistent with the desired ends.

The second result of the extremely high velocities is to remove immediately from about each droplet the saturated atmosphere resulting from evaporation of liquid therefrom so as to continuously expose all portions of a droplet to an unsaturated atmosphere.

As the size of a droplet decreases, the ratio of surface to volume (or mass) enormously increases, so that the disrupting action due to fluid friction which increases as a power greater than the square of the velocity results in the exposure of a maximum surface area to the atmosphere.

Other results than those enumerated will become apparent hereafter, and, in accordance with the invention, it has been found that complete drying even of material fed into the apparatus in the form of a solution is accomplished in times of contact of the order of fractions of a second. While, as will be made apparent hereafter, the thermodynamic conditions of the drying may be readily controlled, it will be obvious that this very minute time of contact is of extreme importance in the case of drying temperature-sensitive materials, with the result that materials may be dried under optimum conditions of elevated temperatures to which they could not possibly be subjected safely under any other conditions of drying.

The invention also contemplates the provision of nozzles of desirable forms for the production of jets, the maximum comminution, of the material and the securing of the best thermodynamic and kinematic results. It also contemplates the provision of apparatus which may be said to correlate the actions of successive jets or to handle the material after drying is accomplished for the purpose of separating the dried material from the vapor laden atmosphere. The apparatus is also designed in accordance with the invention to secure the best efficiencies in the use of heat and of elastic fluid for removing the evaporated vapors.

The various objects of the invention may be briefly stated to be the accomplishment of the results indicated above and described hereafter.

They will be more fully understood from the following description read in conjunction with the accompanying drawings, in which:

Figure 1 is a diagrammatic view illustrating corresponding structural, kinematic and thermo-

dynamic features of one modification of the invention;

Figure 2 is a similar diagram representative of an alternative modification;

Figures 3 and 4 are sectional diagrammatic views illustrating modified forms of nozzles usable in accordance with the principles of the invention;

Figure 5 is a diagrammatic view illustrating a desirable form of apparatus for carrying out the principles of the invention;

Figure 6 is an enlarged sectional view showing the adaptation of an abrupt type of nozzle to the apparatus of Figure 5; and

Figure 7 is an elevation, partly in section, of a modified form of apparatus particularly designed for the admixture or coating of materials in the process of drying.

The kinematic and thermodynamic features of my invention will be best appreciated from a consideration of specific examples of conditions within and in the vicinity of nozzles represented diagrammatically in Figures 1 and 2. It is to be understood that these figures are explanatory only and are not intended to represent either quantitatively or qualitatively the actual extremely complicated conditions existing which include, inter alia shock conditions, different pressure conditions locally existing about particles, the effects of particle size on equilibrium conditions, etc., all as pointed out hereafter.

In the upper portion of Figure 1 there is represented a nozzle 2 of abrupt type having an approach passage indicated at 4 and serving to expel the elastic fluid with which it is supplied in the form of a jet which first narrows down to a vena contracta 6 and then expands as indicated at 8, meanwhile slowing down and finally reaching the relatively low velocity of flow of the fluid through the surrounding casing. Surrounding the region of the vena contracta is means for delivering the solution or wet material from which liquid is to be evaporated. This means is illustrated as comprising a tube 10 containing the material 12 which is to be dried. The tube 10 is provided with an outlet located closely adjacent the vena contracta of the jet. Below this diagrammatic illustration of the nozzle and its jet are shown various diagrams having as abscissa lengths measured along the axis of the nozzle into the region of delivery therefrom and illustrating the temperature, pressure and velocity values for points measured along the nozzle axis.

As is well known in the theory of nozzles, if there is provided a nozzle which is smoothly converging and then smoothly and properly diverging (the De Laval type), and if the pressure at the outlet is less than some critical pressure relative to the inlet pressure, the vena contracta of the jet will occur within the nozzle boundary and there will exist in it a pressure bearing a definite relationship to the initial pressure. In the case of air the pressure at the vena contracta will be 0.58 times the value of the initial pressure, while for steam it will be 0.55 times the value for the initial pressure. The velocity at the vena contracta will be the acoustic velocity corresponding to the pressure and temperature existing thereat. The velocity beyond the vena contracta will be greater than the acoustic velocity.

In the case of an abruptly terminating nozzle of the type illustrated at 2, however, the vena contracta occurs beyond the discharge end of

the nozzle, and, though it is not bounded with solid walls, the resulting conditions are similar to those in a De Laval nozzle up to the vena contracta. At the vena contracta, the velocity will be the acoustic velocity corresponding to the pressure and temperature thereat, but this will now be the highest velocity existing in the jet. The pressures considerably lower than the pressures initial pressure the theoretical ratio for the gas or vapor used so long as the pressure in the receiver is less than this.

The jet, however, no longer involves smooth flow, but at its boundaries, due to friction with relatively still fluid, cavitation will result in the region surrounding the vena contracta and adjacent portions of the jet with the production of pressure considerably lower than the pressures within the jet. As an example, with a pressure of 45 pounds per square inch absolute of air entering a nozzle of abrupt type and with discharge into atmospheric pressure, it was found that there was produced in the region surrounding the vena contracta a suction of 21 inches of mercury corresponding approximately to 4.5 pounds per square inch absolute. This suction condition may be utilized to draw the material to be evaporated into the jet and the utilization of this condition is illustrated in Figure 1, wherein the low pressure surrounding the vena contracta may result in the delivery into the jet of material the source of which is subjected to atmospheric or other pressure. The existence of cavitation in this region means the presence of considerable turbulence, breaking up any entering liquid and resulting in the formation of droplets in the usual fashion of an atomizer.

Referring specifically to the curves, the curve *abc* represents the temperature conditions which would exist in the jet if wet material was not introduced thereto. The initial temperature of the entering elastic fluid is indicated at *a*. At the vena contracta, the temperature drops to a value *b* and thereafter some temperature rise again occurs to *c*, due to transformation of velocity energy into heat, the final temperature being that of the elastic fluid flowing in the vessel into which discharge takes place.

The curve *def* represents average pressure conditions of interest. The first portion of this curve up to the first downward bend, that is, the portion indicated at *d*, may be taken to represent the initial pressure of the elastic fluid fed to the nozzle. From *d* to *e* there is represented the pressure, not in the jet, but surrounding it, i. e., the pressure upon the material as it is being entrained by the jet. The portion of the curve from *e* to *f* may be taken to represent the average pressure upon the droplets or particles entrained by the jet. It may be remarked that the pressure existing along the center line of the jet in the case of this abrupt type of nozzle would not drop below the final value indicated at *f*, and the drop at *e* represented in the diagram corresponds to the low pressure condition produced by cavitation.

The pressure curve is referred to above as showing "average" pressure conditions. Actually, there exists considerable shock as the velocity of the jet drops with the production of vibrations causing violent local changes in the pressure conditions. Likewise, enormous pressure gradients must exist in the vicinity of droplets or particles due to differential velocities as later described.

The velocity of the elastic fluid in the jet is

represented by the curve *ghi*. The low approach (pipe) velocity is indicated at *g*. At *h* there is indicated acoustic velocity for the conditions of the gas in the jet, which velocity is attained at the vena contracta. Thereafter the velocity falls off (with shock disturbances, not illustrated) until at *i* it is substantially the velocity of flow existing in the discharge chamber.

The velocity of the material which is entrained is represented by the curve *jk*. The approaching material has a very low approach velocity. Its velocity rapidly increases until ultimately somewhere beyond the vena contracta it has acquired the velocity of the jet at that point, this being indicated at *k*. From this point on, the gas is rapidly slowing down; but the entrained particles (droplets or grains) have a momentum considerably greater than that of the jet, and consequently beyond the point *k* they will tend to lead the jet, being slowed down gradually by friction (with shock disturbances) until ultimately they too acquire the final velocity existing in the receiver.

The curve *opq* is used to represent the boiling point of the liquid which is being evaporated at the pressures corresponding to the pressure curve *def*.

The curve *lpm* represents the temperature of the material particles which are introduced into the jet, *l* being the initial temperature which, in the instance indicated in Figure 1, is assumed to be low, i. e., the material is not preheated. The temperature of the elastic fluid in the jet is indicated at *n*. It will be noted that it departs from the temperature curve of the elastic fluid flowing idly at the point of introduction of the material, since cooling takes place due to the entrance of the material to be dried.

With the above preliminary explanation, the conditions of operation may be followed. At the vena contracta the jet has acquired its highest velocity and the surrounding region its lowest pressure. Consequently, entrainment of the material takes place. The material is accelerated as indicated by the initial portion of the curve *jk*, and since this acceleration takes place in a region of intense turbulence surrounding the vena contracta, the material is broken up into minute droplets which are rapidly accelerated up to the point *k*. Up to this point, however, there is a high relative velocity between the gas and droplets, with the result not only of tearing the droplets apart by surface friction, but also the almost immediate removal of vapor resulting from evaporation, and the production of a high vacuum at each droplet as described below. If the conditions are such as those illustrated in Figure 1, the droplets have their temperature almost immediately raised to the boiling point if, as is assumed, the boiling point under the conditions of pressure existing is lower than the temperature of the gas of the jet. This is true through the region indicated at *A*, which is shaded to show the excess of gas temperature over the boiling point. Consequently, the region *A* represents intense average boiling conditions. By "average" boiling conditions are meant the conditions which would exist if all portions of the particle surfaces were exposed to the average pressure of the jet in their vicinity.

There is, furthermore, a much more effective local boiling condition on the downstream side of each particle because, if the difference of particle and fluid velocities exceeds the acoustic velocity, there will be a perfect vacuum (less the

pressure existing because of active evaporation) on that side of the particle, and even if the velocity difference is less than acoustic there will be a high vacuum on the downstream side until the velocities approach equality at *k*. The acceleration of the particles from low velocity through the region of maximum velocity of the jet is thus of very great value in promoting evaporation. It will be seen to be desirable that the particles should, if possible, be introduced at quite low velocity, or even at a high velocity opposite the motion of the jet, directly into the highest velocity portions of the jet to secure maximum relative velocity rather than to have the particles gradually acquire high velocity with the jet fluid by reason of introduction into the fluid in advance of the region of maximum velocity.

Minute particle size, resulting from the intense disturbance and disintegration of the particles is also a factor in producing intense evaporation since, as is well known from theoretical considerations and experiments on turbine nozzles, as the size of a drop decreases, it may be in equilibrium with an increasingly supersaturated atmosphere. Thus there results in my improved apparatus an apparent decrease in the latent heat of evaporation of the liquid.

As boiling proceeds the temperature of the gases is lowered, and as progress along the jet takes place, the pressure also rises, so that eventually the boiling point curve intersects and passes above the gas temperature curve. Where this occurs, boiling (from the average standpoint), ceases, but nevertheless, if the gas is not saturated with the evaporated vapors, rapid evaporation will continue to take place. This results in keeping down the temperature of the material as shown at *m*. Under the conditions assumed for Figure 1, the region of transition from boiling to evaporation below the boiling point is shown as involving the region of rapid slowing down of the velocity of the gas. The particles under these conditions are moving faster than the gas, and consequently are being continuously exposed to new atmosphere so that local saturation about them does not tend to occur. The particle does not return into a region saturated with its own evaporated moisture since by this time the jet will be radially dissipated and admixed with other air in the receiver. Furthermore, a reduction of pressure now occurs on the upstream side of the particles and may be sufficient to produce boiling.

As a matter of fact, the conditions of flow will be highly turbulent during this region of slowing down of the jet due to shock and boundary disturbances, with resulting cavitation along the walls of the receiver resulting in local pressure drops reflected in lower boiling point of the liquid, as indicated roughly at *s*. The pressure drops may well cause the boiling point to drop below the temperature of the droplets, and consequently semi-evaporation and semi-boiling in the average sense may take place.

It will be observed that the conditions are such as to provide in an extremely minute interval of time the attainment of an equilibrium which corresponds to complete drying providing conditions are such that saturation of the evaporating atmosphere does not occur and heat is amply available. The breaking up of larger droplets into extremely small ones (which it has been observed occurs by initial elongation and then breakage) provides an enormous increase

of ratio of surface area to volume, thus exposing the liquid to the gas under the optimum conditions for most rapid evaporation. The relative motions between the liquid and the gas further contribute to this result, as explained above.

The existence or non-existence of average boiling conditions depends, of course, upon the initial conditions which are adopted. If possible, it is desirable to have boiling occur rather than mere evaporation, since boiling is independent of the humidity conditions of the surrounding gas, whereas evaporation is dependent upon humidity conditions and the removal of saturated atmosphere. A maximum region in which boiling takes place is, therefore, desirable for best results. This is particularly true in the case of substances having a hygroscopic nature.

The conditions illustrated in Figure 1 have been chosen to illustrate a requirement that is sometimes imposed, namely, that the evaporation must take place at a temperature not exceeding a certain limit indicated by the line *L*. It will be noted that the conditions of operation are such that at no time does the temperature of the material rise above this limit, though the gas at the vena contracta, and even substantially beyond it, is above this limit. The conditions are provided, of course, by insuring the introduction of sufficient material such that drying cannot take place before the temperature of the gas has dropped below the upper permissible limit. If the material can be preheated, it will be obvious that the region of boiling may be substantially increased, since the temperature of the carrying gases will drop more slowly. It will be obvious that with the imposition of given limitations upon the operation, the consideration of the factors graphically represented in Figure 1 will readily indicate optimum conditions for most economical and rapid drying.

If the material which is being dried can stand high temperatures, the temperatures of the elastic fluid should obviously be as high as possible because the amount of liquid which may be carried by a gas or vapor increases very greatly with the temperature. For example, whereas one pound of air at 140° F. can carry 1,100 grains of water at saturation, a pound of air at 200° F. can carry 16,100 grains of moisture. Accordingly, a given quantity of air or other elastic fluid can be made to act much more efficiently if its temperature is raised. In general, it is much better for overall efficiency to raise the temperature than to maintain a lower temperature and handle large quantities of elastic fluid.

The specific example of Figure 1 may be taken to represent the evaporation of an aqueous liquid by means of air. Very similar conditions will occur, however, in the evaporation of an aqueous liquid by the use of steam, or in the evaporation of any liquid by means of any elastic fluid. In the first case, humidity conditions of the air play an important part in the rapidity of evaporation, while in the second case it will be obvious that the degree of superheating of the steam is the important factor. If steam is used to evaporate non-aqueous liquids, the considerations which apply are similar to those applying in the case of evaporation of liquids, aqueous or otherwise, by air or some other gas. It will be obvious that the conditions are quite general. The material introduced to be dried may, of course, be initially in the form of suspended particles, or in solution, in emulsion or in paste or wet granular form, being reduced in the jet

to the form of particles, which term is used herein to include droplets or granules. In the case of solutions, the boiling point rises and evaporation becomes more difficult as concentration ensues, but even highly hygroscopic materials may be dried readily with the proper relationship of temperatures and relative quantities of the jet fluid and material to be dried.

In order to secure the best results, it is essential that substantially acoustic or higher velocities should be attained in the nozzle in the region where the material to be dried is introduced or, at least, through which the material to be dried is carried. The material may be obviously be introduced under pressure within the nozzle so as to pass with the gas or vapor through the outlet thereof and through the region of acoustic or higher velocities of flow, though, as pointed out above, this is less desirable than the introduction of the material from substantial rest suddenly into the highest velocity region of the jet. It may be pointed out that the greater density of the material to be dried causes it to lag behind the gas during the acceleration period and consequently produces intense turbulence, preventing ordinary nozzle theory based on smooth flow from applying. Local heating also occurs due to friction. The material, in case it must be introduced into a region of low velocity, as, for example, in the approach passage 4, may be introduced in an already atomized form so as to be more readily carried by the fluid in its low velocity regions without depositing on the nozzle walls. If a number of jets discharge into the same receiver, the cloud of material fed from one nozzle may pass in the vicinity of suction of another nozzle, whereupon a further breaking up and evaporation may take place.

To illustrate a different condition, but one which bears a close resemblance in basic principles to that already outlined, reference may be made to Figure 2, the upper portion of which illustrates a nozzle of an over expanded type and of a so-called "Venturi" type rather than "De Laval" type, in that smooth approach and divergence from the throat is not provided, but rather an extended cylindrical portion 40 is provided at the throat extending from the approach passage 38 to the over expanding discharge portion 42. The flow of an elastic fluid through a nozzle such as this involves first a vena contracta the boundaries of which break away from the throat of the nozzle, i. e., the nozzle up to and including the throat portion is essentially similar to the abrupt nozzle of Figure 1. Beyond the vena contracta, the fluid may again follow the walls of the nozzle, but eventually, somewhere between the throat and the outlet, will break away from the walls because of their large divergence producing the over expansion condition. The fact that the vena contracta breaks away from the throat makes it possible to introduce material as indicated at 44, since a low pressure region occurs thereat. Material may be alternatively introduced at another low pressure region where the fluid breaks away from the region of expansion. This is described later in connection with Figure 4.

The curves extending to the nozzle just described have been designated similarly to the curves of Figure 1, but with the reference characters primed. Considering first the pressure curve $d'e'e''f'$, the first portion d' represents the

pressure of the gas approaching the nozzle throat, while the portion in the vicinity of e' represents the pressure at the boundary of the jet as it passes through the throat in the vicinity of the vena contracta. The later portions of the curve represent the pressures existing on the material. If the nozzle were of the De Laval type, at least through the vena contracta the curve representing the pressure drop from d' to e'' , that is, the outlet, would extend smoothly downward. Due, however, to the cylindrical throat, there is a sharp dip of pressure at e' which may be utilized to draw in the material. If steam is used as the elastic fluid, some condensation may occur here due to contact with the cold material, creating a considerably greater pressure drop. The condensate will be reevaporated in later portions of the jet. If the nozzle were of the De Laval type, the final pressure at e'' would be the receiver pressure. In the case of the over expanded nozzle, however, the pressure in the mouth drops below the receiver pressure with a resulting shock condition creating great turbulence at the outlet, the pressure rising ultimately to the receiver pressure f' .

The theoretical temperature curve $a'b'b''c'$ can be readily seen to follow from the pressure curve. The introduction of material, as in the previous case, results in an actual fluid temperature curve departing from the theoretical at b' and, therefore, taking the form n' . It will be noted that after the exit a slight temperature rise may take place, though this may be prevented by the cooling effect of the evaporation of liquid from the entrained material.

Velocity conditions of the elastic fluid and material are illustrated by the curve $g'h'h''i'$ and $j'k'$, respectively. The maximum fluid velocity is reached at the outlet of the nozzle and may greatly exceed acoustic velocities which are reached as indicated at h' at the vena contracta. It may be remarked that the scales of Figures 1 and 2 are quite different in respect to the velocities. The material will again first lag behind the elastic fluid and then flow more rapidly than the fluid.

Average boiling point conditions are illustrated by the curve $o'p'p'q'$.

In Figure 2, it is assumed that the material has been substantially heated initially, as indicated at l' . As the material enters, it finds the pressure of the elastic fluid initially such that its temperature is above its boiling point. There may, therefore, be an initial region of average boiling indicated at C. Immediately after the vena contracta, however, the boiling point may rise above the temperature of the material, but average boiling may be resumed as the pressure again drops in the over expanding portion of the nozzle. The initial heating of the material may very substantially prevent rapid cooling of the elastic fluid, so that the elastic fluid temperature may exceed the boiling point even as the receiver pressure is reached. Complete drying may, therefore, be effected at some point such as m'' , whereupon the dried material will be heated to gradually approach the temperature of the elastic fluid, which will be slightly lowered. The boiling region may, therefore, be a quite extended one, as indicated at D and all of the drying may, therefore, occur under boiling conditions. Intense local boiling due to vacuum on the downstream side will occur as previously described. Likewise it will be understood that all the other

factors previously mentioned enter into the operation.

The type of nozzle just described is very desirable because intense turbulence is produced at three points, first in the throat, second in the over expanded portion of the nozzle, and third where the shock waves occur in the rise of pressure at the exit. The result is to secure most minute droplets and final particles. If large size wet particles originally enter the nozzle, they are ground by the turbulent action, with resulting production of very fine powder.

The above descriptions will indicate the actions of other nozzles which need be referred to only briefly. The type of nozzle illustrated in Figure 2 may have a De Laval type of expanding portion, as illustrated by the nozzle 14 in Figure 3. The approach 16 delivers into a cylindrical throat 18, wherein the vena contracta becomes smaller than the throat boundaries producing suction and turbulence, and, with steam, possible temporary condensation. In the expanding portion 20 of the nozzle, however, the expansion may take place at the proper rate to secure parallel flow, smooth jet conditions and extremely high velocities at the outlet. These conditions are not generally desirable unless definite direction of delivery of the jet is required.

Figure 4 represents an over expanded nozzle 24, which has a smooth throat 28 fed by the approach 26, with the result that little or no turbulence is produced thereat, and consequently no pressure dip of the type illustrated at e' , to provide a suction for material introduced at receiver pressure. However, if an over expanded mouth is provided as indicated at 30, intense turbulence and suction may be produced in this region as indicated at 32 due to the breaking away of the jet from the walls (cavitation), with a resulting pressure drop capable of drawing in material from inlets 34. In this case the introduction of material at the mouth does not detract from the attainment of extremely high superacoustic discharge velocities, and maximum velocities of flow may thereby be secured.

The De Laval type of nozzle is generally less desirable than the other forms because it results in minimum turbulence which is a condition to be desired in this method of drying. An improvement over the De Laval nozzle is to provide an outlet arranged for under expansion, whereby though superacoustic velocities are secured, there is a great impact at the discharge, producing intense shock waves and also some secondary expansion at the mouth with accompanying pressure drop so that material may be there introduced. In such cases, it is generally desirable to introduce the material to be dried under pressure either at the vena contracta or prior thereto.

References have been made above to shock waves of acoustic nature occurring at the mouths of nozzles. When the velocity of discharge is the acoustic velocity (as in the case of discharge from an abrupt type nozzle) the waves appear stationary. If the velocity is superacoustic, the waves appear to move forward with the jet, their rearward propagation relative to the jet taking place at acoustic velocity. In general, they can arise only when the mean velocity of the jet exceeds the acoustic velocity. These waves, in common with acoustic waves in general, with the exception that they are very intense, involve regions of compression and rarefaction which, applied to drying in accordance with the present invention, create successively low pressures

promoting vaporization followed by high pressures, with accompanying creation of heat, but without, apparently, condensation in the sense that it may cause an increase of wetness of the particles in the jet. As indicated above, the particles or droplets are so small that the tendency toward evaporation greatly exceeds the tendency toward condensation, and the equilibrium condition corresponds to super-saturation as this would be measured under static conditions. Due to the intense agitation existing because of friction and the waves, the droplets do not agglomerate, and since friction occurs providing additional heat, evaporation continues rather than condensation. Inasmuch as the gas velocities are greater than the particle velocities in the regions of the jet in which such waves occur, the vapors from the evaporation are immediately moved away from the particles so that appreciable recondensation on the particles could not occur even if the particles were of large size.

The above illustrations serve to point out the salient advantages of the method and apparatus of this invention. For a more detailed reference to the kinematic and thermodynamic conditions existing in nozzles of the types herein utilized, together with the considerations of design and pressure variations giving rise to acoustic and superacoustic velocities, cavitation, shock waves and the like, reference may be made to chapter III of "Steam and Gas Turbines," by Stodola, translation by Loewenstein, volume I, McGraw-Hill Book Company, Inc., 1927. While in that chapter, since turbines are being considered, the reference is to the action of nozzles discharging a homogeneous elastic fluid, there are discussed flow conditions through nozzles of the types referred to herein, which are generally unsuited for turbine use, and it is found that even though liquid or solid material is introduced into the nozzle jets together with the elastic fluid, the conditions for attainment of acoustic or superacoustic velocities and the other conditions of flow mentioned above are substantially the same as those involved when a homogeneous elastic fluid is used. For example, similar critical pressure drops occur and the velocities of the elastic fluid stream are substantially those obtained with a homogeneous elastic fluid. The differences involved primarily arise from the additional cooling due to evaporation and the departure from smooth flow occasioned by the presence of liquid or solid particles moving with a velocity different from that of the jet fluid.

Referring to Figure 5, there is illustrated therein in diagrammatic fashion an apparatus desirably associated with nozzles of the type described for properly effecting drying. The apparatus specifically disclosed is designed for the use of air as the drying elastic fluid, though it will be obvious that steam or other elastic fluid may be substituted. In this connection, it may be remarked that in the specification and claims where reference is made to an unsaturated elastic fluid, it is to be understood that this term implies a condition of the fluid such that it is capable of producing evaporation under the conditions to which it subjects the wet material. In the case of air evaporating water, it means, of course, that the humidity should be low. On the other hand, air saturated with water vapor may well evaporate other liquids and, to this extent, air so saturated with water vapor is to be considered unsaturated with respect to another liquid. Superheated steam is also to be considered unsaturated

with respect to an aqueous liquid, while even saturated steam is capable of producing evaporation of liquids other than water and is to be regarded as unsaturated from this standpoint.

An air compressor is illustrated at 102. The compressed air provided by the compressor is preferably cooled so that moisture content therein will separate out and may be drawn off through the drip outlet 106 in the bottom of the cooler. The cool compressed air may be contained in a tank 108, which is also provided with an outlet 110 for the removal of any moisture which may separate therein. Inasmuch as variable amounts of air may be used, the air compressor may be provided with a conventional unloading arrangement so as to maintain in the air tank a predetermined pressure. If, on the other hand, it is found desirable to keep the air compressor operating, the air tank may be provided with a safety valve so that the pressure does not rise too high.

Air is delivered from the tank 108 through a valve 112 to a heater 114 from which it passes through conduit 120 to the drying apparatus. A by-pass 116 controlled by a valve 118 is arranged to cause cooled air in regulated amounts to pass to the conduit 120. Suitable automatic regulation of the valves 112 and 118, as hereafter described, thus may be made to insure a predetermined temperature of the air in the conduit 120. The air heater may thus be conveniently heated by exhaust or waste gases, for example by the exhaust gases of an engine driving the air compressor, the proper temperature being maintained irrespective of substantial variations in the temperature of the air heating medium.

The conduit 120 controlled by a valve 122 delivers the heated and compressed air to a chest 124 associated with the lower bend 126 of a closed tubular dryer casing 128 comprising, in the direction of flow from the portion 126, an upright straight portion of substantial height 130, an upper bend 132 and a vertically extending straight portion 134 serving to return air to the portion 126.

Arranged on the outer side of the portion 126 of the casing and directed inwardly as indicated are a series of nozzles 136 (detailed in Figure 6) adapted to discharge into the casing at acoustic or superacoustic velocities air from the chest 124, the discharge being so effected, as indicated, as to impart to the gases a substantial tangential component of motion in the direction of motion of flow through the casing.

The material to be dried is delivered from a storage tank indicated at 138 by means of a pump 140 into a tube 142 closely approaching a low pressure region surrounding the jet produced by a nozzle 144 which receives heated compressed air from the conduit 120 through a line 145 controlled by a valve 146. For example, if the nozzle 144 is of the abrupt type illustrated in Figure 1, the tube 142 may approach the vena contracta of the jet in the fashion of the tube 10 illustrated in that figure.

The portion 130 of the dryer casing is surrounded by a jacket 148 to which steam or other heating fluid may be supplied from a connection 150 through valve 152. The jacket 148 may discharge the heating fluid through a connection 154 to a jacket 156 on the portion 134 of the casing, whence it may be discharged as indicated at 158. These two jackets may be connected in series as illustrated, or may be sepa-

5 rately provided with temperature controlling fluid. In some instances, for example, it is desirable to cool the jacket 148, though in general it is desirable to heat the jacket 156 in order that the returning gases may meet the inflowing material at an elevated temperature.

10 Discharge from the casing is provided by the conduit 160 joined to the inside of the casing just beyond the bend 132. This arrangement of the outlet, as will be hereafter indicated, insures removal only of minute particles and provides for the return of large particles for grinding action. The connection 160 may communicate with a conventional separator 161 for removing 15 dry dust from the spent fluid.

As indicated in the previous discussion of Figures 1 and 2, control of the conditions of operation may produce various results as, for example, the optimum drying conditions consistent with no overheating of the material being dried. In Figure 5 there are illustrated at 162, 164, 166, 168 and 170 thermocouples located in various significant parts of the apparatus and connected into a master instrument board 172, so as to give visual indications of the temperatures at such parts of the apparatus. The thermocouple 162, for example, indicates the temperature of the inflowing air. Pressure gauges are also desirably provided and may be connected by remote indicating devices of known type with dials on a master board. The thermocouples in the apparatus serve to indicate the effects of heating or cooling taking place in various parts thereof. The thermocouple 166 in particular is indicative of the degree of drying which is attained.

The thermocouples may not only be used to control visual indicators, but desirably control continuous recorders such as 174 and may also control automatic valve operating motors indicated at 178, 180, and 184 and the pump operating motor 182. The conditions of control may be adjusted by manipulatable devices 176 to secure desired conditions of operation. The motors 178 and 180 desirably operate differentially so as to control the amounts of air going through and by-passing the heater to maintain at desired values the temperature indicated by the thermocouple 162. For a constant flow of material to the apparatus, the conditions of operation are dependent upon the amount of material to be dried which is fed thereto, and this may be controlled by the control of motor 182 which is desirably responsive to the conditions indicated by the thermocouples 164 and 166. The temperatures of the apparatus may be independently controlled by the operation of valve 152 by the motor 184 which is subjected to operation under the conditions of temperature of, for example, the thermocouple 170. The specific means for operating these control devices are well understood and form no part of the present invention. For the purpose of the present invention, it may be considered that the operator observing the readings of the thermocouples as indicated on the panel 172 may so manipulate the various motors as to maintain the optimum conditions of operation.

In the specific operation of the device illustrated, in Figure 5, the dried and heated air passing through the nozzle 144 (of one of the types heretofore described) entrains the material from the tube 142. The jet, having at least an acoustic velocity in a region in which material is entrained, immediately reduces the introduced

material to extremely fine particles or droplets and subjects them to the drying action of the type heretofore described. The jet ultimately merges with the elastic fluid returning through the portions 134 of the casing, which is reheated to the desired degree by the jacket 156. While not moving at velocities approaching acoustic velocities, the returning fluid is nevertheless travelling at substantially high velocities, and consequently the effective jet is substantially elongated, thus giving increased zones of operation corresponding to the right hand portions of the graphs of Figures 1 and 2. In the region where the jet is losing its individuality and high velocity, the material, now in the form of a cloud of minute particles, may be subjected to the action of a number of auxiliary jets from nozzles 136. The nozzles 136 may be of De Laval type if the material is already in extremely finely divided form. The De Laval nozzles then have the advantage of producing the highest velocities possible considering the conditions of operation, i. e., the conditions of the introduced fluid and the pressure within the dryer. However, any of the other types of nozzles may be used and in Figure 6 there is illustrated the adaptation of the abrupt type of nozzle in this position. Desirably, at this part of the apparatus, particularly if the portion is curved so as to impart an outward centrifugal force to the flowing particles, the nozzles are so arranged as not to project inwardly beyond the smooth surface of the casing. If they project beyond this surface, there is likely to be an accumulation of the wet material behind them. Consequently, they may be cut off so as to provide a beveled outlet, as illustrated in Figure 6. In such case, the jet does not flow in the direction of the center line of the nozzle, but rather the direction of the jet is as indicated by the arrow 137 in Figure 6. The jet, however, maintains the characteristics described above. When the vena contracta is inside the casing beyond the mouth of the nozzle a region of high vacuum is produced around it serving for the drawing into the jet of the material in the casing. The characteristics of the oblique jet are given in the work by Stodola mentioned above. Strong shock waves accompany the discharge from such jet.

The material is picked up by the high velocity streams from nozzles 136 and subjected to further acceleration with attendant subjection to disintegrating velocities of flow of the elastic fluid and the extremely rapid removal of saturated surrounding atmosphere. The number of nozzles to be provided depends, of course, upon their necessity for drying and/or further drying. The arrangement of nozzles is subject to variation depending upon the material handled and conditions of operation. Material may be introduced at various points and auxiliary nozzles so located as to maintain the material suspended and subjected to the optimum conditions of velocity, turbulence, pressure and temperature to secure the desired drying.

If the material was of relatively coarse form, for example, being fed in the form of a wet powder, the particles of which were not in a fine state, the first nozzle may not be sufficient to produce complete disintegration to the extent desired. Consequently, the relatively smooth flow from a De Laval nozzle may not be as satisfactory as a type of nozzle giving rise to a highly turbulent flow. In such case, the abrupt nozzle or nozzles of the other types heretofore described are particularly desirable. Preferably,

the abrupt type of nozzle is used because this forms the vena contracta surrounded by a region of very much reduced pressure exterior of the nozzle itself, with the result that the material in the casing will be drawn into the vena contracta and then accelerated by the jet under highly turbulent conditions giving rise to disintegration and grinding.

As indicated previously, in the region where a jet from a nozzle impinges upon the walls of an apparatus, or even where it joins flow of relatively low velocity there occurs intense turbulence with cavitation and the production of regions of low pressure. These regions are highly desirable for drying purposes since the evaporation is accelerated thereat. Consequently, in the portion of the apparatus following the auxiliary nozzles, as well as following the introductory nozzle, there occurs substantial evaporation, if that has not been completed in the jets.

Desirably, the jets are introduced on the outside of a curved portion of the apparatus, since centrifugal action at the high velocities tends to throw the particles into the jets. If desired, and to prevent any accumulation of material in wet state on the inside of the curved portion of the casing, nozzles may be located there as well as along the outside.

In the upright portion of the casing, the extremely fine mist (so fine that it exhibits a blue color if examined in white light) is undergoing continued evaporation, if that has not been completed. Inasmuch as the evaporation will result in cooling, particularly rapid cooling occurring after the kinetic energy has been transformed into heat energy, it is desirable to provide additional heat by means of the jacket 148. The proper design of the apparatus should result in complete drying by the time the upper end of the portion 130 of the casing is reached. The curved portion 132 of the casing then tends to produce centrifugal separation of the larger particles carried in the fluids stream. In case it is permissible to return the larger particles for further grinding an exit such as that indicated at 160 should be provided communicating with the inside of the portion of the apparatus immediately beyond the curved portion 132. Particles can only be removed through this exhaust by substantially completely reversing their direction of motion, and it is obvious, therefore, that with high velocities existing in the casing only quite small particles will be removed with the spent fluid. In some cases, particularly when the material is sensitive to heat, it is not desirable that it should return to the jet gases in a dry condition, and in such case the outlet may communicate tangentially with the outside of the casing so that substantially only gases devoid of particles will return. If return of the material must be prevented absolutely, then it is desirable that the apparatus should not be of cyclic form and all of the gases should be passed with their entrained particles to a separator.

The primary object of return of the gases, aside from further grinding where that is desirable, is to conserve the heat necessary for the operation. By recirculation accompanied by heating of the recirculated gas, the addition of drying gas may be held down to that merely necessary for the production of the jets without taking into consideration the much larger volume required to maintain the particles in suspension. It is far more economical to heat the recirculated gas than to compress and heat gas which is to be

used only once and then discharged while retaining a very considerable amount of heat energy. Unless recirculation is impossible by reason of the material being handled, it is desirable that it should be used. Jacketing of the nozzles may also be resorted to to secure the benefit of low grade and inexpensive heat. The returning blast of gases serves to admix them with the jet gases and thus aid in removing from the particles the more saturated portions of the jet gases. The jets are deflected laterally by this blast, and, as will be obvious from Figure 5, the jets tend to intersect each other, producing a turbulent region heated by the returning gases.

The pressure differential necessary to secure a critical pressure drop which is essential to the acquisition of acoustic or superacoustic velocities of the nozzle jets may be secured in various ways. For example, in the case of air elastic fluid may be provided at sufficiently high pressure to the nozzles, the exhaust being at atmospheric or somewhat higher or lower pressures. If air or other noncondensable elastic fluid is used, it is not generally economical to provide substantially reduced receiver pressures by evacuating apparatus. On the other hand, if steam or other condensable elastic fluid is fed to the nozzles a quite high vacuum may exist in the receiver, since a conventional condenser will suffice to produce that vacuum if associated with a vacuum pump merely sufficient to take care of the noncondensable gases which accumulate. A large drop of pressure beyond that necessary for the acquisition of the desired velocities may be effectively used for the production of the shock waves mentioned above. Condensation also serves to lower the pressure in the receiver and hence the boiling point of the liquid being evaporated.

The method and apparatus in accordance with the invention are applicable not only for simple drying, but processing in which drying is merely one step. For example, by introducing different materials capable of reacting on each other through different nozzles so arranged as to admit the suspensions which are formed may result in the attainment of an economical reaction characteristic of the substances followed by immediate drying of the product. This is advantageous where, as is frequently the case, the end product may not be safely exposed to the atmosphere because of oxidation. The reaction in such case may be carried out in an atmosphere of steam, and the products separated so that the material prior to drying does not come into contact with air. It also happens that in some cases a material in a fine state of division is not merely to be mixed with another material in the sense that the final particles may contain either material outermost or merely consist of a mixture of particles of both materials, but the first material may require a coating of the second material, so that the latter forms a protective layer preventing, for example, adhesion of the particles of the first material or, if the first material is hygroscopic in nature, the exposure of the particles of the first material to the atmosphere.

Figure 7 represents an apparatus capable of performing the results indicated above, for example, the chemical reaction of materials in fine suspension or, as specifically illustrated, the coating of one material by another. The apparatus comprises a continuous casing of generally tubular form having lower bend 200 from which flow takes place into an upwardly extending portion 202 surrounded by a jacket 204. From the

portion 202 the stream passes through a loop 206 into another straight portion 208 jacketed as indicated at 210. This in turn communicates with an outer bend 212 from which flow takes place into a downwardly extending portion 214 communicating with the bend 200 and jacketed as indicated at 216. The first material (that to be coated) is introduced through a conduit 218 discharging in the vicinity of the vena contracta of the jet from a nozzle 220 arranged as shown. The nozzle 220 may be of the abrupt type heretofore described designed to pick up and finely divide the wet material fed at 218. The cloud of material thus produced is subjected to the further actions of the jets (preferably intersecting) from nozzles 222, which may, for example, be of either De Laval or other expanding type in order to secure superacoustic velocities of discharge capable of effecting the proper drying of the suspended material. If the material as it reaches the first of these nozzles is not expected to be in a sufficiently fine state of division, the first of these nozzles may be of abrupt type, or other type designed to secure further breaking up of the particles. The material may be heated or cooled as it passes through the portion 202 of the casing, depending upon the types of materials used and the results desired.

If the material passing through 202 is dry, it will tend to separate centrifugally in the loop 206 and will thus be caused to pass directly across the mouth of the flaring entrance passage 228, which is arranged to feed into the loop in finely dispersed condition the second material entering it at 227, which is drawn inwardly and dispersed by the abrupt nozzles 229 fed with the elastic fluid through 226. In order to insure the complete admixture of the two materials, the entrance passage 228 may be distorted to open over a substantial portion of the circumference of the bend. The material previously dried is thus admixed with the wet droplets or particles of the material entering at 226. Further admixture is occasioned by the use of nozzles 230, which may be similar to nozzles 222, and produce, preferably, intersecting jets as indicated. These nozzles receive the elastic fluid from the chest 234. The result is the drying of the second material upon the first material, producing, for example, an impervious coating if this is desired. The finished material passes through the portion 208 of the casing where it is heated or cooled as may be desirable. Discharge may take place at 236, or further along the bend 212 if it is desired to produce a substantially complete separation in centrifugal fashion. If only extremely fine particles are to be separated, then the connection of the outlet is made to the inside of a portion of the apparatus, as in the case of the apparatus of Figure 5. The spent fluid may be returned through the portion 214 of the apparatus where it is reheated by means of the jacket 216.

It will be obvious that conditions in an apparatus of the type illustrated in Figure 7 may be widely varied for the purpose of producing chemical reaction and/or coating or admixture. The use of cooling is frequently desirable if crystals are to be obtained. For example, if a material is fed into the apparatus in solution, it may be subjected to the elevated temperatures and other action of jets to produce a preliminary concentration. If the concentration is carried out to the proper degree, then sudden cooling will produce crystallization. Thereafter, the further

evaporative action of the carrying fluid will dry the crystals.

It will be clear that numerous variations may be made in specific embodiments of the invention without departing from its scope.

What I claim and desire to protect by Letters Patent is:

1. The method of drying material including passing elastic fluid into a receiver through a nozzle to produce a jet having in at least a portion thereof a velocity of flow at least equal to the velocity of sound in the fluid of the jet having the same pressure and temperature as said portion of the jet, and being in the same portion unsaturated with vapors of the liquid to be evaporated so that evaporation may occur therein, introducing into said portion of the jet at a comparatively low velocity the material to be dried whereby the material is accelerated and subjected to a relative high velocity stream of the jet fluid under drying conditions, and separating the dried material from the spent fluid and vapor.

2. The method of drying material including passing elastic fluid into a receiver through a nozzle to produce a jet having in at least a portion thereof a velocity of flow at least equal to the velocity of sound in the fluid of the jet having the same pressure and temperature as said portion of the jet, introducing into said portion of the jet at a comparatively low velocity the material to be dried whereby the material is accelerated and subjected to a relatively high velocity stream of the jet fluid, and separating the dried material from the spent fluid and vapor.

3. The method of drying material including passing elastic fluid into a receiver through a nozzle to produce a jet having in at least a portion thereof a velocity of flow at least equal to the velocity of sound in the fluid of the jet having the same pressure and temperature as said portion of the jet, the receiver pressure being substantially different from the jet pressure at its entrance into the receiver so that shock waves are produced, introducing into the jet for flow through the region of said shock waves the material to be dried, and separating the dried material from the spent fluid and vapor.

4. The method of drying material including passing elastic fluid into a receiver through a nozzle to produce a high velocity jet, introducing into the jet material to be dried, separating dried material from partially dried material spent fluid and vapor, removing said dried material from the receiver, reheating at least a part of the spent fluid, and recirculating reheated fluid containing partially dried material through the region into which said nozzle discharges.

5. Apparatus for drying material comprising a receiver, a nozzle arranged to discharge into the receiver, means for supplying to the nozzle an elastic fluid under pressure, the pressure and nozzle construction being such that a jet is produced thereby having in at least a portion thereof a velocity of flow at least equal to the velocity of sound in the fluid of the jet having the same pressure and temperature as said portion of the jet, means for introducing into said portion of the jet at a comparatively low velocity the material to be dried whereby the material is accelerated and subjected to a relative high velocity stream of the jet fluid, and means for separating the dried material from the spent fluid and vapor.

6. Apparatus for drying material comprising a receiver, a nozzle arranged to discharge into the receiver, means for supplying to the nozzle an elastic fluid under pressure, the pressure and nozzle construction being such that a jet is produced thereby having in at least a portion thereof a velocity of flow equal to the velocity of sound in the fluid of the jet having the same pressure and temperature as said portion of the jet, the receiver pressure being substantially different from the jet pressure at its entrance into the receiver so that shock waves are produced, means for introducing into the jet for flow through said portion thereof the material to be dried, and means for separating the dried material from the spent fluid and vapor.

7. The method of drying material including passing elastic fluid into a receiver through a nozzle to produce a jet having in at least a portion thereof a velocity of flow at least equal to the velocity of sound in the fluid of the jet having the same pressure and temperature as said portion of the jet, introducing into said portion of the jet at a comparatively low velocity the material to be dried whereby the material is accelerated and subjected to a relatively high velocity stream of the jet fluid, providing relatively slow flow of elastic fluid from behind the nozzle about the jet and partaking of the general direction of flow of the jet, and separating the dried material from the spent fluid and vapor.

8. The method of drying material including providing a flow of elastic fluid within a receiver along a wall thereof, passing elastic fluid into the receiver through a nozzle having an outlet flush with said wall to produce a jet directed in the general direction of said flow and having in at least a portion thereof a velocity of flow at least equal to the velocity of sound in the fluid of the jet having the same pressure and temperature as said portion of the jet, introducing into the jet for flow through the said portion thereof the material to be dried whereby the material is subjected to a relatively moving stream of the jet fluid, and separating the dried material from the spent fluid and vapor.

9. The method of drying material including providing a flow of elastic fluid in a curved path within a receiver along a wall thereof, passing elastic fluid into the receiver through a nozzle having an outlet flush with said wall at the outside of the curved path to produce a jet directed in the general direction of said flow and having in at least a portion thereof a velocity of flow at least equal to the velocity of sound in the fluid of the jet having the same pressure and temperature as said portion of the jet, introducing into the jet for flow through the said portion thereof, and by centrifugal action of the curved flow of the first mentioned elastic fluid, the material to be dried whereby the material is subjected to a relatively moving stream of the jet fluid, and separating the dried material from the spent fluid and vapor.

10. The method of drying material including passing elastic fluid into a receiver through a nozzle to produce a jet having in at least a portion thereof a velocity of flow at least equal to the velocity of sound in the fluid of the jet having the same pressure and temperature as said portion of the jet, introducing into the jet for flow through the said portion thereof the material to be dried whereby the material is subjected to a relatively moving stream of the jet

fluid, passing elastic fluid into a receiver through a second nozzle to produce a second jet having in at least a portion thereof a velocity of flow at least equal to the velocity of sound in the fluid of the second jet having the same pressure and temperature as said portion of the second jet, causing material from the first jet to flow through said portion of the second jet whereby the material is again subjected to a relatively moving stream of jet fluid, and separating the dried material from the spent fluid and vapor.

11. The method of drying material including passing elastic fluid into a receiver through a nozzle to produce a jet having in at least a portion thereof a velocity of flow at least equal to the velocity of sound in the fluid of the jet having the same pressure and temperature as said portion of the jet, the nozzle being of a form providing breaking of the jet from its walls at said portion of the jet in which the velocity is at least equal to said sound velocity thereby providing a low pressure region about the jet at said portion thereof, introducing into said region the material to be dried whereby the material is subjected to a relatively moving stream of the jet fluid, and separating the dried material from the spent fluid and vapor.

12. The method of drying material including passing elastic fluid into a receiver through a nozzle to produce a high velocity jet, introducing into the jet material to be dried, separating dried material from the spent fluid, removing said dried material from the receiver, and recirculating, solely by the action of at least one jet into which material to be dried is introduced, at least part of the spent fluid through the region into which said nozzle discharges.

13. The method of drying material including passing elastic fluid into a receiver through a nozzle to produce a high velocity jet, introducing into the jet the material to be dried thereby to form a suspension thereof in a travelling stream of fluid, guiding said stream to follow a

curved path to separate centrifugally material carried thereby to cause fine dry material to separate from undried and coarse material, removing said fine dry material from the receiver, and recirculating at least part of the fluid containing coarse material, and from which fine dry material is separated, through the region into which said nozzle discharges.

14. The method of drying material including passing elastic fluid into a receiver through a nozzle to produce a high velocity jet, introducing into the jet the material to be dried, thereby to form a suspension thereof in a travelling stream of fluid, guiding said stream to follow a curved path to separate centrifugally material carried thereby to cause fine dried material to separate from undried and coarse material, removing said fine dried material from the receiver, reheating at least part of the fluid containing coarse material, and from which fine dry material is separated, by flow through an exteriorly heated passage, and recirculating said reheated fluid through the region into which said nozzle discharges.

15. Apparatus for drying material comprising a receiver, a nozzle arranged to discharge into the receiver, means for supplying to the nozzle an elastic fluid under pressure to produce a high velocity jet from the nozzle, means for introducing into the jet the material to be dried thereby to form a suspension thereof in a travelling stream of fluid, guiding walls for causing said stream to follow a curved path, thereby to separate centrifugally material carried thereby to cause fine dry material to separate from undried and coarse material, means for guiding said fine dry material in suspension from the apparatus, means for reheating at least part of the fluid containing coarse material, and from which fine dry material is separated, and means for recirculating said reheated fluid through the region into which said nozzle discharges.

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