May 30, 1967 H. COANDA 3,321,891

APPARATUS FOR TRANSPORTING ATOMIZABLE MATERIAL

Filed July 14, 1964

5 Sheets-Sheet 1

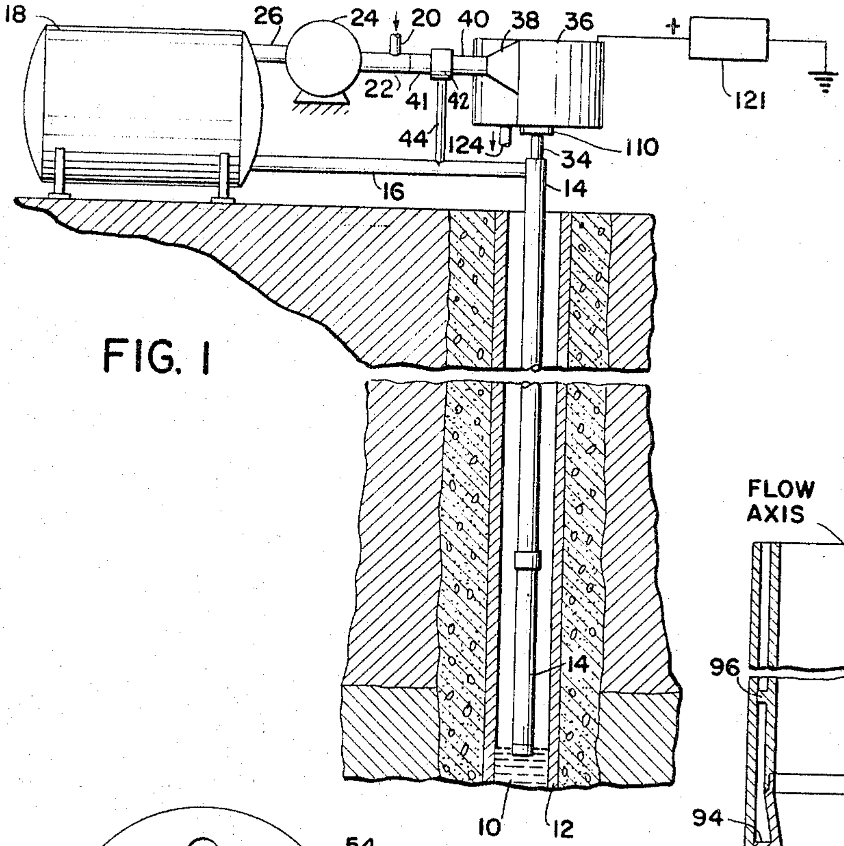

FIG. 1

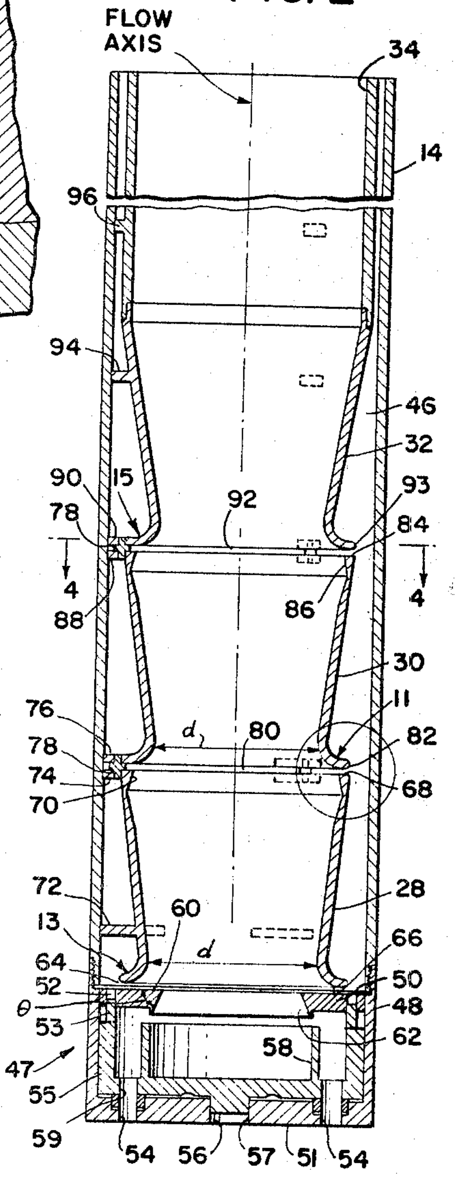

FIG. 2

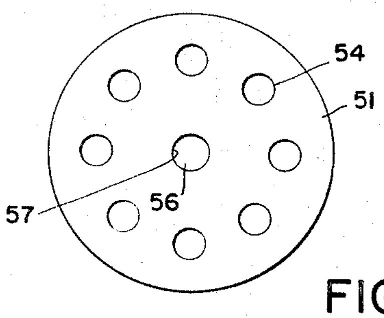

FIG. 3

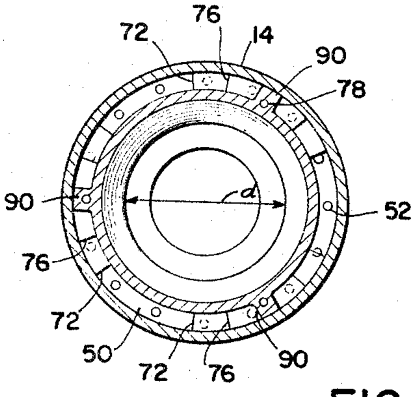

FIG. 4

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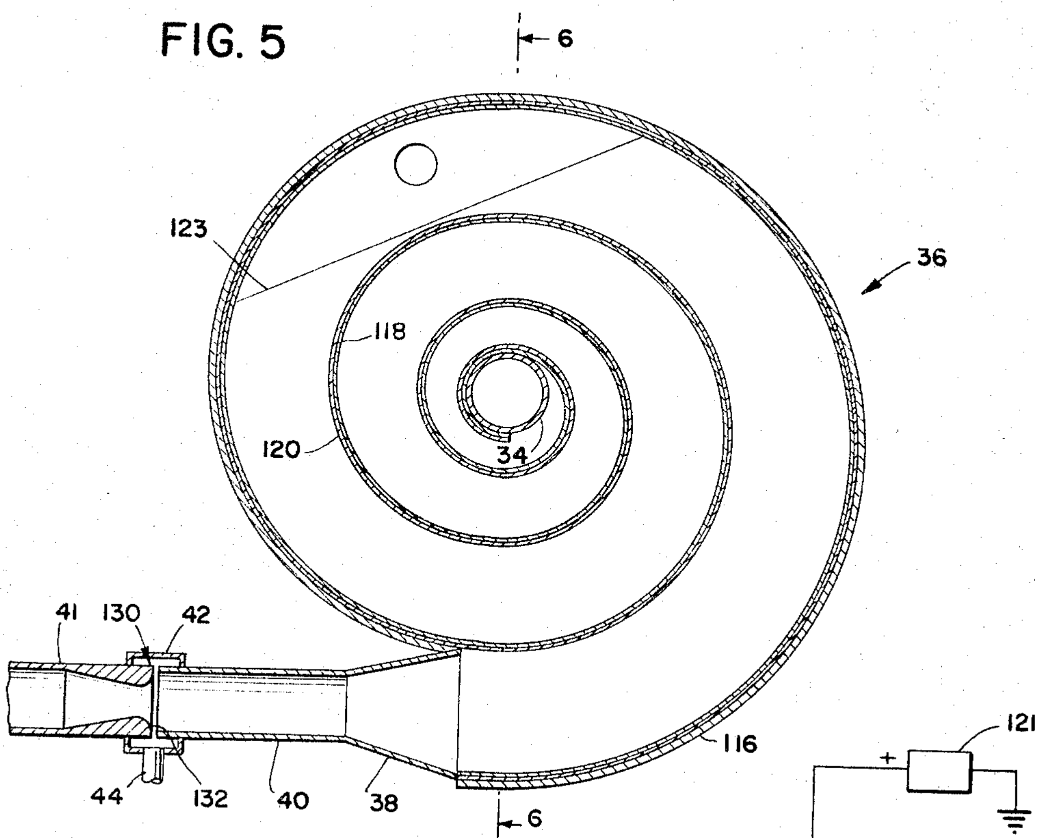
FIG. 5



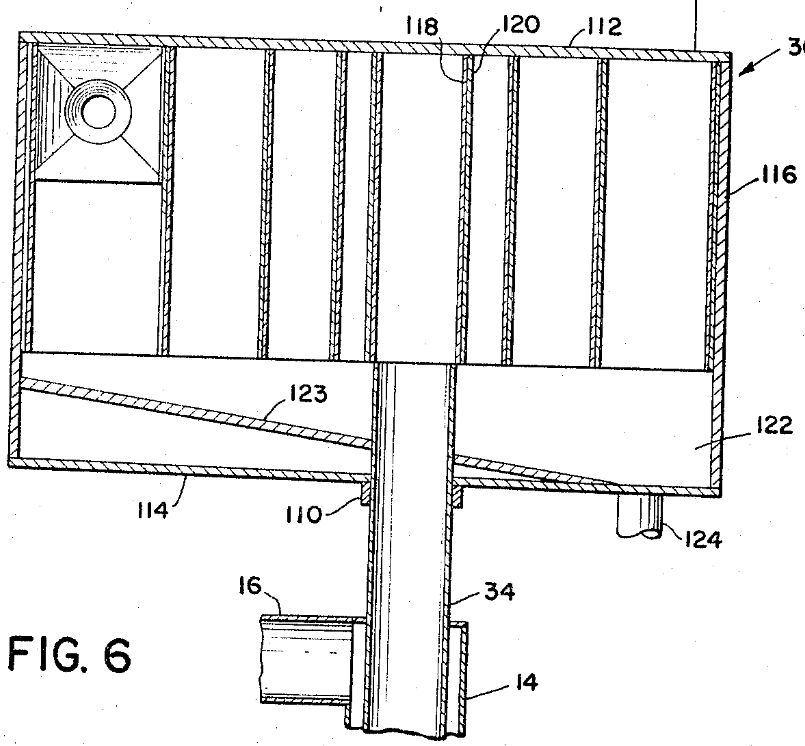


FIG. 6

APPARATUS FOR TRANSPORTING ATOMIZABLE MATERIAL

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FIG. 7

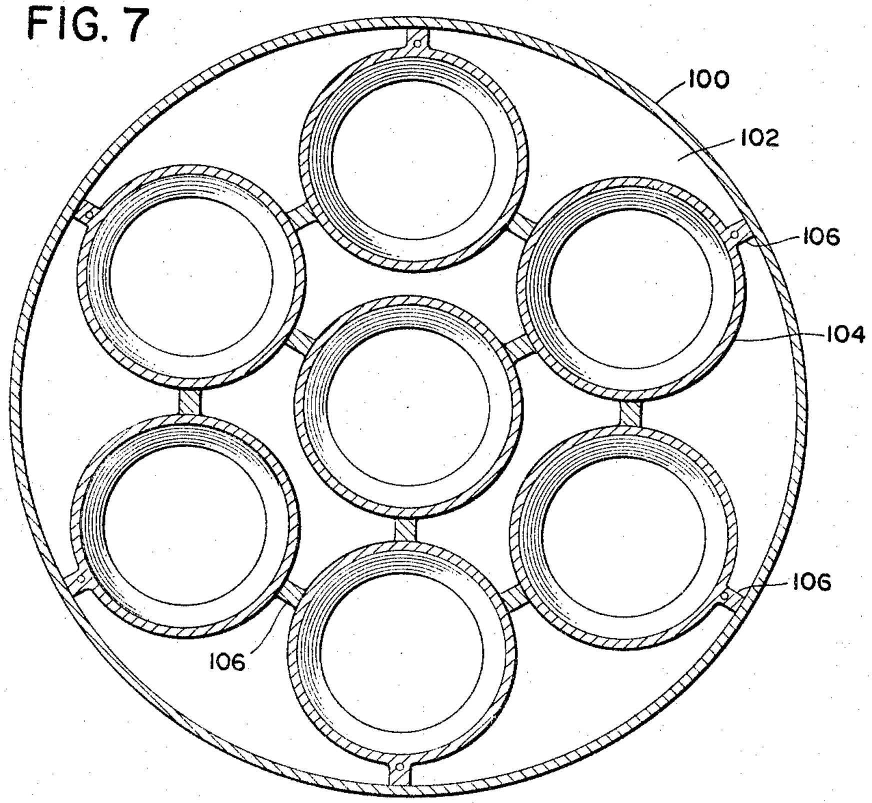
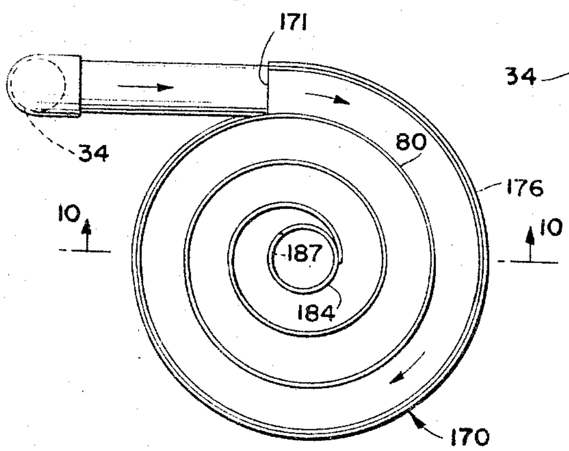


FIG. 9



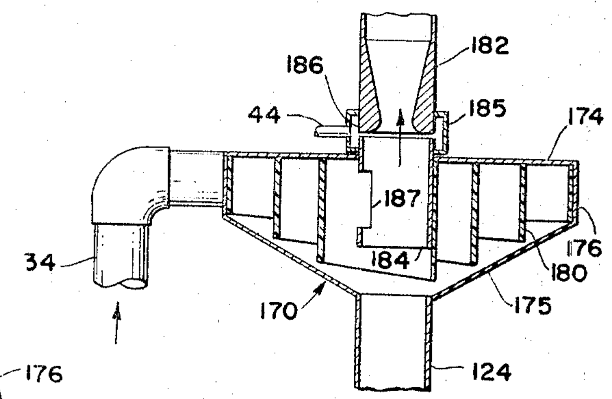


FIG. 10

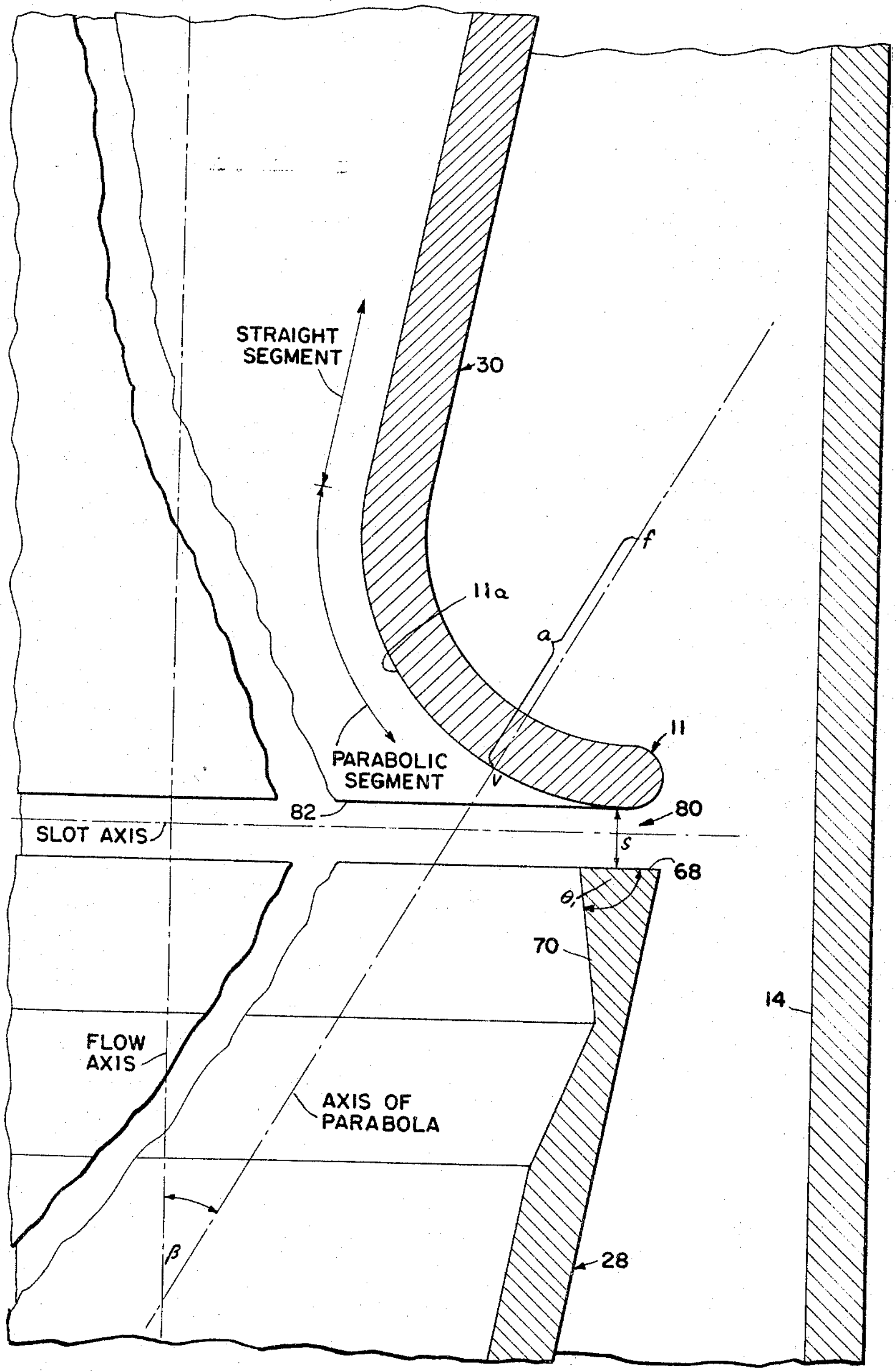
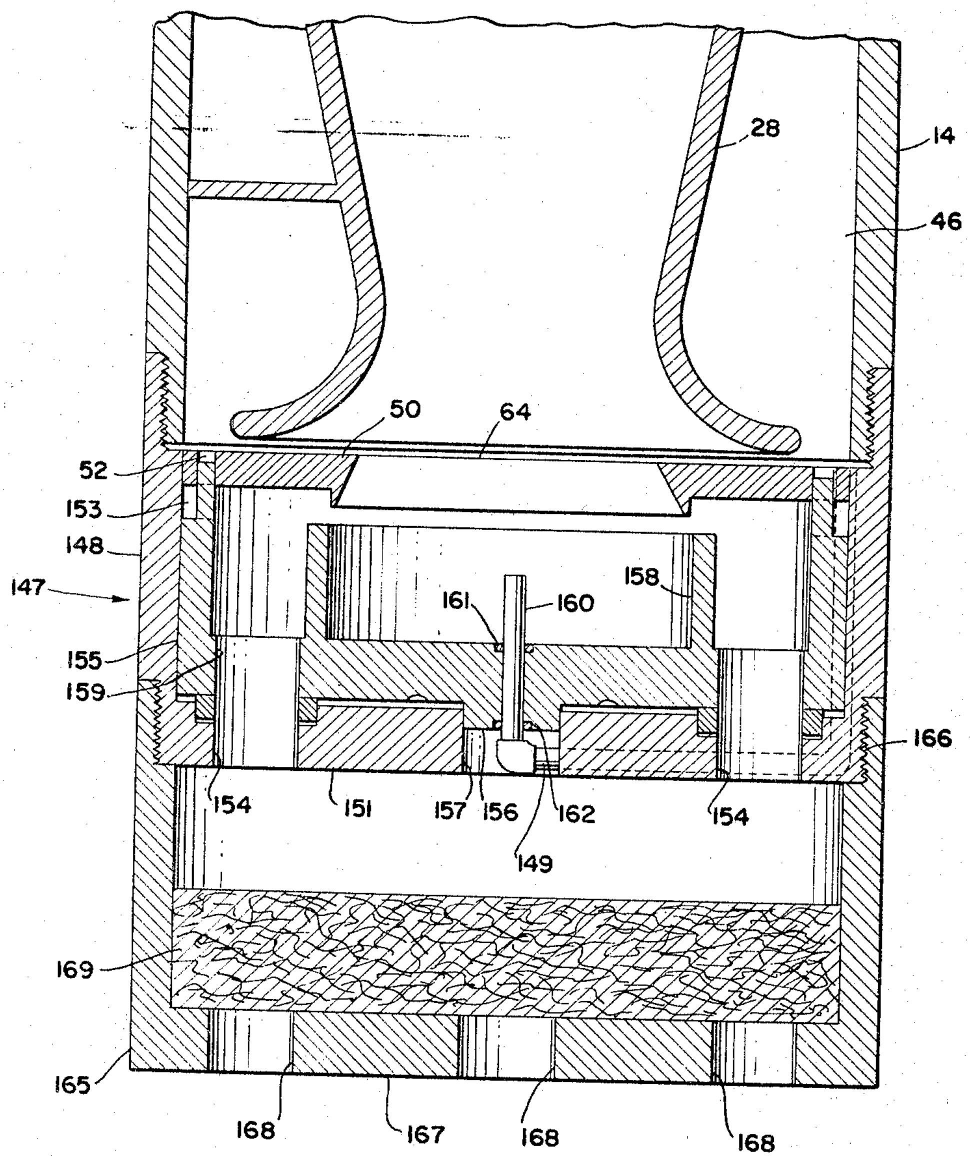

STRAIGHT SEGMENT
30
f
11a
a
11
PARABOLIC SEGMENT
V
82
80
SLOT AXIS
S
68
θ1
70
14
FLOW AXIS
AXIS OF PARABOLA
β
28

FIG. 8


28
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148
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FIG. 11

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APPARATUS FOR TRANSPORTING ATOMIZABLE MATERIAL

Henri Coanda, Paris, France
(777 Summer St., Stamford, Conn. 06902)

Filed July 14, 1964, Ser. No. 382,601
16 Claims. (Cl. 55—103)

This invention relates to an apparatus for transporting atomizable material and more particularly to such apparatus utilizing the physical phenomenon known as the Coanda effect.

The Coanda effect is the tendency of a jet of fluid to follow a wall contour when discharged adjacent to a surface, when that surface curves away from the jet discharge axis. As more fully described in U.S. Patent 2,052,869, granted Sept. 1, 1936, to Henri Coanda, the Coanda effect is apparent when a stream of fluid emerges from a container under pressure, through a slot or other aperture, if one of the lips of the slot orifice is extended and recedes continuously from the direction of the axis of the slot. Under such conditions, the fluid clings to the extended lip and tends to increase in velocity, producing a reduced pressure and therefore a suction and intake of large quantities of the surrounding fluid. For a more detailed discussion of representative Coanda nozzles for producing this effect, reference may be had, for example, to U.S. Patent 3,047,208, granted July 31, 1962, to Henri Coanda.

The atomization of liquids, for example, can be achieved by the removal of particles from a liquid mass by a stream of gas or other fluid, the separated or removed particles subsequently being capable of being projected in any desired direction. As soon as a quantity of the liquid is atomized, and due to the continuing presence of a zone of reduced pressure over the remaining liquid, another quantity of liquid may be atomized. This phenomenon may be realized by the use of a jet of fluid emerging from a slot, the nozzle being situated immediately above the liquid. By employing one or more Coanda nozzles to form the reduced pressure zone, the material is converted into an extremely fine and dry mist which may be readily transported along a flow path.

The present invention, while of general application, is particularly well suited for use in the removal of petroleum products from oil wells. Present day oil wells may reach depths of 5,000 feet or more. The cost of apparatus suitable for removing oil from such depths may be quite large, and the operation of the apparatus may be expensive. Under conditions where it is desired to increase the rate of flow of the oil from the well, as during primary recovery, etc., it often has been necessary heretofore to use comparatively complicated pumping equipment to bring the oil to the surface at the desired rate. These difficulties have been further compounded in cases in which it is desired to realize secondary recovery from the well, that is, to recover additional crude after the subsurface pressure has decreased sufficiently to prevent the efficient primary recovery of oil by natural pressure conditions. Oil at a depth of 5,000 feet or more is quite hot in its natural state, the temperature of the earth increasing at the rate of about 1° centigrade for each 100 foot increase in depth. Thus, oil at 5,000 feet will be about 50° hotter than oil just below the surface, reaching a temperature of about 70° C. In accordance with the invention, oil or other atomizable material at such temperatures is easily converted to a fine mist which may be readily elevated to the surface.

It is an object of this invention to provide an apparatus for elevating or otherwise transporting atomizable material along a flow path by application of the principles of the Coanda effect.

It is a particular object of this invention to provide

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such apparatus for economically removing petroleum products from deep wells.

It is another object of the invention to provide an improved apparatus for facilitating the primary and secondary recovery of sub-surface crude oil from a well.

It is a further object of this invention to provide apparatus for entraining atomizable material in a carrier fluid and subsequently separating the material from the carrier.

It is another object of this invention to provide a separator for the removal of atomized material from an entraining fluid.

Another object of this invention is to provide entraining apparatus for facilitating the secondary recovery of oil from a well.

Still another object of this invention is to provide entraining apparatus of the character indicated which is economical to manufacture and thoroughly reliable in operation.

Other objects will be apparent to those skilled in the art from reading the following description of various illustrative embodiments of the invention, taken in conjunction with the attached drawings, in which:

FIGURE 1 is a schematic view, with portions shown in section, of an oil well using the apparatus of this invention;

FIGURE 2 is a longitudinal cross-sectional view of one embodiment of apparatus for elevating material in accordance with the invention;

FIGURE 3 is a bottom view of the apparatus of FIGure 2;

FIGURE 4 is a transverse cross-sectional view taken generally along line **4—4** of FIGURE 2;

FIGURE 5 is a horizontal cross-sectional view of one type of seperator useful with the apparatus of FIGURE 1;

FIGURE 6 is a cross-sectional view taken generally along line **6—6** of FIGURE 5;

FIGURE 7 is a transverse cross-sectional view of apparatus for elevating material in accordance with another embodiment utilizing the principles of this invention;

FIGURE 8 is an enlarged cross-sectional view, partly broken away, of a portion of the apparatus of FIGURE 2;

FIGURE 9 is a horizontal cross-sectional view in general similar to FIGURE 5 but illustrating another type of separator useful with the apparatus;

FIGURE 10 is a cross-sectional view taken generally along line **10—10** of FIGURE 9; and

FIGURE 11 is an enlarged longitudinal cross-sectional view in general similar to a portion of FIGURE 2 but illustrating still another embodiment utilizing the principles of the invention.

In several particularly advantageous embodiments of the invention, a Coanda nozzle having a parabolic lip is positioned adjacent the atomizable material. The pressure along the lip is reduced by directing pressurized fluid (the primary fluid) through the Coanda nozzle and out its discharge aperture. As a result of this pressure reduction, a zone of high vacuum is formed which acts on the atomizable material to combine it with the pressurized fluid and form an extremely fine and dry mist of liquid particles. The mist is carried at a comparatively high velocity to a seperation point, where the atomized material is separated from the fluid by unique separating means.

The apparatus of the present invention will be described with regard to a preferred embodiment, that of elevating oil from a well, but it is to be understood that the invention is equally applicable to other embodiments for transporting material, whether solid or liquid, which is capable of being atomized by a flowing fluid.

In a preferred embodiment, there is provided a plurality of a coaxial convergent-divergent nozzles placed in operative relation to the oil or other atomizable material to be elevated. These nozzles define a flow path for the atomizable material and communicate with an elongated conduit which serves to carry the material to the surface of the well. Each nozzle has an inlet and a discharge end, and the nozzles are arranged in spaced relation with each other to define a narrow annular slot or annular aperture therebetween. The configuration of the inner walls of the convergent-divergent nozzles is such that the ends forming this slot or aperture serve as a Coanda nozzle. One or a plurality of Coanda nozzles may be used; however, three such nozzles are preferred for maximum economy and ease of operation. An outer member surrounds, substantially coaxially, the convergent-divergent nozzles and defines, with their outer surface, a chamber for the passage of gas or other fluid under pressure. The fluid preferably comprises a low boiling point, easily compressible gas, such as methane, which is inert to the materials which it will contact.

Pressurized gas from the outer chamber passes through a Coanda nozzle adjacent the inlet of the first convergent-divergent nozzle and forms a zone of reduced pressure along the portion of the inner convergent wall which defines the protruding lip of the Coanda nozzle. The reduced pressure causes the adjacent atomizable material, such as hot oil, to vaporize, thereby forming an exceedingly fine mist, and the entraining action of the moving gas carries the atomized particles into the first convergent-divergent nozzle. As the atomizable material is entrained in the carrier gas, a substantial pressure drop takes place adjacent the throat of this latter nozzle which serves to draw additional atomizable material into the continuing gas stream.

The entrained material and the entraining gas forming the mist pass through the discharge end of the first convergent-divergent nozzle and are accelerated by the succeeding assemblies of Coanda and convergent-divergent nozzles. The assemblies may be placed immediately adjacent one another, or if desired, may be spaced many feet apart, even hundreds of feet apart, by conduits, such as pipe. In oil wells, this is a subtantially vertical movement, but in other embodiments the flow may be horizontal or at any angle between vertical and horizontal or may change direction.

Upon reaching the surface or other destination, the atomized material and the entraining gas pass into a separator which advantageously is made in the form of a spiral. The gas passes from the middle to the periphery of the spiral and is subjected to centrifugal forces during passage through the separator. The partition forming the spiral configuration in the separator is made of an electrophorus material so that the friction between the atomized material and the surface of the partition causes a differential electrostatic charge to be induced between the atomized material and the partition material. Electrostatic attraction serves to draw the atomized material to the partition where it is condensed and flows downwardly to a common collection point. One example of a suitable electrophorus material for use with oil is Plexiglas (methyl methacrylate).

The nature of one form of nozzle assembly in accordance with the invention can best be understood with reference to FIGURES 2 and 8. As may be seen in FIGURE 2, the assembly includes a generally tapered hollow cylinder **30** having an inner wall which forms a convergent-divergent nozzle. The cylinder **30** has an inlet end **82** and an outlet end **84**, the inlet and outlet ends being substantially similar in size. The cylinder or nozzle **30** converges sharply to a throat having a minimum planar area of a diameter "*d*" and then continuously increases in size to its outlet end. The inlet end **82** is in spaced relationship with a surface **68** at the outlet end of a tapered hollow cylinder **28** forming a second convergent-divergent nozzle. The surface **68** and the end **82** define an annular Coanda nozzle **11** having a substantially circular discharge slot **80**.

FIGURE 8 is an enlarged, partially schematic view of the circled area in FIGURE 2. The inner convergent wall of the convergent-divergent nozzle **30** defines a protruding lip **11*a*** for the Coanda nozzle **11**. This lip continuously recedes from the axis of the slot **80** and is in the form of a parabolic segment which extends from the slot to a point adjacent the throat of the nozzle **30**. The axis of the parabola advantageously forms an acute angle "β" with the axis of flow of the materials through the nozzle **30**. The lip merges with a substantially straight segment which continuously diverges from the flow axis.

In certain important embodiments of the invention, the angle "β" is critical and lies within predetermined, well defined limits. This angle is determined in part by the viscosity of the material to be atomized and the width "*s*" of the Coanda slot **80**. In cases in which the fluid is of comparatively high viscosity, such as heavy crude oil, for example, the angle "β" is large, e.g., 37°–38°, while for fluids of lower viscosity a somewhat smaller angle is used, 30°, for example. In some advantageous arrangements, the angle "β" ranges between about 12° and 47° to achieve the optimum Coanda effect. In other cases, particularly when the fluid to be atomized is of extremely high or low viscosity, the angle may lie outside this range, again with good results. The vertex "*v*" of the parabola forming the Coanda lip is located on the inner convergent surface of the nozzle **30** and is spaced from the outlet of the Coanda slot **80**. The shape of the parabolic segment of the lip may be expressed in terms of the distance "*a*" between the vertex "*v*" and the focus "*f*" lying along the parabolic axis. In several good embodiments this distance "*a*" is closely related to the throat diameter "*d*" of the nozzle **30** such that the ratio d/a lies within a predetermined range. Preferably, the ratio extends between 2 and 40 to provide a lip of optimum shape.

Turning now to FIGURE 1, a body of oil **10** is shown adjacent to the base of a well casing **12**. A conduit **14** extends from the body of oil **10** to a point at the surface of the well and is connected by a gas conduit **16** to a high pressure gas receiver or storage tank **18**. The receiver **18** is filled with gas or other fluid which conveniently may comprise methane or other natural gas normally available at the well location. The gas is fed to the receiver through conduits **20** and **22** leading to a compressor **24** which compresses the gas to a comparatively high pressure and discharges it through a conduit **26** into the receiver **18**.

As is best shown in FIGURE 2, the lower portion of the conduit **14** contains within it a plurality of generally tapered hollow cylinders which form convergent-divergent nozzles **28**, **30** and **32**. The nozzles **28**, **30** and **32** are coaxially interconnected one above the other, and the uppermost nozzle **32** is connected to a conduit **34**. The conduit **34** extends through the conduit **14** to the surface of the well and connects to an electrostatic separator **36** (FIGURE 1). The separator **36** as, further described below, is connected through a duct **38**, a conduit **40** and a sleeve **42** to the conduit **22** leading to the compressor **24**. A conduit **44** connects the conduit **16** to the sleeve **42**.

The outer conduit **14** and the convergent-divergent nozzles **28**, **30** and **32** define an elongated, generally annular chamber **46**. A foot valve **47** is located beneath the nozzles **28**, **30** and **32** at the extreme bottom of conduit **14** and includes a hollow cylindrical member **48** which threadably engages the conduit. The upper end of the member **48** is partially closed by an annular plate **50** fixedly secured thereto, while a second plate **51** integrally formed with the member **48** partially closes its lower end. The plate **50** includes a series of circular openings **52** equally spaced around its periphery. These openings respectively accommodate a plurality of upstanding columns **53** which are integrally formed on the upper rim of a generally cup-shaped valve element **55**. The valve element 55 is reciprocably disposed within the member 48, and its central portion is provided with a depending pin 56 which is coaxial with the axis of flow and is slidably positioned in a mating aperture 57 in the bottom plate 51. The element 55 additionally includes an upwardly extending annular extension 58 concentric with the flow axis. The extension 58 is of a diameter smaller than the outer diameter of the element 55, and in the operated position (the position shown) its upper rim is oriented in spaced relationship with the adjacent portion of the annular plate 50.

The bottom plate 51 contains apertures 54 (FIGURE 3) adjacent its periphery which communicate with corresponding apertures 59 in the valve element 55. These apertures permit the flow of sub-surface oil into the annular chamber between the element 55 and the extension 58. The sub-surface pressure is comparatively high, illustratively being of the order of about 800 pounds per square inch. During the time the atomizing apparatus is shut down, the pressure produces a force acting on the lower surface of the pin 56 which urges the valve element 55 in an upward direction from the position shown in FIGURE 2 to bring the extension 58 into contact with the adjacent portion of the annular plate 50. The extension 58 and the plate 50 are thus effective to prevent the introduction of oil into the interior of the convergent-divergent nozzles 28, 30 and 32 and to block any outflow of oil which might remain within the nozzles or the conduit 14. As soon as fluid pressure of, say, 50 pounds per square inch is applied within the chamber 46, however, the relationship between the aggregate area of the exposed surfaces of the columns 53 and the lower surface area of the pin 56 is such that the force acting on the columns exceeds that acting on the pin. The element 55 thereby moves to its lower, operated position to enable the free transfer of oil into the space immediately beneath the nozzle 28.

The inner peripheral edge of the annular plate 50 tapers inwardly to form a converging surface 62 adjacent thel ower converging portion of the convergent-divergent nozzle 28. The upper horizontal surface 60 of the member 48 meets the surface 62 at an acute angle θ The nozzle 28 is supported in spaced relationship with the member 48 by three integrally formed brackets 72 affixed to the outer conduit 14. The facing portions of the nozzle 28 and the member 48 define an annular Coanda nozzle 13 having a protruding lip which is formed by the converging portion of the nozzle 28. The nozzle 28 then diverges continuously throughout the major portion of its axial length.

The inner wall of the convergent-divergent nozzle 28 is cut away adjacent the upper annular surface 68 of the nozzle such that the uppermost wall surface 70 meets the surface 68 at an acute angle θ_1 (FIGURE 8). The arrangement is such that the upper portion of the nozzle 28 converges and complements the converging portion of the convergent-divergent nozzle 30 thereabove. As indicated heretofore, the nozzles 28 and 30 are spaced apart to form the Coanda nozzle 11. The upper part of the nozzle 28 includes three integrally formed brackets 74 which act as spacers to maintain the spacial relation and disposition of the nozzle 28 within conduit 14. Moreover, the brackets 74 are maintained in spaced relation to three brackets 76 on the intermediate convergent-divergent nozzle 30 by spacers 78. The spacers 78 hold the nozzles 28 and 30 in spaced-apart relationship to form the annular slot 80 for the Coanda nozzle 11.

The convergent-divergent nozzle 30 has the same internal configuration as the nozzle 28, and its upper portion terminates in a surface 84 forming an acute angle θ_1 with the uppermost inner wall surface 86. The nozzle 30 is spaced apart from the uppermost convergent-divergent nozzle 32 by spacers 78 which are supported by three integrally formed brackets 88 and 90. The adjacent portions of the nozzles 30 and 32 form an annular Coanda nozzle 15 which defines a slot 92.

The convergent-divergent nozzle 32 has the same internal configuration as the convergent-divergent nozzles 28 and 30, except that the upper inner wall of the nozzle 32 continues to diverge and forms a smooth surface of substantially the same internal size as the conduit 34. The nozzle 32 is rigidly secured to the conduit 34, for instance by welding. Three brackets 94 support the nozzle 32 within the conduit 14. Similarly, three spacers 96 maintain the conduit 34 in substantially concentric relationship to the conduit 14.

As best shown in FIGURES 5 and 6, a separator 36 is connected to the upper end of the conduit 34 and is supported by a ring 110. The separator 36 includes an electrically conductive top plate 112, a bottom plate 114 and a spiral member 116 which forms the sides of the separator. Internally, the separator comprises a continuous spiral partition made up of an electrophorus material 118 on the inner side and a continuous metal band 120 on the outer side. As indicated heretofore, in some embodiments a differential electrostatic charge is induced on the electrophorus material as a result of frictional effects. In the illustrated embodiment, however, the metal band 120 is in electrically conductive relationship with the top plate 112, and the plate 112 is connected to the positive terminal of an electrostatic generator 121, the opposite terminal of which is at ground potential. The generator 121 is of conventional construction and is arranged to apply a high voltage positive charge to the band 120. An opposite or negative charge is thus formed on the electrophorus material. The partition formed by the electrophorus material and the band 120 does not extend to the bottom 114 of the separator but terminates above it, thus defining a chamber 122. A generally circular member 123 is positioned within the chamber 122 and is sloped to a discharge conduit 124 leading to the outlet line (not shown) for the well.

The upper interior portion of the separator 36 is connected by a tapered conduit 38 to a line 40. A sleeve 42 maintains the line 40 in spaced relationship with one end of a convergent-divergent nozzle 41. The line 40 and the nozzle 41 form a Coanda nozzle 130 which includes an annular slot 132. This slot is arranged to receive fluid under pressure from a conduit 44 connected to the conduit 16. The opposite end of the nozzle 41 is connected to the conduit 22 (FIGURE 1) leading to the compressor 24.

In operation, natural gas is compressed by the compressor 24 and is stored in the receiver 18, from which it is withdrawn through the conduit 16 into the chamber 46 between the conduit 14 and the convergent-divergent nozzles 28, 30 and 32. As best shown in FIGURE 4, the brackets 90 immediately above the uppermost Coanda slot 92 are somewhat narrower than the brackets 76 immediately above the intermediate Coanda slot 80, and these latter brackets are narrower than the brackets 72 above the lowermost Coanda slot 64. The openings between the brackets thus become progressively smaller, with the result that the pressure of the gas adjacent the slots 92, 80 and 64 progressively decreases. In the illustrated embodiment, the gaseous pressure adjacent the slot 80 is approximately eight-tenths the pressure adjacent the slot 92, while the pressure adjacent the slot 64 is about six-tenths the slot 92 pressure. The arrangement is such that the lifting action of the gas admitted through the slots is increased during each successive stage as the fluid within the nozzles 28, 30 and 32 moves toward the surface of the well.

The apparatus is arranged in the well such that the lowermost Coanda nozzle 13 is positioned immediately adjacent the sub-surface oil 10 to be atomized. The gas passing through the slot 64 and into the convergent-divergent nozzle 28 is drawn toward the Coanda lip formed by the throat of the nozzle 28 and flows in an upward direction. A zone of reduced pressure is formed which begins along the Coanda lip and extends across the throat. The reduced pressure causes the pool of oil 10 to be atomized and sucked into the nozzle 28, thus combining the oil and gas to form a fine mist. The higher pressure gas passing through the slot 80 for the Coanda nozzle 11 similarly produces suction of the atomized and entrained particles and greatly accelerates their movement toward the surface. A third stage of acceleration and lifting takes place as a result of the high pressure gas passing into the Coanda nozzle 15. The gas is directed through the Coanda slot 92 and serves to impart sufficient velocity to the mist to carry it to the surface. By propelling the oil to the surface in mist form, considerably less energy need be expended than would otherwise be the case.

At the surface, the atomized oil particles and accompanying gas pass from the conduit 34 into the separator 36. Because of their rapid movement from the bottom of the well, the oil particles exhibit an electron loss and acquire a comparatively high positive charge. In the separator 36, the individual particles are attracted by the negatively charged electrophorus material 118 (FIGURE 6) and are collected thereon. This action is enhanced by the centrifugal forces acting on the particles as a result of the spiral passageway within the separator, the centrifugal forces tending to throw the relatively heavy particles against the material 118. The spiral passageway preferably is of continuously increasing horizontal width, so that the gas entraining the oil particles continuously slows during its passage through the separator. The slowing of the entraining medium reduces the tendency of the particles to remain entrained and aids in their separation.

The oil particles contacting the electrophorus material 118 are agglomerated or condensed and flow by gravity down the partition into the chamber 122. The condensed particles move along the sloping member 123 and are discharged in liquid form through the conduit 124.

It is preferable that the entraining gas be recoverable. Accordingly, the gas circulates in a closed system, the recovered gas from the separator 36 being returned to the storage tank 18 (FIGURE 1). The gas stripped of the oil enters the conduits 38 and 40 and is accelerated by high pressure gas passing through the Coanda nozzle 130. The thus accelerated oil-stripped gas is returned to the tank 18 through the conduit 22, the compressor 24 and the conduit 26.

Referring to FIGURE 7 of the drawings, there is shown an alternate embodiment in which a plurality of mist producing apparatus 104, each generally similar to the mist producing apparatus of FIGURE 2, are spaced apart on parallel axes. An outer casing 100 surrounds the apparatus 104 and defines a pressurized gas chamber 102. The apparatus are maintained in spaced relationship with each other and with the casing 100 by supporting brackets 106. Because each coaxial assembly of Coanda and convergent-divergent nozzles is capable of elevating a particular amount of material, depending on the throat size, etc., the amount of material elevated is increased in direct proportion to the number of assemblies employed.

In the embodiment of FIGURES 5 and 6, the separator 36 is arranged to receive the oil and gas mist from the conduit 34 at a centrally located opening and to discharge the separated gas through the duct 38 adjacent the separator periphery. In other advantageous embodiments, the mist is received at a peripheral opening in the separator, and the gas is discharged through a central opening. As an illustration, in FIGURES 9 and 10 there is shown a separator 170 which receives the incoming mist from the conduit 34 at a peripherally located opening 171. The separator 170 includes a top plate 174, a substantially conical bottom plate 175 and a spiral member 176 which defines the sides of the separator. A continuous spiral band 180 of electrophorus material is arranged inside the separator in spaced relationship with

the bottom plate 175. The lower portion of the bottom plate defines a circular opening which is in communication with the outlet line 124 for the well. The interior of the separator communicates with a centrally located convergent-divergent nozzle 182 which extends in an upward direction, as viewed in FIGURE 10. The nozzle 182 is maintained in spaced relationship with one end of a coaxial conduit 184 within the separator by a sleeve 185. The facing portions of the nozzle 182 and the sleeve 185 form a Coanda nozzle 186. This sleeve is connected to the conduit 44 and is supplied with fluid under pressure in a manner similar to that described heretofore.

As the oil and gas mist from the conduit 34 is introduced into the separator 170 through the opening 171, the mist spirals inwardly along the path defined by the band 180. The positively charged oil particles are attracted toward the inner surface of the band and are collected thereon. The collected particles are condensed and flow by gravity down the inner band surface and along the bottom plate 175 to the outlet line 124. The entraining gas, on the other hand, passes through an aperture 187 in the centrally located conduit 184 and is drawn by the Coanda nozzle 186 into the convergent-divergent nozzle 182. The thus accelerated oil-stripped gas returns from the nozzle 182 to the storage tank 18 (FIGURE 1).

The electrostatic separators 36 and 170 are of particular utility in facilitating the secondary recovery of crude oil from the well after the sub-surface pressure has decreased sufficiently to prevent the efficient recovery of oil by natural pressure conditions. In some cases, however, separation following secondary recovery is accomplished by other types of separating apparatus. As an illustration, apparatus of the so-called "heater-treater" type conventionally employed to facilitate secondary recovery sometimes may be used with good effect.

Apparatus in accordance with the invention also may be employed to provide increased production during the initial or primary recovery of oil from the well. In some arrangements, assemblies of Coanda and convergent-divergent nozzles, each of the type shown in FIGURE 2, for example, are positioned at intervals of, say, a thousand feet to provide thrust augmentation at particular points during the passage of the oil to the surface.

As indicated heretofore, in the illustrated embodiments of the invention the primary or pumping fluid advantageously comprises methane or other gaseous material. In other arrangements, however, a liquid such as water, various petroleum products, etc., may be directed down the well and through the Coanda nozzles, again with good results. The use of such liquids is particularly advantageous during primary recovery, but in some cases they also may be employed during secondary recovery.

Referring now to FIGURE 11, there is shown a modified foot valve 147 which is threadably secured to the lower portion of the conduit 14 in a manner similar to that described heretofore with respect to the discussion of the foot valve 47 (FIGURE 2). The valve 147 comprises a hollow cylindrical member 148 and a bottom plate 151 integrally formed therewith. These components are generally similar to the member 48 and the plate 51 of the valve 47 but include a fluid conduit 149 which extends vertically through the cylindrical wall of the member 148 and then radially through the plate 151. One end of the conduit 149 communicates with the annular chamber 46, while the other end protrudes into the centrally located aperture 157 of the plate 151. The protruding end of the conduit 149 is connected to an upstanding conduit 160 which is disposed within an axial opening in the depending pin 156 and the adjacent portion of the cup-shaped valve element 155. Two O-rings 161 and 162 surround the conduit 160 to prevent leakage during the movement of the element 155. With this arrangement, the chamber 46 at all times is maintained in communication with the inlet chamber formed by the annular extension 158 of the valve element 155, for purposes that will become more fully apparent hereinafter.

A hollow cylindrical member 165 is disposed immediately beneath the valve element 147 and is suitably affixed thereto, as by threads 166. The lower end of the member 165 is closed by an integrally formed plate 167 which includes a series of apertures 168 therein to permit the free passage of sub-surface crude oil into the interior of the member 165. The plate 167 supports a filter 169 which advantageously is fabricated from individually felted metal fibers bonded into a permanent porous structure.

The sub-surface crude oil flows through the apertures 168 and is filtered by the filter 169 in the cylindrical member 165. Prior to the atomizing operation, the pressure of the oil within the member 165 acts on the lower surface of the pin 156 to urge the valve element 155 upwardly from the position shown in FIGURE 11 such that the extension 158 contacts the annular plate 50 to maintain the valve in its closed position. The sub-surface oil is thus prevented from flowing from the apertures 154 and 159 in the plate 151 and the element 155 into the chamber formed by the extension 158.

Upon the introduction of compressed gas or other primary fluid into the annular chamber 46, the pressure of the fluid acting on the exposed surfaces of the upstanding columns 153 on the valve element 155 serves to move the element to its lower, open position (the position shown) in a manner similar to that described heretofore with respect to the element 55 (FIGURE 2). The crude oil within the apertures 154 and 159 thereby flows into the space immediately beneath the convergent-divergent nozzle 28. A portion of the primary fluid is led through the conduits 149 and 160 and is directed upwardly in an axial direction into the oil within this space. The fluid discharged from the conduit 160 entrains a quantity of the surrounding oil and directs the oil to a position adjacent the Coanda slot 64. The lifting action of the fluid moving through the Coanda slot produces substantial acceleration of the thus entrained oil to form a fine mist which is carried to the surface of the well in the manner described above.

The entrainment of the oil beneath the convergent-divergent nozzle 28 by the fluid discharged from the conduit 160 is particularly effective to facilitate the initiation of the atomizing operation and to ensure that the various Coanda and convergent-divergent nozzles operate at optimum efficiency. In addition, the fluid exhibits a damping effect on the valve element 155 and thereby further stabilizes its operation under widely varying pressure conditions.

Although the invention has been described as having particular application in the transporting of crude oil by means of a gas or liquid under pressure, it is not, in its broadest aspects, restricted to such application. Thus, the invention is broadly applicable to the movement of a wide variety of atomizable materials through the use of various pressurized fluids. As an illustration, some particularly effective arrangements are useful as air purification devices in coal mines, for example, to transport solid particles of coal, silicone dust, etc., from working locations. The fluid directed through the individual Coanda slots may be gaseous in form, or water or other liquid may be used as the driving fluid with good effect. Other uses for the apparatus will suggest themselves to those skilled in the art upon a perusal of the foregoing description.

The terms and expressions which have been employed are used as terms of description and not of limitation, and there is no intention in the use of such terms and expressions of excluding any equivalents of the features shown and described or portions thereof, but it is recognized that various modifications are possible within the scope of the invention claimed.

What is claimed is:

1. Apparatus for transporting an atomizable material along a flow path comprising a Coanda nozzle defining an aperture adjacent said atomizable material, means for directing pressurized fluid into said Coanda nozzle and through said aperture, said Coanda nozzle including a parabolic lip surface that recedes continuously from the axis of said aperture, the parabolic axis of said parabolic lip surface forming an acute angle with the axis of said Coanda nozzle, whereby the flow of fluid through said aperture into and through said nozzle reduces the pressure along said lip surface and causes the atomization of the atomizable material and its entrainment by said fluid, said axis of said aperture meeting said flow path at a substantial angle, means for carrying the atomized entrained material to a point of separation from said fluid, and means for separating said entrained material from said fluid.

2. Mist producing apparatus comprising means defining a flow path in juxtaposition with a supply of atomizable material, a Coanda nozzle including an aperture in communication with said flow path, said Coanda nozzle having a parabolic lip surface that recedes continuously from the axis of said aperture, the parabolic axis of said surface forming an acute angle with the direction of flow along said path, said acute angle lying within the range of from about 12 degrees to about 47 degrees, means for directing pressurized fluid to said Coanda nozzle and through said aperture, the direction of the pressurized fluid as it moves through said aperture being at substantially right angles to said flow path, said fluid providing a reduced pressure within said path defining means and combining with said atomizable material to form a finely divided mist, means for carrying said mist to a point of separation of the atomized material, and means for separating said atomized material from said fluid.

3. Apparatus for conveying atomizable material comprising path defining means in juxtaposition with a supply of atomizable material including a first nozzle and a second nozzle in axial alignment with one another, said first and second nozzles being axially spaced apart in nonoverlapping relationship with each other, the facing portions of said nozzles forming a Coanda nozzle and defining a discharge slot therefor, said Coanda nozzle including a parabolic lip surface that recedes continuously from the discharge axis of said slot, the parabolic axis of said parabolic lip surface forming an acute angle with the axis of said Coanda nozzle, conduit means surrounding and spaced apart from said first and second nozzles, means for directing pressurized fluid into the space between said conduit means and said first and second nozzles, said fluid flowing through said Coanda nozzle and out said discharge slot to induce the atomization and entrainment of said atomizable material, and means for transporting the atomized material to a point of separation from said fluid.

4. Apparatus for conveying atomizable material comprising means including a first nozzle and a second nozzle in coaxial alignment with one another, said first and second nozzles being axially spaced apart in nonoverlapping relationship with each other, the facing portions of said nozzles forming a Coanda nozzle positioned adjacent the material to be atomized, said Coanda nozzle defining a discharge slot and having a parabolic lip surface that recedes continuously from the discharge axis of said slot, the parabolic axis of said surface forming an acute angle with the axis of said first and second nozzles, said acute angle lying within the range of from about 12 degrees to about 47 degrees, conduit means surrounding and spaced apart from said first and second nozzles, means for directing pressurized fluid into the space between said conduit means and said first and second nozzles, said fluid flowing through said Coanda nozzle and out said discharge slot to induce the atomization and entrainment of said atomizable material, means for transporting the atomized material to a point of separation from said fluid, and electrostatic means for separating said atomized material from said fluid.

5. Mist producing apparatus comprising a first nozzle and a second nozzle positioned adjacent a supply of atom-

izable material, said first and second nozzles being in coaxial alignment with and spaced from one another, the facing portions of said nozzles forming a Coanda nozzle and defining a discharge slot therefor, said Coanda nozzle having a parabolic lip surface that recedes continuously from the discharge axis of said slot, the parabolic axis of said surface meeting the axis of said first and second nozzles at an acute angle which lies within the range of from about 12 degrees to about 47 degrees, the ratio between the minimum internal diameter of at least one of said first and second nozzles and the distance from the vertex to the focus of said parabolic surface being about 2 to about 40, conduit means surrounding and spaced apart from said first and second nozzles, means for directing pressurized fluid into the space between said conduit means and said first and second nozzles, said fluid flowing through said Coanda nozzle and out of discharge slot to induce the atomization and entrainment of said atomizable material,to thereby form a finely divided mist, the fluid flowing through said slot being at a substantial angle with respect to the axis of said first and second nozzles, and means for transporting said mist to a point of separation of the atomized material from said fluid.

6. Apparatus for conveying atomizable material comprising a pair of convergent-divergent nozzles in coaxial alignment with one another to define a flow path for said atomizable material, said nozzles being axially spaced apart in non-overlapping relationship with each other to form an axially extending gap therebetween, the portions of said nozzles facing each other forming a Coanda nozzle and said axial gap defining discharge slot therefor, the convergent portion of at least one of said convergent-divergent nozzles having the form of a parabola revolved about the axis of material flow, to form a parabolic lip for said Coanda nozzle that recedes continuously from the discharge axis of said slot, the axis of said parabola forming an acute angle with the axis of said convergent-divergent nozzles, means defining an annular chamber surrounding said convergent-divergent nozzles, means for directing pressurized fluid into said chamber, said fluid flowing through said Coanda nozzle and out of said discharge slot to induce the atomization and entrainment of said atomizable material, said material combining with said fluid to form a finely divided mist, means for transporting said mist to a point of separation of the atomized material from said fluid, and means including a separator connected to said last-mentioned means for separating said atomized material from said fluid.

7. Apparatus for conveying atomizable material comprising means defining a flow path for said atomizable material, a plurality of Coanda nozzles positioned adjacent said flow path, each of said Coanda nozzles having a discharge slot and a parabolic lip surface that recedes continuously from the discharge axis of said slot, the parabolic axis of said surface forming an acute angle with the direction of flow along said path, means for directing pressurized fluid through said Coanda nozzles and out the discharge slots thereof to induce the atomization and entrainment of said atomizable material, said material combining with said fluid to form a finely divided mist, the fluid flowing through said slots being at a substantial angle with respect to said flow path, means for transporting said mist to a point of separation of the atomized material from said fluid, and means including a separator connected to said last-mentioned means for separating said atomized material from said fluid.

8. Apparatus of the character set forth in claim 7 which includes means for maintaining an increasingly higher fluid pressure at successive ones of said discharge slots.

9. Apparatus for elevating petroleum from a well comprising first, second and third convergent-divergent nozzles positioned in juxtaposition with the petroleum to be elevated, conduit means connecting said convergent-divergent nozzles to the surface of said well to define a flow path for said petroleum, said convergent-divergent nozzles being arranged in coaxial alignment with one another and being axially spaced apart in nonoverlapping relationship with each other, means in spaced relationship with said first convergent-divergent nozzle for forming a first Coanda nozzle therewith, the facing portions of said convergent-divergent nozzles forming a second and a third Coanda nozzle, each of said Coanda nozzles having a discharge slot and a parabolic lip surface that recedes continuously from the discharge axis of said slot, the parabolic axis of said surface forming an acute angle with the axis of said convergent-divergent nozzles, means defining an annular chamber surrounding said conduit means and said convergent-divergent nozzles, a source of fluid under pressure, means for directing fluid from said source into said chamber and through said Coanda nozzles to induce the atomization and entrainment of said petroleum, said petroleum combining with said fluid to form a finely divided mist, means connected to said conduit means at the surface of said well for receiving said mist, and separator means at said well surface for separating the atomized petroleum from said fluid.

10. Apparatus of the character set forth in claim 9 in which said separator means includes a fourth Coanda nozzle supplied with fluid from said source for facilitating the separation of fluid from said petroleum.

11. Apparatus for elevating petroleum from a well comprising first, second and third convergent-divergent nozzles positioned in juxtaposition with petroleum to be elevated, conduit means connecting said convergent-divergent nozzles to the surface of said well to define a flow path for said petroleum, said convergent-divergent nozzles being arranged in coaxial alignment with one another and being axially spaced apart in nonoverlapping relationship with each other, means in spaced relationship with said first convergent-divergent nozzle for forming a first Coanda nozzle therewith, the facing portions of said convergent-divergent nozzles forming a second and a third Coanda nozzle, each of said Coanda nozzles having an annular discharge slot and a parabolic surface the axis of which forms an acute angle with the axis of said convergent-divergent nozzles, means defining an annular chamber surrounding said conduit means and said convergent-divergent nozzles, means for directing pressurized fluid into said chamber and through the discharge slots of said Coanda nozzles to induce the atomization and entrainment of said petroleum, said petroleum combining with said fluid to form a finely divided mist, means connected to said conduit means at the surface of said well for receiving said mist, and a separator at said well surface and including a housing having a spiral wall of dielectric material therein for separating the atomized petroleum from the carrier fluid.

12. Apparatus of the character set forth in claim 11 in which the acute angle between the parabolic axis for each of said Coanda nozzles and the axis of said convergent-divergent nozzles lies within the range of from about 12 degrees to about 47 degrees, the ratio between the throat diameter of each said convergent-divergent nozzle and the distance from the vertex to the focus of the parabolic surface for the corresponding Coanda nozzle being about 2 to about 40.

13. In apparatus for elevating atomized petroleum from a well, an electrostatic separator at the surface of said well for separating the atomized petroleum from a carrier gas, said separator comprising a housing, a spiral wall supported within said housing in spaced relationship with the bottom thereof, said wall defining a substantially spiral chamber and including an inner surface of dielectric, electrophorus material and an outer surface of electrically conductive material, first conduit means for introducing a finely divided mist of said atomized petroleum and carrier gas into said spiral chamber, the petroleum particles within said mist having a predetermined electrostatic charge, means for producing a different electrostatic

charge on the inner surface of said wall, whereby said petroleum particles are attracted to said inner surface and are collected thereon, second conduit means communicating with said spiral chamber and including a Coanda nozzle for withdrawing the separated carrier gas from said chamber, and discharge means located at the bottom of said housing for receiving the petroleum particles collected on said surface.

14. Apparatus for elevating petroleum from a well comprising a plurality of convergent-divergent nozzles positioned in juxtaposition with the petroleum to be elevated, said convergent-divergent nozzles being arranged in coaxial alignment with and spaced from one another, the facing portions of said nozzles forming a first Coanda nozzle, valve means in spaced relationship with the convergent end of one of said convergent-divergent nozzles for forming a second Coanda nozzle therewith, each of said Coanda nozzles having a parabolic surface the axis of which forms an acute angle with the axis of said convergent-divergent nozzles, means defining an annular chamber surrounding said convergent-divergent nozzles, conduit means communicating with said annular chamber and including a portion adjacent the petroleum to be elevated in coaxial relationship with said convergent-divergent nozzles, a source of fluid under pressure, means for directing fluid from said source into said annular chamber and through said conduit means and said Coanda nozzles, said valve means including means for preventing the flow of petroleum into said one convergent-divergent nozzle until the fluid in said conduit means reaches a predetermined pressure, the fluid discharged from said conduit means then entraining said petroleum and directing the same to a position adjacent said second Coanda nozzle, the fluid discharged from said Coanda nozzles accelerating and atomizing said petroleum as it passes through said convergent-divergent nozzles, said petroleum combining with said fluid to form a finely divided mist, and means connecting said convergent-divergent nozzles to the surface of said well for transporting said mist to a point of separation of the atomized petroleum from said fluid.

15. Apparatus for elevating atomizable liquid comprising a plurality of convergent-divergent nozzles in coaxial alignment with and spaced from one another, the facing portions of said nozzles forming a first Coanda nozzle, valve means in spaced relationship with one of said convergent-divergent nozzles for forming a second Coanda nozzle therewith, each of said Coanda nozzles having a discharge slot and a parabolic surface the axis of which forms an acute angle with the axis of said convergent-divergent nozzles, conduit means surrounding and spaced apart from said convergent-divergent nozzles, means for directing pressurized fluid into the space between said conduit means and said convergent-divergent nozzles, said valve means including a movable element having a first portion communicating with said space and a second portion communicating with the liquid to be atomized, the pressure of said liquid on said second portion holding said element in a position to prevent liquid flow to said convergent-divergent nozzles until the pressurized fluid enters said space, said fluid thereupon acting on said first portion to move said element in a direction to permit the flow of liquid to said convergent-divergent nozzles, said fluid flowing through said Coanda nozzles and out the discharge slots thereof to induce the atomization and entrainment of said liquid and thereby form a finely divided mist, means for transporting said mist to a point of separation of the atomized liquid from said fluid, and means including a separator connected to said last-mentioned means for separating said liquid from said fluid.

16. Apparatus of the character set forth in claim **15**, in which said valve means includes a fluid conduit communicating with said space and having a portion extending in coaxial relationship with said convergent-divergent nozzles, said conduit directing pressurized fluid from said space into said one convergent-divergent nozzle.

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HARRY B. THORNTON, *Primary Examiner.*

ROBERT F. BURNETT, D. TALBERT, *Assistant Examiners.*