

Feb. 16, 1960

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2,925,224

NOZZLES FOR THE PRODUCTION OF FINE PARALLEL JETS

Original Filed March 28, 1957

2 Sheets-Sheet 1

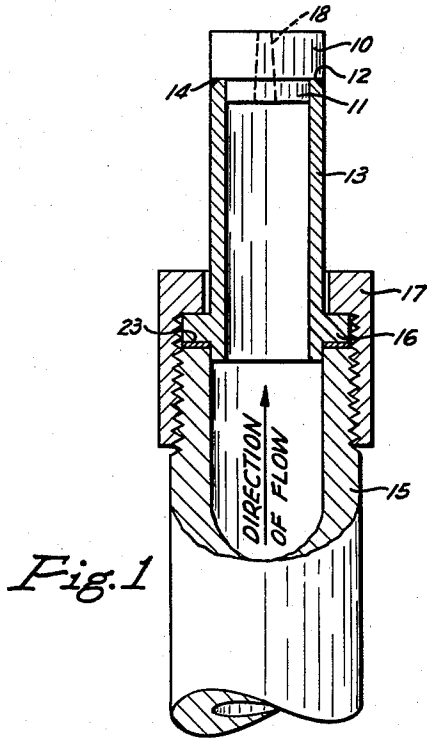


Fig. 1

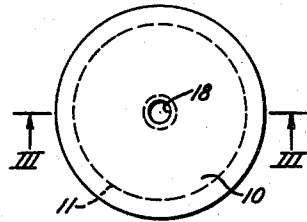


Fig. 2

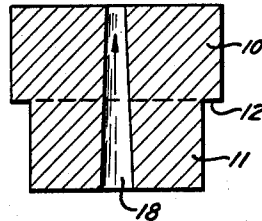


Fig. 3

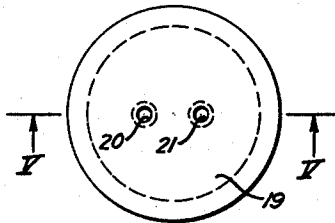


Fig. 4

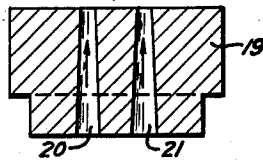


Fig. 5



Fig. 6

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2 Sheets-Sheet 2

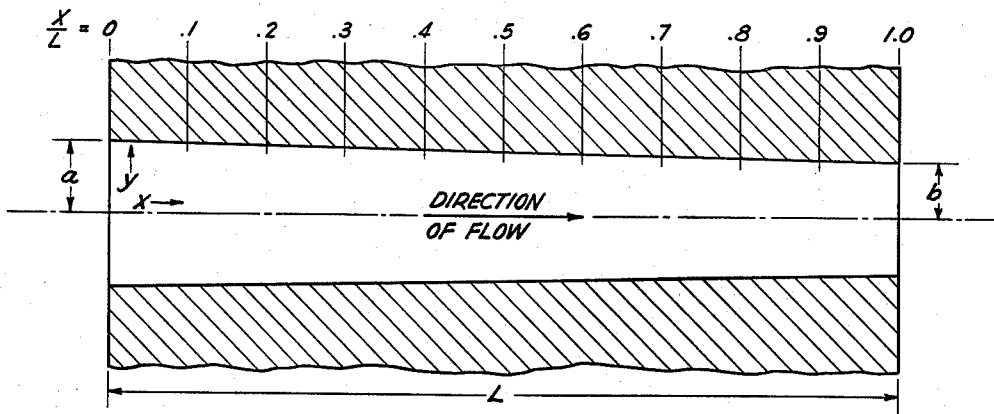


Fig. 7

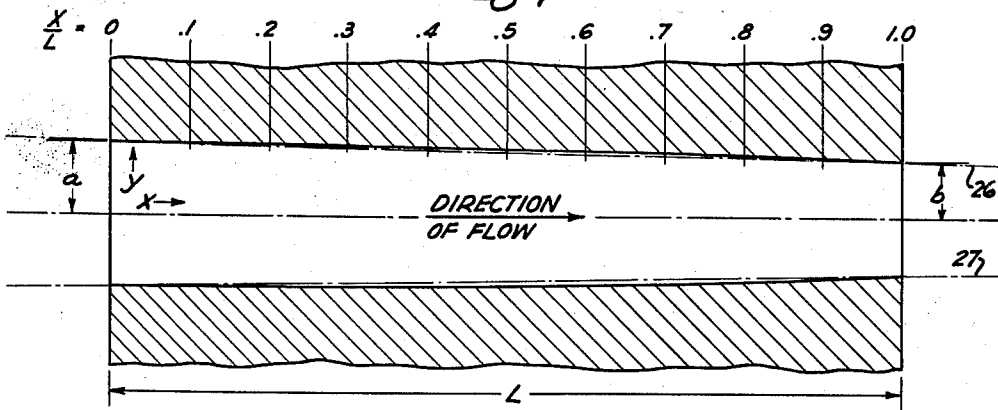


Fig. 8

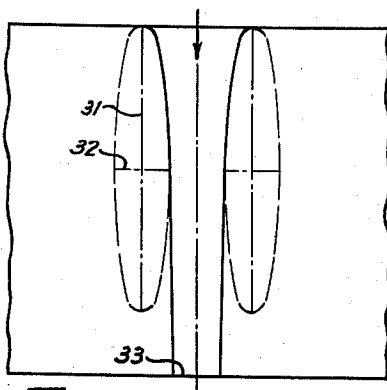


Fig. 9

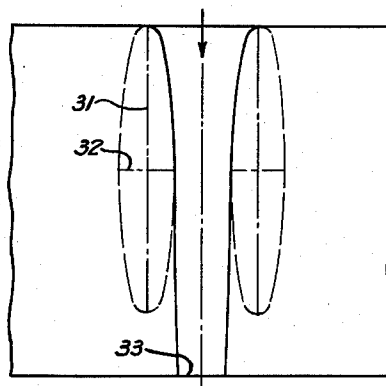


Fig. 10

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1

2,925,224

NOZZLES FOR THE PRODUCTION OF FINE PARALLEL JETS

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Continuation of application Serial No. 649,188, March
28, 1957. This application November 19, 1958, Serial
No. 774,877

9 Claims. (Cl. 239—548)

This invention relates to improved nozzles for directing a fine coherent needle-like jet or liquid stream at high speed with a high degree of directive accuracy.

More particularly, the invention relates to nozzles having one or more small orifices of improved form, said orifices directing a high velocity flow of liquid from the nozzle with high directive accuracy, i.e. accurately square with the nozzle dimensions and without deflection or deviation in direction, and which, where a multiple arrangement of orifices is employed produces small accurately-parallel high-velocity jets that may be made to impinge with precision on a target or into a small space.

This application is a continuation of application Serial No. 649,188, filed March 28, 1957, now abandoned, said application being by the same inventor and the same assignee as the present invention.

It is common experience that a high-velocity jet or liquid stream emerging from a small hole under high pressure oftentimes goes off in a peculiar askew direction, and in fact the direction may change with pressure, the jet may break up into a succession of high speed droplets, or be otherwise unstable and unpredictable particularly with respect to direction and continuity of the jet. While it is apparent that these variations are due to the nature of the hole or nozzle from which the jet emerges, no way has heretofore been known to avoid these accidental variations. It is the primary purpose of this invention to provide orifice profiles whose use insures a high degree of precision in the direction of the emerging jet and a high degree of cohesion in the jet so as to reduce the tendency to break up into droplets.

By way of example, one application in which directive precision and cohesion of a high-velocity jet is important is in directing cutting fluid into the narrow angular clearance space between a metal-cutting tool and a work piece to strike with high impact effect at the line of cut. By employing nozzles of this invention an accurately-directed high-velocity jet may be placed with precision in the extremely small space at the apex of the cutting-tool clearance angle, and by employing a linear array of such nozzles a plurality of small accurately-parallel high-velocity jets may be placed in the clearance space along the line of cut and substantially at right angles thereto.

In the above-mentioned example of applying high-velocity jets of cutting fluid to a cutting tool, it is important that the cutting fluid impinge with maximum kinetic energy at or closely behind the cutting edge of the tool where the clearance is extremely small. For effective application it must be placed with great precision

2

inasmuch as any side splash will greatly reduce the impact energy of the jet. The kinetic energy of the needle-like jet, upon impact and abrupt turning of the stream parallel to the cutting edge, is converted into useful static pressure which assists in forcing the fluid over the cutting edge of the tool, notwithstanding that the pressure of the tool entering the work may be fifty thousand pounds per square inch or higher. The patent to R. J. S. Pigott, No. 2,653,517, discloses such a system and discloses the use of a sharp-edged orifice or short rounded-approach orifice to form a thin, non-spreading jet for this purpose. Moreover, the emerging jet must be of such form that its vena contracta is far enough from the nozzle so that the latter may be placed in the limited space available between the tool-carrier and work piece being cut.

The manufacturer and mounting of nozzles provided with such orifices present serious problems. The orifices are extremely small, being less than $\frac{1}{16}$ " in diameter and usually of the order of .018 to .033 inch in diameter. Even slight imperfections due to roughness, which destroys the symmetry of the orifice, or due to inaccurate direction of the drilled hole, are highly magnified in the efflux and result in mid-directed jets, whereas, if nozzles are to be readily replaceable without special fitting and adjustment, they should project jets which are square with the nozzle dimensions so that each nozzle will have the same characteristics as any which may replace it. The formation of orifices to produce a plurality of parallel jets has in the past proven extremely troublesome, for in this case all of the jets must strike along a line at the apex of the clearance angle in order that the static pressure developed by impact may be applied over the entire width of the cutting edge of the tool. Multiple jet nozzles having sharp-edged orifices and also those having straight-drilled, short-tube orifices, when subjected to pressure-pattern tests, revealed a high frequency of non-parallel jets probably caused by unavoidable variations in the minute dimensions involved. Attempts which were made to re-direct or straighten the jet streams by reaming were not successful and, furthermore, the jet dimensions were destroyed requiring complete remaking of the nozzles. (By way of illustration 1000 man-hours were required to produce a nozzle having two parallel jets when sharp-edged orifices were used, whereas only 10 man-hours were required to produce a nozzle having two parallel jets using orifices shaped according to this invention.)

An object of the present invention is to provide a nozzle with an orifice capable of discharging a high-velocity needle-like jet whose direction is square with the nozzle dimensions, so that the nozzle may be readily aimed to direct the jet to a desired location, whereby replacement or substitution of the nozzle may be made without laborious trial and adjustment of its mounting such as would be required to compensate for orifice variations which are commonly encountered where dimensions are small.

Another object of this invention is to provide an orifice profile such that a nozzle with multiple orifices will produce accurately-parallel jets giving substantially the same pattern at impact as at emergence.

A further object of this invention is to provide an orifice which produces a high-energy jet by flow of fluid under pressure through a passage of small convergence such that the boundary flow does not separate from the

wall of the passage and the lines of flow are caused to continue to converge after the jetted fluid leaves the nozzle, resulting in increased velocity of the jet at a distance remote from the emergence opening as compared with a nozzle which develops maximum velocity approximately at emergence of the jet.

A still further object of this invention is to provide a nozzle capable of discharging a high-velocity needle-like jet which has a high degree of coherence and which may be projected considerable distance without breaking up into droplets.

Other objects and advantages of the invention will appear from the following description and accompanying drawings, in which:

Figure 1 is a side view partly in section of one form of nozzle having a single orifice of circular transverse section;

Figure 2 is an end view of one form of nozzle having a single orifice of circular transverse section;

Figure 3 is a longitudinal sectional view taken along line III—III of Figure 2 and showing the general form of the orifice;

Figure 4 is an end view of a second form of nozzle embodying the present invention, having multiple circular orifices for producing parallel jet streams;

Figure 5 is a sectional view taken along line V—V of Figure 4;

Figure 6 is a sectional view of an orifice plate formed with a series of circular orifices each provided with an elliptical entrance profile;

Figure 7 is a cross section of an orifice which has a linear-taper profile according to one embodiment of this invention;

Figure 8 is a cross section of an orifice which has a curved-taper profile according to another embodiment of this invention;

Figure 9 is a cross section of an orifice whose profile is a combination of linear taper with elliptical entrance according to another embodiment of this invention; and

Figure 10 is a cross section of an orifice whose profile is a combination of curved taper with elliptical entrance according to another embodiment of this invention.

Referring more particularly to the drawings, Figure 1 shows a desirable and convenient form of nozzle assembly. The nozzle proper comprises a flat orifice plate or disc 10, a portion 11 of which may be of reduced diameter to provide an annular shoulder 12 seated on nipple 13 and soldered or brazed thereto as at 14. The opposite end of the nipple 13 fits within a pipe 15 to the limited extent permitted by an annular flange 16 which abuts the threaded end of the pipe. The nipple 13 is secured to the pipe 15 by a nut 17 and may be provided with a gasket 23 to prevent leakage.

The orifice plate 10 of the nozzle shown in Figure 1 and in enlarged detail in Figures 2 and 3, is of the order of $\frac{5}{32}$ to $\frac{1}{16}$ inch thick and is formed with an orifice 18 which is circular in cross-section and which tapers from approximately 0.024 inch diameter at entrance to approximately 0.018 inch at emergence. These measurements are given here as merely exemplary to indicate the order of size, the orifices of this invention being smaller than $\frac{1}{16}$ inch diameter and having a profile shape to be described in detail later. These dimensions indicate the small size of the orifice required for the purposes of this invention, which remove it entirely from the category of nozzles of general utility. It will be readily appreciated that accidental variations in the various dimensions of such a small orifice may produce a relatively large or magnified effect on a jet emerging therefrom under high pressure at high velocity. It has been found that in such small orifices the characteristics of the flow is substantially completely determined by the boundaries of the flow stream and consequently the boundary contours are of utmost importance in governing the characteristics of the resulting jet.

This invention is characterized by having a nozzle orifice less than $\frac{1}{16}$ inch diameter whose profile shape is such that small variations therein produce a minimum effect on the emerging jet, particularly as to direction of the jet, as well as to its stability and convergence contour. The invention is further characterized in producing jets whose vena contracta is far from the orifice plate which insures that the jet will have a high ratio of delivered energy to input energy. Furthermore, the orifices converge gradually from entrance to emergence and are sufficiently short to have low loss whereby high delivered energy is attained in the jet.

In Figures 4 and 5 the orifice plate 19 is formed with two circular orifices 20 and 21, each of which tapers from the inlet side to produce gradual constriction of the respective flow streams and their projection in accurately-parallel jets. It is apparent that the nozzle 13 (Figure 1) may be properly proportioned to have an orifice plate of larger dimensions which is provided with any desired larger number of orifices such as 18, 20 and 21. The orifices may be located on any desired pattern and for the above-mentioned purpose of directing cutting oil into the clearance of a cutting tool a linear array is desirable, for example as illustrated in Figure 6 by the array of orifices 22. When the orifices are formed as herein specified and are manufactured with ordinary close mechanical tolerances, the resulting jets will be accurately parallel and will be directed square to the nozzle dimensions.

An important advantage of this invention arises when the jets are to be directed with maximum energy to a particular location as in the present example for placement of cutting oil, in that the vena contracta of the emerging jet is a considerable distance from the emergence opening of the orifice plate. This means that the sides of the jet continue to contract even after leaving the orifice with resultant increase in kinetic energy of the stream. Under high motivating pressure the vena contracta may be several inches from the orifice plate, with the result that the nozzle 13 (Figure 1), though placed some distance from the target, e.g. cutting tool, still is able to develop a jet whose maximum velocity or kinetic energy is concentrated exactly at the target, i.e. point of impact under the cutting edge of the tool. It has been found that the minimum distance of the vena contracta for the orifices of this invention is from 10 to 50 times larger than the corresponding distance from a thin-disc orifice, and at high operating pressures at which the orifices of this invention are normally used the vena contracta has been found to be located from $1\frac{1}{2}$ to 3 inches downstream from the outlet opening of the orifice plate 10 (Figure 1), thus permitting placing the nozzle so as to take advantage of the maximum kinetic energy of the jet. In other words the orifices herein disclosed provide a high ratio of kinetic energy in the jet to orifice input energy whereby the vena contracta is displaced downstream a large distance sufficient to permit location of the nozzle at the most favorable location, which could not be done with other orifices whose vena contracta is so close to the orifice plate that the nozzle cannot be placed in its optimum position.

It has been found that in a nozzle having extremely small dimensions in the flow passage, as in those to which this invention relates, the boundary flow predominates in fixing the form and direction of the emerging jet. With liquid flow at high velocity, the separation of the flow stream from the boundary which occurs at a sudden change in section within the orifice not only entails a loss of velocity but decreases the stability of the accelerated downstream flow. For ordinary orifices this instability manifests itself in causing the emerging liquid to break up into droplets forming a spray instead of a jet, and even if a more or less coherent jet is formed its direction will generally be directed askew as a result of microscopic

5

roughness or minute geometrical irregularities which are practically unavoidable in the manufacture of such small orifices. These adverse effects are largely avoided in nozzles employing the orifice profiles of this invention.

The orifices of this invention have the following characteristics:

- (1) Less than $\frac{1}{16}$ inch in diameter;
- (2) Gradually converge from entrance opening to emergence opening so that the ratio of inlet area to outlet area is equal to or greater than 1.414 (i.e. $\sqrt{2}$);
- (3) Have an overall taper drawn from inlet to outlet as defined later of from $1\frac{1}{4}^\circ$ to $5\frac{3}{4}^\circ$ included angle; and
- (4) Conform to either a straight line (linear) taper or to a profile curve which is more particularly defined later.

Under certain circumstances also prescribed later, an elliptical entrance profile may be employed with either of the herein-described linear or curved profiles in order to reduce the effective thickness of a thick orifice plate.

Tests have shown that by employing a nozzle whose passage or passages conform to the herein-described form there is achieved a jet which is square with the dimensions of the nozzle even in the presence of normal manufacturing variations in dimension and finish, whereby parallelism in the jet streams emerging from a multiple-orifice nozzle can be achieved. Furthermore the jet emerging from an orifice of this invention is stable, attains a high velocity with its vena contracta relatively remote from the orifice plate, and there is high efficiency in conversion of input energy to kinetic energy of the jet.

Figures 7 to 10 show in enlarged cross section some orifice profiles made according to this invention and conforming to the aforementioned criteria. An arrow indicating the direction of flow is shown on each of the figures. The orifices shown in Figures 7 to 10 have a circular transverse cross section of varying diameter, the inlet radius being denoted by a , the outlet radius being denoted by b , and radius of intermediate sections being denoted by y which is a function of the distance x from the entrance surface. The thickness of the orifice plate is denoted by L . Therefore when $x=0$, $y=a$ and when $x=L$, $y=b$ in all cases. Inasmuch as the actual dimensions of the orifice will be different for every particular application and desired rate of flow, the profiles of the orifices of this invention will be defined in terms of inlet and outlet radii and the ratio x/L from which the actual shape may easily be computed in any particular instance.

The criterion that the ratio of inlet area to outlet area shall be equal to or greater than the square root of 2, i.e. greater than 1.414, means that the sides of the passage converge toward the emergence or outlet end as shown in Figures 7 to 10. By inlet area is meant the area of the orifice at the upstream surface of the orifice plate, and by outlet area is meant the area of the orifice at the downstream or emergence surface of the orifice plate. It is apparent from this criterion that an orifice of this invention does not have a parallel-sided profile, but converges gradually from entrance opening to emergence opening. The criterion may be expressed as $a^2/b^2 \geq \sqrt{2}$.

The criterion that the overall convergence of the orifice passage must lie in the region $1\frac{1}{4}^\circ$ to $5\frac{3}{4}^\circ$ included angle is also illustrated in Figures 7 to 10. The overall included angle is defined as the angle between two lines lying in a longitudinal plane passing through the geometrical axis of the orifice, said lines being drawn between corresponding diametrically-opposite points on the perimeter of the inlet and outlet openings, as shown for example in Figure 8 by the lines 26 and 27. The profile of the passage intermediate the inlet and outlet may follow these lines (as in a linearly-tapered orifice) but certain curved profiles may be employed as will be described later. In Figure 7 the profile is a straight-line taper and follows these lines, but in Figure 8 the profile is curved and does not follow lines 26 and 27 intermedi-

6

ate the inlet and outlet openings. Nevertheless, in order to attain the advantages of this invention the lines 26 and 27 drawn as in Figure 8 must have a convergence of from $1\frac{1}{4}^\circ$ to $5\frac{3}{4}^\circ$. This criterion may be expressed as $1\frac{1}{4}^\circ < 360(a-b)/\pi L < 5\frac{3}{4}^\circ$. For best results it is preferred to have the overall convergence angle in the range of 2° to $2\frac{1}{2}^\circ$, whereby the most uniformly-accurately-directed jet of maximum velocity is obtained for a given input pressure and volume rate of flow.

- 10 Referring now specifically to the orifice profile, Figure 7 shows a profile conforming to a straight line or linear taper from inlet to outlet. Figure 7 is a very much enlarged illustration and is not to scale. Such a linear taper corresponds to that given by the equation

$$15 \quad (1) \quad y = a[1 - (x/L)] + b(x/L)$$

where y is the radius of the orifice at any transverse plane whose distance from the inlet plane is x , and L is the thickness of the orifice plate. In this equation the constants a and b for any specific nozzle are respectively the radii of the inlet and outlet openings.

Example A

By way of example an orifice having a taper given by Equation 1 is given by the dimensions below:

- Inlet radius $a=.01172$
 Outlet radius $b=.00900$
 Thickness of orifice plate $L=.01250$
 Included angle $=2\frac{1}{2}^\circ$
 30 Ratio inlet area/outlet area $=1.7$

The intermediate radii are given in the following table:

x	x/L	y
.0000	0	.01172
.0125	.1	.01145
.0250	.2	.01117
.0375	.3	.01090
.0500	.4	.01063
.0625	.5	.01036
.0750	.6	.01009
.0875	.7	.00981
.1000	.8	.00954
.1125	.9	.00927
.1250	1.0	.00900

- 45 Such orifices are relatively easy to make, this being done most conveniently by reaming a drilled hole with an appropriately-ground reamer. Whereas the jet emerging from a parallel-sided hole will be found to be erratic in direction, the jet emerging from an orifice conforming to the above example or otherwise meeting the herein-specified criteria is found to be accurately directed along the axis of the orifice.

As indicated above, the orifice profile may meet the previously-specified criteria with certain types of non-linear profiles one of which is illustrated by Figure 8. The figure is of course very much enlarged and is not to scale. One such shape which has excellent characteristics as to uniformity of jet direction within manufacturing tolerances is one having a parabolic shape. The curve of this profile is that of a parabola expressed by the

$$60 \quad (2) \quad \frac{a^2}{y^2} = 1 + \left(\frac{x}{L}\right)^2 \left[\frac{a^2}{b^2} - 1\right]$$

- 65 In this equation y is the radius of the orifice at any transverse plane whose distance from the inlet plane is x , and L is the thickness of the orifice plate. The constants a and b for any specific nozzle are respectively the radii of the inlet and outlet openings.

Example B

By way of example, an orifice having a profile given by Equation 2 is given by the dimensions below:

- Inlet radius $a=.01200$
 75 Outlet radius $b=.00900$

Thickness of orifice plate $L=.1563$

Included angle $=2.2^\circ$

Ratio inlet area/outlet area $=1.78$

The intermediate radii are given in the following table:

x	x/L	y
.0000	0	.01200
.0156	.1	.01195
.0312	.2	.01182
.0468	.3	.01160
.0624	.4	.01132
.0782	.5	.01098
.0938	.6	.01061
.1094	.7	.01021
.1250	.8	.00980
.1407	.9	.00940
.1563	1.0	.00900

Such orifices are easily made by first reaming a drilled hole with an appropriately-tapered reamer and subsequently reaming with a reamer whose profile is ground to the prescribed dimensions. The jet emerging from the above type of orifice will have even greater uniformity of directive accuracy than the linearly-tapered orifice of Example A.

Another form of curved profile that may be employed is one conforming with the equation:

$$(3) \quad \frac{a^2}{y^2} = 1 + \frac{x}{L} \left(\frac{a^2}{b^2} - 1 \right)$$

where x and y , as well as the constants a , b , and L have the same meanings as in the previous examples.

Example C

By way of example, an orifice having a profile given by Equation 3 is given by the following dimensions:

Inlet radius $a=.01200$

Outlet radius $b=.00900$

Thickness of orifice plate $L=.1563$

Included angle $=2.2^\circ$

Ratio inlet area/outlet area $=1.78$

The intermediate radii are given in the following table:

x	x/L	y
.0000	0	.01200
.0156	.1	.01156
.0312	.2	.01116
.0468	.3	.01081
.0624	.4	.01048
.0782	.5	.01018
.0938	.6	.00991
.1094	.7	.00966
.1250	.8	.00942
.1407	.9	.00920
.1563	1.0	.00900

The profiles of Equations 2 and 3, as exemplified by Examples B and C, are characterized by producing a jet in which the tangential velocity of the stream line in the jet as it flows through the nozzle is proportional to x^2 and to x respectively.

Still further forms of curved profiles which may be employed are those corresponding to fourth-power parabolas. The following are equations of this type:

$$(4) \quad \frac{a^4}{y^4} = 1 + \frac{x}{L} \left(\frac{a^4}{b^4} - 1 \right) \quad (\text{Example D})$$

$$(5) \quad \frac{a^4}{y^4} = 1 + \left(\frac{x}{L} \right)^{3/2} \left(\frac{a^4}{b^4} - 1 \right) \quad (\text{Example E})$$

$$(6) \quad \frac{a^4}{y^4} = 1 + \left(\frac{x}{L} \right)^2 \left(\frac{a^4}{b^4} - 1 \right) \quad (\text{Example F})$$

$$(7) \quad \frac{a^4}{y^4} = 1 + \left(\frac{x}{L} \right)^3 \left(\frac{a^4}{b^4} - 1 \right) \quad (\text{Example G})$$

Nozzle profiles conforming to Equations 4, 5, 6, and 7 will effect fluid acceleration in the nozzle in the direction of flow which is constant (for Eq. 4) or which is

proportional to $x^{1/2}$, x , and x^2 for Equations 5, 6, 7 respectively.

Examples D, E, F, and G

By way of example, orifices corresponding to Equations 4, 5, 6, and 7 may have the following dimensions:

Inlet radius $a=.01200$

Outlet radius $b=.00900$

Thickness of orifice plate $L=.1563$

Included angle $=2.2^\circ$

Ratio inlet area/outlet area $=1.78$

The intermediate radii for the respective examples D, E, F, and G corresponding respectively to the Equations

4, 5, 6, and 7 are given in the following table:

x	x/L	$y(\text{Ex. D})$	$y(\text{Ex. E})$	$y(\text{Ex. F})$	$y(\text{Ex. G})$
.0000	0	.01200	.01200	.01200	.01200
.0156	.1	.01143	.01180	.01194	.01199
.0312	.2	.01097	.01148	.01175	.01195
.0468	.3	.01059	.01112	.01148	.01183
.0624	.4	.01027	.01076	.01114	.01162
.0782	.5	.00999	.01041	.01077	.01130
.0938	.6	.00975	.01009	.01039	.01090
.1094	.7	.00953	.00978	.01002	.01045
.1250	.8	.00934	.00950	.00966	.00994
.1407	.9	.00916	.00924	.00932	.00947
.1563	1.0	.00900	.00900	.00900	.00900

Any of the various nozzle profiles described above may be provided with an elliptical entrance section. The elliptical entrance section and the profile according to any of the above equations have a common tangent at the point of transition. If such elliptic entrance is employed it must satisfy two conditions in order that there be separation-free flow at the transition from the elliptical to the respective nozzle profile. An example of a linear-taper orifice with an elliptical entrance profile is illustrated in Figure 9, and an example of a curved-profile orifice with elliptical entrance is illustrated in Figure 10. Figures 9 and 10 are of course very much enlarged illustrations and are not to scale. In each case where the elliptical entrance is employed, the previously-mentioned criteria pertaining to the orifice passage pertain only to that part of the orifice beyond the elliptical entrance and the elliptical entrance is not to be included in computing these criteria. It has been found that in order to function properly with the herein-disclosed orifice passages, the elliptical entrance must satisfy two conditions namely (1) the ratio of major radius 31 of the ellipse to minor radius 32 of the ellipse must be substantially equal to 6, and (2) the ratio of minor radius 32 of the ellipse to the radius of the emergence opening 33 of the nozzle must be substantially equal to $1/2$.

Example H

By way of example, an orifice having a profile comprising an elliptical entrance followed by a linear taper is given by the following dimensions:

Elliptical entrance section:

Major radius $=.0270$

Minor radius $=.0045$

Ratio major rad./minor rad. $=6$

Linear-taper section:

Length $L=.0780$

Entrance radius $a=.01070$

Emergence radius $b=.00900$

Ratio inlet area/outlet area $=1.414$

Included angle $=2.5^\circ$

Ratio minor radius of ellipse/emergence radius of linear-taper section $=.5$

Point of tangency of ellipse and linear-taper occurs at $x=.0235$

Total thickness of orifice plate $=.1015$

The intermediate radii y are given in the following table:

x	y	
.0000	.01516	Elliptical entrance.
.0027	.01381	Do.
.0054	.01246	Do.
.0081	.01195	Do.
.0108	.01156	Do.
.0135	.01126	Do.
.0162	.01104	Do.
.0189	.01087	Do.
.0216	.01075	Do.
.0235	.01070	Point of tangency.
.0265	.01042	Linear taper.
.0495	.01014	Do.
.0625	.00985	Do.
.0755	.00957	Do.
.0885	.00929	Do.
.1015	.00900	Do.

In the above example x is measured from the beginning of the elliptical entrance section. It is apparent that that part of the above-dimensioned orifice preceding the point $x=.0235$ has less resistance to fluid flow than it would have if the linear taper were continued to the point $x=0$, because the radii y are larger in the elliptical entrance section than they would be if the linear taper were continued. By employing such an elliptical entrance section it becomes possible to reduce the resistance of a thick orifice plate. The thickness of the plate is usually dictated by strength requirements since the nozzles of this invention operate under high pressure. For example, a multi-orifice plate such as that shown in Figure 6, must have lateral dimensions consonant with those of the array of jets to be produced and therefore must be made thicker in order to hold the applied pressure over a larger area. The flow resistance of the orifices in such a plate may then be reduced by providing the orifices with a tangential elliptical entrance section as above described and conforming to the above-stated conditions. That part of the orifice downstream of the elliptical entrance section must conform to the criteria previously disclosed. Alternative to a linear-taper profile employed in Example H, any of the herein-described curved profiles may be combined with a tangential elliptical entrance profile fulfilling the conditions above stated.

In the foregoing examples no units are given for the dimensions inasmuch as any unit may be used provided only that the same unit is employed for all of the dimensions of any one orifice and that the unit does not result in dimensions which exceed the absolute criteria specified.

What I claim as my invention is:

1. Apparatus for producing a plurality of fine parallel liquid jets comprising an orifice plate having a plurality of perforations of circular cross section, the axes of said perforations being parallel and the maximum diameter of said perforations being less than one-sixteenth inch, and the diameter of said perforations converging gradually from entrance opening to a smaller emergence opening in such manner that the ratio of entrance-opening area to emergence-opening area is greater than 1.414, and such that the over-all convergence from the entrance opening to the emergence opening is in the range of $1\frac{1}{4}^\circ$ to $5\frac{3}{4}^\circ$.

2. Apparatus for producing a plurality of fine parallel liquid jets comprising an orifice plate having a plurality of perforations of circular cross section, the axes of said perforations being parallel and the maximum diameter of said perforations being less than one-sixteenth inch, and the diameter of said perforations converging gradually from entrance opening to a smaller emergence opening in such manner that the ratio of entrance-opening area to emergence-opening area is greater than 1.414, said perforations having an over-all convergence from the entrance opening to the emergence opening in the range $1\frac{1}{4}^\circ$ to

$5\frac{3}{4}^\circ$, and said perforations having a profile curve conforming substantially to that given by the equation

$$y=a[1-(x/L)]+b(x/L)$$

3. Apparatus for producing a plurality of fine parallel liquid jets comprising an orifice plate having a plurality of perforations of circular cross section, the axes of said perforations being parallel and the maximum diameter of said perforations being less than one-sixteenth inch, and the diameter of said perforations converging gradually from entrance opening to a smaller emergence opening in such manner that the ratio of entrance-opening area to emergence-opening area is greater than 1.414, said perforations having an overall convergence from the entrance opening to the emergence opening in the range $1\frac{1}{4}^\circ$ to $5\frac{3}{4}^\circ$, and said perforations having a profile curve conforming substantially to that given by the equation

$$\frac{a^2}{y^2}=1+\left(\frac{x}{L}\right)^2\left[\frac{a^2}{b^2}-1\right]$$

4. Apparatus for producing a plurality of fine parallel liquid jets comprising an orifice plate having a plurality of perforations of circular cross section, the axes of said perforations being parallel and the maximum diameter of said perforations being less than one-sixteenth inch, and the diameter of said perforations converging gradually from entrance opening to a smaller emergence opening in such manner that the ratio of entrance-opening area to emergence-opening area is greater than 1.414, said perforations having an overall convergence from the entrance opening to the emergence opening in the range $1\frac{1}{4}^\circ$ to $5\frac{3}{4}^\circ$, and said perforations having a profile curve conforming substantially to that given by the equation

$$\frac{a^2}{y^2}=1+\left(\frac{x}{L}\right)^n\left[\frac{a^2}{b^2}-1\right]$$

where y is the radius of the perforation at a distance x from the entrance opening, L is the distance between entrance opening and emergence opening, a is the radius of the entrance opening, and b is the radius of the emergence opening.

5. Apparatus for producing a plurality of fine parallel liquid jets comprising an orifice plate having a plurality of perforations of circular cross section, the axes of said perforations being parallel and the maximum diameter of said perforations being less than one-sixteenth inch, and the diameter of said perforations converging gradually from entrance opening to a smaller emergence opening in such manner that the ratio of entrance-opening area to emergence-opening area is greater than 1.414, said perforations having an overall convergence from the entrance opening to the emergence opening in the range $1\frac{1}{4}^\circ$ to $5\frac{3}{4}^\circ$, and said perforations having a profile curve conforming substantially to that given by the equation

$$\frac{a^4}{y^4}=1+\left(\frac{x}{L}\right)^n\left[\frac{a^4}{b^4}-1\right]$$

where y is the radius of the perforation at a distance x from the entrance opening, L is the distance between entrance opening and emergence opening, a is the radius of the entrance opening, b is the radius of the emergence opening, and the exponent n has a value not less than one and not greater than three.

6. Apparatus for producing a plurality of fine parallel liquid jets comprising an orifice plate having a plurality of perforations of circular cross section, the axes of said

perforations being parallel and the maximum diameter of said perforations being less than one-sixteenth inch, and the diameter of said perforations converging gradually from entrance opening to a smaller emergence opening in such manner that the ratio of entrance-opening area to emergence-opening area is greater than 1.414, said perforations having an overall convergence from the entrance opening to the emergence opening in the range $1\frac{1}{4}^{\circ}$ to $5\frac{3}{4}^{\circ}$, and said perforations having a profile curve conforming substantially to that given by the equation

$$\frac{a^4}{y^4} = 1 + \left(\frac{x}{L}\right) \left[\frac{a^4}{b^4} - 1\right]$$

where y is the radius of the perforation at a distance x from the entrance opening, L is the distance between entrance opening and emergence opening, a is the radius of the entrance opening, and b is the radius of the emergence opening.

7. Apparatus for producing a plurality of fine parallel liquid jets comprising an orifice plate having a plurality of perforations of circular cross section, the axes of said perforations being parallel and the maximum diameter of said perforations being less than one-sixteenth inch, and the diameter of said perforations converging gradually from entrance opening to a smaller emergence opening in such manner that the ratio of entrance-opening area to emergence-opening area is greater than 1.414, said perforations having an overall convergence from the entrance opening to the emergence opening in the range $1\frac{1}{4}^{\circ}$ to $5\frac{3}{4}^{\circ}$, and said perforations having a profile curve conforming substantially to that given by the equation

$$\frac{a^4}{y^4} = 1 + \left(\frac{x}{L}\right)^{3/2} \left[\frac{a^4}{b^4} - 1\right]$$

where y is the radius of the perforation at a distance x from the entrance opening, L is the distance between entrance opening and emergence opening, a is the radius of the entrance opening, and b is the radius of the emergence opening.

8. Apparatus for producing a plurality of fine parallel liquid jets comprising an orifice plate having a plurality of perforations of circular cross section, the axes of said perforations being parallel and the maximum diameter of said perforations being less than one-sixteenth inch, and the diameter of said perforations converging gradually from entrance opening to a smaller emergence opening in

such manner that the ratio of entrance-opening area to emergence-opening area is greater than 1.414, said perforations having an overall convergence from the entrance opening to the emergence opening in the range $1\frac{1}{4}^{\circ}$ to $5\frac{3}{4}^{\circ}$, and said perforations having a profile curve conforming substantially to that given by the equation

$$\frac{a^4}{y^4} = 1 + \left(\frac{x}{L}\right)^2 \left[\frac{a^4}{b^4} - 1\right]$$

where y is the radius of the perforation at a distance x from the entrance opening, L is the distance between entrance opening and emergence opening, a is the radius of the entrance opening, and b is the radius of the emergence opening.

9. Apparatus for producing a plurality of fine parallel liquid jets comprising an orifice plate having a plurality of perforations of circular cross section, the axes of said perforations being parallel and the maximum diameter of said perforations being less than one-sixteenth inch, and the diameter of said perforations converging gradually from entrance opening to a smaller emergence opening in such manner that the ratio of entrance-opening area to emergence-opening area is greater than 1.414, said perforations having an overall convergence from the entrance opening to the emergence opening in the range $1\frac{1}{4}^{\circ}$ to $5\frac{3}{4}^{\circ}$, and said perforations having a profile curve conforming substantially to that given by the equation

$$\frac{a^4}{y^4} = 1 + \left(\frac{x}{L}\right)^3 \left[\frac{a^4}{b^4} - 1\right]$$

where y is the radius of the perforation at a distance x from entrance opening, L is the distance between entrance opening and emergence opening, a is the radius of the entrance opening, and b is the radius of the emergence opening.

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