SUPERSONIC STREAMING

Filed April 3, 1968 2 Sheets-Sheet 1

FIG 1

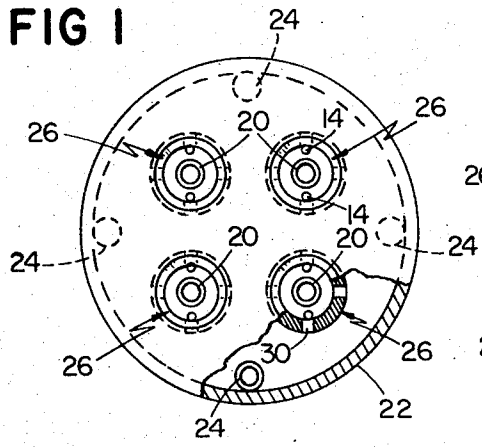
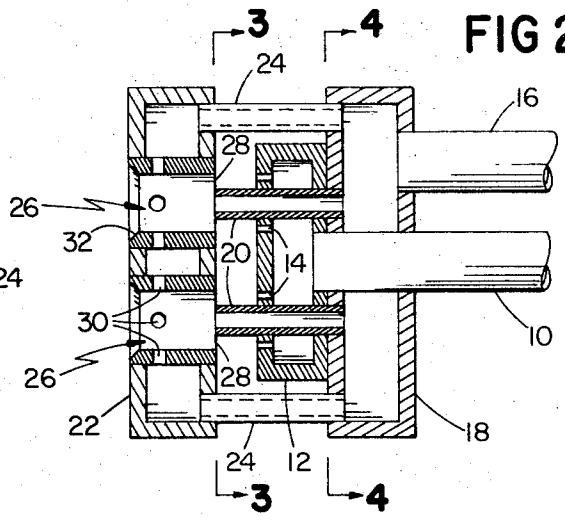


FIG 2



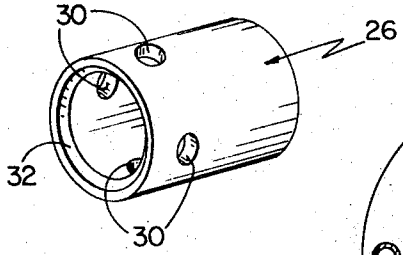


FIG 5

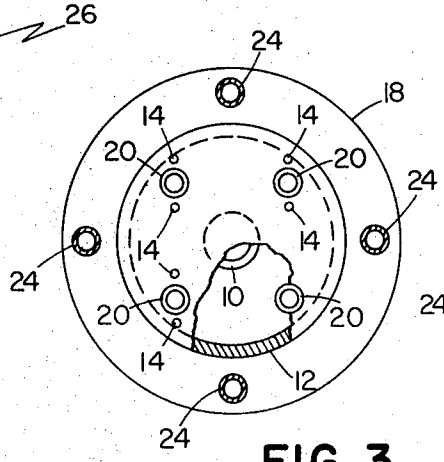


FIG 3

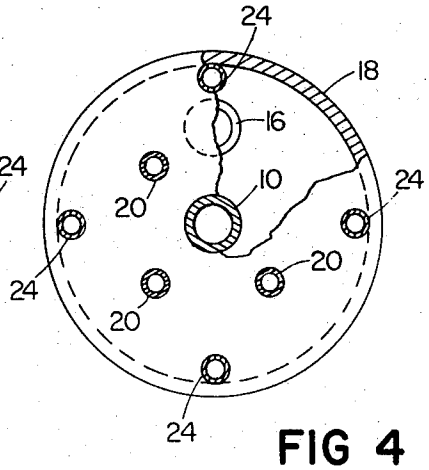


FIG 4

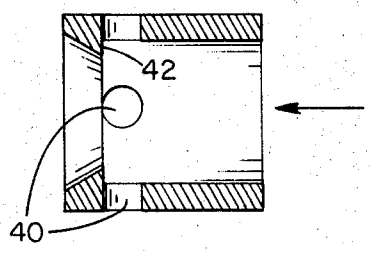


FIG 6

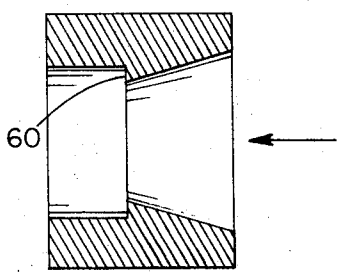


FIG 7

Sept. 29, 1970 N. HUGHES 3,531,048

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FIG 8

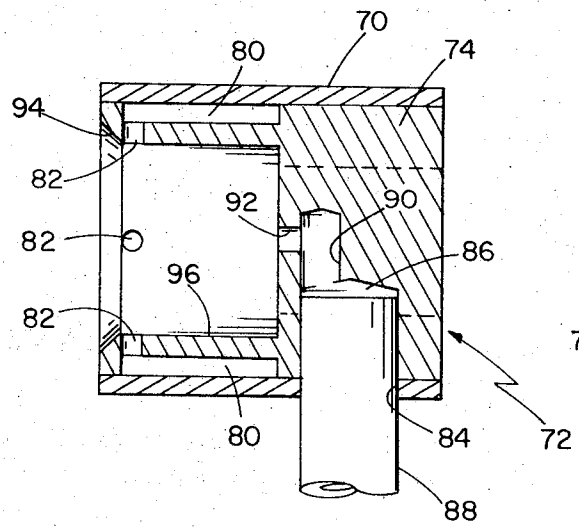
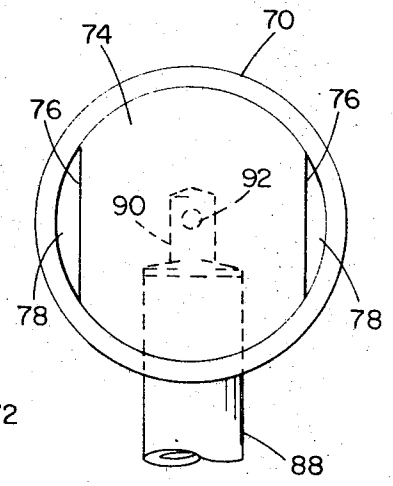


FIG 9



United States Patent Office 3,531,048 Patented Sept. 29, 1970

3,531,048

SUPERSONIC STREAMING

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Int. Cl. B05b *17/04*
U.S. Cl. 239—1 17 Claims

ABSTRACT OF THE DISCLOSURE

A small supersonic nozzle operating on very low inlet pressures, using planned boundary layer growth to sculp effective nozzle shape, and axially stabilized nozzle throat position.

This invention relates to supersonic gas streams.

That supersonic flow can be achieved with a fairly small nozzle and a fairly small inlet pressure (P_i) is known (e.g., my U.S. Pats. Nos. 3,230,923; 3,230,924; 3,232,267; 3,240,253; and 3,240,254).

Objects of this invention are to make possible supersonic streaming with yet smaller nozzles and inlet pressures; to make possible in any event greater simplicity, flexibility, and efficiency; and, in preferred embodiments, to make possible effectively harnessing the energies of supersonic streams for efficient use without any need for cooperating tuned resonators and to make practical massing a plurality of such streams to cooperatively do work corresponding to the sum of their energies.

The invention features use to obtain supersonic streaming of nozzles in each of which the effective throat diameter (D*) is less that half the nozzle forming throat diameter (D_f). If preferred embodiments, the invention features use of a cylindrical inner surface, throat plane stabilization by injection under nozzle inlet pressure (P_i) of four gas streams spaced 90° from one another with their axes in said plane, gas input at an unconfined nozzle inlet, gas implosion around said input and in consequence of it, and injection in the zone of the just-mentioned implosion of a liquid to be atomized. In preferred embodiments, D_f is less than one-quarter inch, D* is less than one-tenth inch, the ratio of the distance from the inlet to the throat plane L* to the nozzle forming diameter D_f is in the range of from 0.9 to 1.5, outlet Mach number (M_o) is less than three, gas is injected at an inlet pressure (P_i) of from 0.1 to 15 p.s.i.g., the volume (V) of gas injected at P_i is from 0.2 to 50 cubic feet per minute (c.f.m.), and from four to one thousand nozzles are multiplexed for cooperatively doing work.

The invention makes possible inexpensive manufacture of supersonic nozzles, relative freedom from supersonic breakdown owing to line pressure fluctuation, higher supersonic burst frequency (number of bursts of supersonic jets per minute; for more efficient atomization, for example, with more smaller bursts in relation to a given volume of liquid), and metering of conditions external to the nozzle (through letting such conditions participate in throat stabilization, to affect D*).

Other objects, features, and advantages will appear from the following description of preferred embodiments of the invention, taken in conjunction with the drawings, in which:

FIG. 1 is a front elevation, partially broken away, of the most-preferred embodiment of the invention;

FIG. 2 is a side elevation, partially broken away, of said embodiment;

FIG. 3 is a sectional view, partially broken away, taken at 3—3 of FIG. 2;

FIG. 4 is a sectional view, partially broken away, taken at 4—4 of FIG. 2;

FIG. 5 is an isometric view of one of the four nozzles of said embodiment;

FIG. 6 is a vertical cross-sectional view taken through the longitudinal centerline of a modified nozzle according to the invention;

FIG. 7 is a vertical cross-sectional view taken through the longitudinal centerline of another modification according to the invention;

FIG. 8 is a vertical cross-sectional view taken through the longitudinal centerline of still another modification according to the invention; and

FIG. 9 is an end elevation of the nozzle of FIG. 8.

Referring now to the drawings, there is shown in FIGS. 1 through 4 an oil burner, in the preferred embodiment of the invention.

Oil supply pipe **10** is mounted in oil manifold **12**, through the forward wall of which extend eight oil delivery holes **14**. The holes **14** are in four sets of two holes each.

Air supply pipe **16** is mounted in a first air manifold **18**, from which extends four nozzle feed tubes **20** and four second air manifold **22** feed tubes **24**. Four nozzles **26** are mounted with inlets coplanar with the outlets of nozzle feed tubes **20**, and have inside diameters greater than the outside diameters of the tubes **20**, so that at annular zones **28** the interiors of nozzles **26** are in communication with the atmosphere. Each nozzle **26** includes four holes **30** with axes coplanar in a plane perpendicular to the nozzle axis and through which holes the second air manifold is in communication with the interiors of nozzles **26**.

In operation, oil under pressure passes through pipe **10** and manifold **12**, and is discharged in eight streams through holes **14**. At the same time, air under pressure passes through pipe **16**, manifold **18**, and nozzle feed tubes **20** into the inlets of nozzles **26**. Movement of the air through the inlet of the nozzle draws into the nozzle both atmospheric air and the oil emerging from the pairs of holes **14** respectively generally aligned with the zones **28** into nozzles **26** through the zones **28**.

The low air inlet pressure and the small nozzle diameter cooperate to produce a rapid buildup in boundary layer thickness downstream of each nozzle inlet, with a consequent rapid diminution of effective diameter for air streaming; i.e., in every practical respect, to form a converging nozzle portion sculptured in boundary layer. The boundary layer becomes, at about the plane in which lie the axes of holes **30**, of such thickness that the effective diameter for air flow (flow occurs in the boundary layer too, of course, but much more slowly, and for purposes of calculating D*, the boundary layer may be treated as though motionless) is D*, the diameter at which effective air flow rate therethrough is such that the ratio of inlet pressure to throat plane pressure (P_i/P^*) is that characteristic of transition from subsonic to supersonic flow; i.e., transonic.

Injection of air through holes **30** (which for balance should be in opposed pairs) stabilizes D* axially, as well as affecting it absolutely (since the greater the rate of flow through holes **30**, the smaller D* tends to be, the

fluid coming in through the holes **30** supplementing the boundary layer growth effects). Injecting at the throat plane using a source of pressure common with that to the nozzle inlet (P_i) has the additional important advantage that the effect of line pressure fluctuations is minimized. If line pressure P_i drops, for example, the volume flowing through the nozzle tends to drop. Unless D* increases, then, the P_i/P^* ratio will tend to move out of that characteristic of transonic flow, and the nozzle will lose its supersonic quality. However, since air is being supplied through holes **30** from substantially a P_i source, if P_i drops at the inlet it drops too at holes **30**, whereupon D* automatically increases to adjust for the lower c.f.m. flow rate, and give much greater flow rate variation tolerance without loss of supersonic character.

Because the diameter of the orifice through which air is introduced to each nozzle inlet (the inside diameter of each tube **20**) is small (less than half the nozzle inlet inside diameter), the sensitivity of nozzle operation to variation in c.f.m. is further reduced.

The specific dimensions of each nozzle **26** in the preferred embodiment are:

	Inch
Overall Length (L)	0.275
I.D. (D_f)	0.200
L*	0.190
Hole **30** diameter	0.063
Hole **14** diameter	0.032
Tube **20** I.D.	0.073

Countersink **32**, designed to smooth divergence of the boundary layer, is at 45° to the nozzle axis (90° included angle). Light fuel oil is introduced through holes **24** at the rate of 32 pounds per hour, at a presssure of 5 p.s.i.g.; P_i is 6 p.s.i.g.; and under these conditions air c.f.m. is 1.2, D* is 0.065 inch, and the effective outlet diameter D_o of the nozzle (the boundary layer still being of sufficient thickness to leave an effective air flow opening of outlet diameter D_o) is 0.100 inch. The vacuum produced at the outlet (P_o) is one p.s.i.a., and the speed of the jet emerging (M_o) is Mach 2.6.

Provision for subsonic implosion in the zone **28** is helpful both in creating the desired thickness of boundary layer with less use of for boundary layer creation, and consequent less waste of energy input from, the air injected into each nozzle; and in counteracting any tendency toward boundary layer separation. The amount of implosion is self-regulating, so that the sizes of zones **28** are not critical. It is essential in practicing my invention that boundary layer conditions be laminar, not turbulent.

After entering the nozzle, the oil is carried through it in the boundary layer, being moved therein, and distributed over the entire inner nozzle surface thereof, in a generally helical way. Because P_o is subatmospheric, as the oil emerges from the nozzle it is sucked from the zones nearer the metal nozzle inside diameter into the supersonic jet, whereupon the atmospheric implosion thereinto does work on the oil to atomize it enormously and efficiently, whereupon it burns with unusual efficiency in the air with which it is by then well mixed.

In this invention, thus, the primary determinant of effective nozzle shape is the boundary layer. While this layer has in the prior nozzle art been regarded only as an unavoidable evil, it is in the present invention the element which makes possible sophisticated function with elemental form. Boundary layer thickens, at subsonic flow rates, at P_i and diameter drop. At supersonic flow rates, in a diverging nozzle, a thick boundary layer rapidly diminishes in thickness. These effects, in conjunction with stabilization to fix D* along the nozzle axis, make possible the invention.

In designing a nozzle, one first fixes on the power required. The power input is simply P_iV, and with power fixed P_i and V may be chosen to give it as their product. Next, one fixes on just how high a vacuum is desired in the supersonic jet for the power application concerned; i.e. the desired outlet pressure P_o. With P_i and P_o thus fixed, standard thermodynamic One-Dimensional Isentropic Compressible Flow Functions tables permit picking off the ratio of effective nozzle outlet area (A_o) to effective throat area (A*) necessary to obtain the chosen P_o. (The Mach number at the outlet, M_o, may also be picked off such tables.) It is then necessary to select a length of nozzle that will, for the inside diameter concerned, provide for a boundary layer buildup from the inlet to the throat plane to there give about the effective throat diameter D* corresponding ot the now-fixed A*, and for boundary layer decay from the throat plane to the outlet, to provide there the effective outlet area A_o now fixed. Boundary layer thickness under various conditions can of course be empirically determined, as by measurement with probes, as is well known, so that a suitable distance from inlet to throat plane may be fixed based on information as to boundary layer growth under particular conditions. (In this connection, I have found that for nozzles of about the same length, and with gases of the same ratio of specific heats, with P_i the same, boundary layer thickness as between two nozzles, at a corresponding position along their length, is greater in the one of smaller diameter, and this, if the larger diameter is no more than five times the smaller in ratio corresponding approximately to the ratio of the cubes of the two diameters.) The throat plane stabilizer is provided at the distance from the inlet thus chosen. The length downstream of the throat plane is preferably the shortest possible, consistent with supersonic maximum divergence, a half-angle of about 45°; and of course consistent too with retaining any remaining boundary layer needed, in a particular design, to maintain A_o at the proper level.

In the modified form of nozzle shown in FIG. 6, I stabilize the location of D* primarily by means of air imploded from the atmosphere through four ports **40** spaced 90° apart with axes coplanar, and secondarily by means of a sharp ring **42** extending into the nozzle. Despite the presence of ring **42**, D_f remains the larger, general inside diameter of the nozzle, since the thickness of the ring **42**, in a direction longitudinal of the nozzle, in relation to the diameter along which such thickness is measured, is less than 0.3 even at a diameter corresponding with the general, cylindrical inside diameter.

In the FIG. 6 embodiment the specific dimensions are:

	Inch
L	0.275
D_f	0.200
L*	0.190
Hole **40** D	0.063
Hole **14** D	0.032
Tube **20** I.D.	0.073

Countersink **46** is at 30° to the nozzle axis. With P_i 6 p.s.i.g. and c.f.m. 1.2, this design provides D* of 0.065 inch, D_o of 0.110 inch, and M_o of 2.60.

As indicated in the table above, this nozzle too is disclosed for use in atomizing oil for burning, and injection of oil, as well as atmospheric subsonic inlet implosion, are just as in the first embodiment described.

If desired, liquid to be atomized may be introduced, not at the inlet, but rather through the plane stabilization holes; and the liquid thus injected may itself be the plane stabilization fluid. It is then again transported to the nozzle outlet in the boundary layer, to be acted on as in the inlet introduction examples. Indeed, liquid to be atomized can if desired be introduced near the supersonic jet without ever passing through any portion of the nozzle, and be drawn into it by the vacuum of the jet to be worked on and atomized, in the same way. If two

liquids are to be brought together for quick reaction, one may be introduced in the last-mentioned manner, and the other in one of the other two. However liquid is introduced, its quantity should of course be matched to the energy and nature of the supersonic jet, so that there will be neither liquid in such amount that its momentum overrides the supersonic implosion effect, nor in quantity insufficient to take advantage of the full supersonic jet energy content.

While I prefer to stabilize the throat plane mainly by introduction of streams of fluid having their axes in the throat plane, I may also stabilize by means of a thin ring projecting into the nozzle alone. (In the preferred embodiment, the nozzle forming throat diameter is simply the inside diameter of the cylindrical nozzle. Strictly speaking, I mean by D_f to designate the innermost diameter, intermediate the nozzle inlet and outlet, at which the dimensions at that diameter in a lengthwise direction (L_f), divided by the diameter (D_f), is in excess of 0.3.)

In the modification of FIG. 7, plane stabilization is achieved by use of sharp ring **60** alone. Again, oil feed is precisely as disclosed in FIGS. 1 through 5. Specific dimensions are:

	Inch
L	0.260
D_f	0.210
L*	0.150

The innermost diameter of ring **60** is 0.165 inch, and the convergent half angle from the inlet to the ring **60** is 17°. With P_i 6 p.s.i.g. and c.f.m. 1.2, this design provides D* of 0.065 inch, D_o of 0.110 inch, and an M_o of 2.60

In this embodiment, D* adjustment to match c.f.m. variation in retaining supersonic function results mainly from inlet implosion rate variation (as it does too to some degree in the embodiments previously described), so that here inlet implosion is especially important.

In the preferred embodiment shown in FIG. 8, plane stabilization is again achieved by transverse atmospheric implosion of four coplanar streams with axes spaced 90°, but there is no inlet atmospheric implosion, the gas introduced at P_i is a low-pressure vaporizing Freon (e.g., Freon 114), and it carries in its entrained still-unvaporized liquid Freon and material (such as hair lacquer) being driven by the Freon from an aerosol can (not shown), in the manner familiar to the art, except for the novel nozzle embodying my invention (although the specific design of this embodiment is the joint invention of James M. Blakely and me).

The FIG. 8 nozzle consists of two inexpensive parts, a housing **70** which is ordinary ¼ inch standard copper tubing, and a copper inner member indicated generally at **72**, which may be made inexpensively on a screw machine.

The inner member **72** includes an upstream portion **74** which in cross-section outer outline is a circle from which two parallel flat surfaces **76** remove segments of corresponding size. The surfaces **76** define with the inner surface of housing **70** passages **78** communicating with annular zone **80**, which in turn communicates through the four holes **82** with the inside of inner member **72**.

Extending through hole **84** in housing **70** and seated in partially blind hole **86** in member **72** is conduit **88** from an aerosol can (not shown). Hole **86** is in communication through blind hole **90** with orifice **92**, which is 0.016 inch in diameter (and concentric with D_f within 0.001 inch). Other specific dimensions are:

	Inch
L (nozzle inlet to nozzle outlet)	0.315
D_f	0.169
L*	0.257
Hole **82** diameter	0.063

Countersing **94** is at 45° to the nozzle axis. The Freon 114 provides gas through orifice **92** to the nozzle at P_i of 2.0 p.s.i.g., and a volume of 0.650 c.f.m. Under these conditions D* is 0.046 inch, D_o is 0.087 inch, and M_o is 2.40. Not only does zone **80** provide for implosion through holes **82**, but provides heat for transfer across ring-like portion **96** of the inner member **72**, to evaporate any Freon remaining liquid, warm up Freon gas cooled by evaporation, and provide heat by conduction to the walls of holes **84**, **90**, and **92**, to aid in evaporation. In consequence, this nozzle produces not only a very fine spray, but one, unlike prior art aerosol sprays, that is not cool to the touch. My nozzle has the additional advantage that the Freon's high density, interacting with air imploded downstream of the nozzle outlet, works to improve yet further atomization, unlike shear nozzles, in which its high density yields no particular advantage.

A particular advantage of the invention is that, because resonators are no longer necessary, extensive multiplexing (i.e., placing the nozzle so close together that their outlet jets or resonators would interfere if resonators were used) is practical.

Other embodiments will occur to those skilled in the art and are within the following claims.

What is claimed is:

1. A supersonic nozzle comprising a gas conduit with an inlet and an outlet and a throat plane stabilizer intermediate thereof, said nozzle being adapted to accept at said inlet a subsonic stream at a pressure P_i, give said stream transonic speed at said plane, and discharge at said outlet a supersonic stream at a pressure P_o, said conduit having a minimum forming diameter D_f at least twice the throat diameter D* characteristic of said P_i with said P_o.

2. The nozzle of claim **1** in which said stabilizer comprises an even plurality of fluid inlets.

3. The nozzle of claim **2** in which said stabilizer fluid inlets and said nozzle inlet are supplied from the same gas source.

4. The nozzle of claim **2** in which said fluid inlets communicate with a fluid source different from that supplying said nozzle inlet.

5. The nozzle of claim **4** in which said fluid source for said fluid inlets is the atmosphere.

6. The nozzle of claim **1** in which said stabilizer comprises a thin ring extending into said nozzle.

7. The nozzle of claim **2** in which said nozzle has a cylindrical inside diameter.

8. The nozzle of claim **1** in which the inside diameter of the conduit supplying said stream to said nozzle is less than the inlet inside diameter of said nozzle.

9. The nozzle of claim **8** in which the outside diameter of said conduit supplying said stream is less than the inlet inside diameter of said nozzle, whereby subsonic implosion occurs through the zone therebetween.

10. The nozzle of claim **9** in which a liquid delivery element is mounted to inject liquid to move into said zone.

11. The nozzle of claim **1** in which L^*/D_f is in the range from 0.9 to 1.5.

12. The method of producing a supersonic jet which comprises the steps of introducing a gas at subsonic velocity and low pressure into a nozzle of small diameter so that boundary layer rapidly thickens along the nozzle length to form in effect the converging portion of a converging-diverging nozzle, stabilizing the longitudinal position at which the boundary layer becomes of thickness great enough to leave a hole for effective gas movement of D* adapted to provide P* required by operating P_i for transition to supersonic flow, decreasing the boundary layer downstream of said position through supersonic parabolic decay, and discharging the effectively moving stream from the nozzle when the boundary layer has diminished so that the effective outlet opening is in the proper ratio to D* for supersonic flow, D* being less than half D_f.

13. The method of claim **12** in which gas is imploded at the inlet of said nozzle by virtue of the said introducing of the first-mentioned said gas.

14. The method of claim **12** in which said gas is introduced at the inlet of said nozzle through an orifice of di-

ameter less than half the inside diameter of said nozzle at said inlet.

15. The method of claim **1** in which said gas is a Freon at low pressure.

16. The nozzle of claim **1** in which D_f is less than one-quarter inch, D^* is less than one-tenth inch M_o is less than three, P_i is in the range 0.1 to 15 p.s.i.g., and V is in the range 0.2 to 50 c.f.m.

17. The nozzle of claim **1** which is multiplexed with from 3 to 999 other nozzles of claim **1**.

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ALLEN N. KNOWLES, Primary Examiner

M. Y. MAR, Assistant Examiner

U.S. Cl. X.R.

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