(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
14 May 2015 (14.05.2015)

WIPO | PCT

(10) International Publication Number
WO 2015/069759 A2

(51) International Patent Classification:
E21B 21/14 (2006.01)

(21) International Application Number: PCT/US20 14/0641 13

(22) International Filing Date: 5 November 20 14 (05.11.20 14)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
61/902,198 9 November 2013 (09. 11.2013) US

(71) Applicant: **HALLIBURTON ENERGY SERVICES, INC.** [US/US]; 3000 N. Sam Houston Parkway E., Houston, TX 77032-3219 (US).

(72) Inventors: **SURJAATMADJA, Jim, B.;** 1105 Timber Creek Dr., Duncan, OK 73533 (US). **PAWAR, Bharat, Bajirao;** 709 Drexal Place, Duncan, OK 73533 (US).

(74) Agents: **Michell Eber** et al; Baker Botts LLP, 910 Louisiana Street, Houston, TX 77002 (US).

(81) **Designated States** *(unless otherwise indicated, for every kind of national protection available):* AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) **Designated States** *(unless otherwise indicated, for every kind of regional protection available):* ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

— *of inventorship (Rule 4.17(iv))*

Published:

— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

(54) **Title:** HYDRAJETTING NOZZLE AND METHOD

(57) **Abstract:** A method of jetting comprises providing a pressurized fluid to an interior flow path disposed in a nozzle body, passing the pressurized fluid through the flow section in the interior flow path and into the expansion section in the interior flow path, and passing a fluid jet out of the nozzle body from the expansion section, wherein the nozzle operates with a coefficient of discharge between about 1.3 and about 1.7. The nozzle body comprises a flow section and an expansion section, and the expansion section is disposed downstream from the flow section.

WO 2015/069759 A2

HYDRAJETTING NOZZLE AND METHOD

BACKGROUND

[0001] Hydrocarbon-producing wells often are stimulated by hydraulic fracturing operations, wherein a fracturing fluid may be introduced into a portion of a subterranean formation penetrated by a wellbore at a hydraulic pressure sufficient to create or enhance at least one fracture therein. Stimulating or treating the wellbore in such ways increases hydrocarbon production from the well. The fracturing equipment may be included in a service assembly used in the overall production process.

[0002] In some hydraulic fracturing operations, the fracturing fluid enters the subterranean formation through one or more openings or bores. The openings may be formed using a variety of techniques including jetting, perforating using explosive charges, and using casing valves. Jetting requires that a fluid pass through a nozzle at high pressure, where the fluid is generally supplied through the use of pumps or other pressurization equipment at the surface of the wellbore. The use of numerous openings may require large volumetric flow rates of fluids at high pressure to form the appropriate openings. These high flow rates can result in a large pressure drop due to friction and other internal fluid forces, which is compounded by the increasing flow path lengths associated with wells being drilled to increasing depths. The maximum operating pressures of the pumping equipment therefore limit the flow rates and number of openings that can be formed using jetting in the subterranean formation.

SUMMARY

[0003] In an embodiment, a method of jetting comprises providing a pressurized fluid to an interior flow path disposed in a nozzle body, passing the pressurized fluid through the flow section in the interior flow path and into the expansion section in the interior flow path, and passing a fluid jet out of the nozzle body from the expansion section, wherein the nozzle operates with a coefficient of discharge between about 1.3 and about 1.7. The nozzle body comprises a flow section and an expansion section, and the expansion section is disposed downstream from the flow section. The expansion section may have a diameter 1.01 to 1.5 times greater than a diameter of the flow section. A length of the flow section may be greater than about three times the diameter of the flow section. A length of the expansion section may be between about one half of a diameter of the flow section and about four times the diameter of the flow section. The nozzle body may also include a shoulder formed at an intersection of the flow section and the expansion section, and a length and diameter of the expansion section may be configured to control the amount of backflow of fluid into the expansion section when a fluid is flowing through the nozzle. The fluid jet may comprise a first portion of fluid in an outer layer of the fluid jet and a second portion of fluid in a core of the fluid jet, and a fluid velocity of the first portion of fluid may be higher than a fluid velocity of the second portion of fluid.

[0004] In an embodiment, a method of jetting comprises providing a pressurized fluid to an interior flow path disposed in a nozzle body, passing the pressurized fluid through the flow section in the interior flow path and into the expansion section in the interior flow path, and passing a fluid jet out of the nozzle body from the expansion section. The nozzle body comprises a flow section and an expansion section, and the expansion section is disposed downstream from the flow section. The fluid jet comprises a first portion of fluid in an outer layer of the fluid jet and a second portion of fluid in a core of the fluid jet, and a fluid velocity of the first portion of fluid is higher than a fluid velocity of the second portion of fluid. The fluid velocity of the second portion of fluid in the core of the fluid jet may be in the range of from about 300 feet per second to about 1,000 feet per second. The fluid velocity of the first portion of fluid in the outer layer of the fluid jet may be in the range of from about 600 feet per second to about 2,000 feet per second. The fluid velocity of the first portion of fluid may be at least 10% higher than the fluid velocity of the second portion of fluid. The method may also include receiving an ambient fluid from downstream of the nozzle to enter into the expansion section, accelerating the ambient fluid out of the expansion section, and accelerating the outer layer of the fluid jet using the ambient fluid that is accelerated out of the expansion section. Receiving the ambient fluid and accelerating the ambient fluid may occur as a cyclic process. The nozzle body may have a coefficient of discharge greater than 1.0 during the jetting. The expansion section may have a diameter about 1.01 to about 1.5 times greater than a diameter of the flow section.

[0005] In an embodiment, a method of hydrajetting comprises pressurizing a fluid using a pump to create a pressurized fluid, providing the pressurized fluid to a nozzle, passing the pressurized fluid through the flow section to the expansion section, passing the pressurized fluid out of the expansion section to create a fluid jet, and contacting the fluid jet with a wellbore wall. The nozzle is disposed in a wellbore in a subterranean formation, and the nozzle comprises a flow section adjacent to an expansion section. A pressure drop across the nozzle is less than a pressure drop across a comparative nozzle having the flow section without the expansion section. The pressurized fluid may comprise an abrasive wellbore servicing fluid. The pressure drop across the nozzle may be at least 10% less than the pressure drop across the comparative nozzle having the flow section without the expansion section. The method may also include forming a slot or a perforation tunnel in the subterranean formation with the fluid jet. The method may also include introducing a second pressurized fluid into the subterranean formation at a pressure sufficient to form one or more fractures in fluid communication with the slot or the perforation tunnel. The method may also include allowing one or more hydrocarbons to flow from the one or more fractures through the slot or the perforation tunnel and into the wellbore.

[0006] These and other features will be more clearly understood from the following detailed description taken in conjunction with the accompanying drawings and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] For a more complete understanding of the present disclosure and the advantages thereof, reference is now made to the following brief description, taken in connection with the accompanying drawings and detailed description:

[0008] Figure 1A is a simplified cross-sectional view of an embodiment of a wellbore servicing apparatus in an operating environment.

[0009] Figure IB is a simplified cross-sectional view of an embodiment of a wellbore servicing apparatus in a wellbore.

[0010] Figure 2 is a cross-sectional view of an embodiment of a nozzle.

[0011] Figure 3A is a schematic flow diagram of a fluid flow through a nozzle.

[0012] Figure 3B is a velocity profile of a fluid flowing through the nozzle illustrated in Figure 3A.

[0013] Figure 4A is a schematic flow diagram of an embodiment of a fluid flow through an embodiment of a nozzle.

[0014] Figure 4B is an embodiment of a velocity profile of a fluid flowing through the nozzle illustrated in Figure 3A.

[0015] Figure 5 is a schematic cross-sectional view of an embodiment of a valve.

[0016] Figure 6A and 6B are schematic cross-sectional views of an embodiment of a pump discharge valve.

[0017] Figure 7 is a schematic cross-sectional view of an embodiment of an exhaust pipe.

[0018] Figure 8 is a schematic cross-sectional view of an embodiment of a launch tube.

[0019] Figure 9 is a schematic cross-sectional view of an embodiment of an engine.

[0020] Figure 10 is a schematic cross-sectional view of an embodiment of a blower assembly.

[0021] Figures HAnad 11B are velocity vector diagrams provided by a computational flow dynamics (CFD) software showing an embodiment of a flow pattern through a nozzle.

[0022] Figures 12A-12C are velocity vector diagrams provided by CFD software showing another embodiment of a flow pattern through a nozzle.

[0023] Figures 13A-13D are velocity vector diagrams provided by CFD software showing still another embodiment of a flow pattern through a nozzle.

[0024] Figure 14 is velocity vector diagram provided by CFD software showing yet another embodiment of a flow pattern through a nozzle.

[0025] Figure 15 is velocity vector diagram provided by CFD software showing still another embodiment of a flow pattern through a nozzle

[0026] Figures 16A-16F are velocity vector diagrams provided by CFD software showing still another embodiment of a flow pattern through a nozzle.

[0027] Figure 17 schematically illustrates an embodiment of a test set-up for testing the flow through a plurality of nozzles.

[0028] Figure 18 illustrates the results of laboratory experiment showing a pressure versus time plot of two nozzles.

DETAILED DESCRIPTION OF THE EMBODIMENTS

[0029] In the drawings and description that follow, like parts are typically marked throughout the specification and drawings with the same reference numerals, respectively. The drawing figures are not necessarily to scale. Certain features of the invention may be shown exaggerated in scale or in somewhat schematic form and some details of conventional elements may not be shown in the interest of clarity and conciseness. Specific embodiments are described in detail and are shown in the drawings, with the understanding that the present disclosure is to be considered an exemplification of the principles of the invention, and is not intended to limit the invention to that illustrated and described herein. It is to be fully recognized that the different teachings of the embodiments discussed infra may be employed separately or in any suitable combination to produce desired results.

[0030] Unless otherwise specified, any use of any form of the terms "connect," "engage," "couple," "attach," or any other term describing an interaction between elements is not meant to limit the interaction to direct interaction between the elements and may also include indirect interaction between the elements described. In the following discussion and in the claims, the terms "including" and "comprising" are used in an open-ended fashion, and thus should be interpreted to mean "including, but not limited to …". Reference to up or down will be made for purposes of description with "up," "upper," "upward," or "upstream" meaning toward the surface of the wellbore and with "down," "lower," "downward," or "downstream" meaning toward the terminal end of the well, regardless of the wellbore orientation. The term "zone" or "pay zone" as used herein refers to separate parts of the wellbore designated for treatment or production and may refer to an entire hydrocarbon formation or separate portions of a single formation such as horizontally and/or vertically spaced portions of the same formation. As used herein, "service" or "servicing" refers to any operation or procedure used to drill, complete, work over, fracture, repair, or in any way prepare or restore a wellbore for the recovery of materials residing in a subterranean formation penetrated by the wellbore. The various characteristics mentioned above, as well as other features and characteristics described in more detail below, will be readily apparent to those skilled in the art with the aid of this disclosure upon reading the following detailed description of the embodiments, and by referring to the accompanying drawings.

[0031] Referring now to Figure 1A, an embodiment of a wellbore servicing apparatus 100 is shown in an operating environment. While the wellbore servicing apparatus 100 is shown and described with specificity, various other wellbore servicing apparatus embodiments consistent with the teachings herein are described infra. The wellbore servicing apparatus 100 comprises a drilling rig 106 that is positioned on the earth's surface 104 and extends over and around a wellbore 114 that penetrates a subterranean formation 102 for the purpose of recovering hydrocarbons. The wellbore 114 may be drilled into the subterranean formation 102 using any suitable drilling technique. The wellbore 114 extends substantially vertically away from the earth's surface 104 over a vertical wellbore portion 116, and in some embodiments may deviate at one or more angles from the earth's surface 104 over a deviated or horizontal wellbore portion 118. In alternative operating environments, all or portions of the wellbore may be vertical, deviated at any suitable angle, horizontal, and/or curved, and may comprise multiple laterals extending at various angles from a primary, vertical wellbore.

[0032] At least a portion of the vertical wellbore portion 116 may be lined with a casing 120 that is secured into position against the subterranean formation 102 in a conventional manner using cement 122. In alternative operating environments, the horizontal wellbore portion 118 may be cased and cemented and/or portions of the wellbore may be uncased (e.g., an open hole completion). The drilling rig 106 comprises a derrick 108 with a rig floor 110 through which a tubing or work string 112 (e.g., cable, wireline, E-line, Z-line, jointed pipe, coiled tubing, casing, or liner string, etc.) extends downward from the drilling rig 106 into the wellbore 114. The work string 112 delivers the wellbore servicing apparatus 100 to a predetermined depth within the wellbore 114 to perform an operation such as perforating the casing 120 and/or subterranean formation 102, creating a fluid path from the flow passage 142 to the subterranean formation 102, creating (e.g., initiating and/or extending) slots, perforation tunnels, and/or fractures (e.g., dominant/primary fractures, micro-fractures, etc.) within the subterranean formation 102, producing hydrocarbons from the subterranean formation 102 through the wellbore (e.g., via a production tubing or string), or other completion operations. The drilling rig 106 comprises a motor driven winch and other associated equipment for extending the work string 112 into the wellbore 114 to position the wellbore servicing apparatus 100 at the desired depth.

[0033] While the operating environment depicted in Figure 1A refers to a stationary drilling rig 106 for lowering and setting the wellbore servicing apparatus 100 within a land-based wellbore 114, one of ordinary skill in the art will readily appreciate that mobile workover rigs, wellbore servicing units (such as coiled tubing units), and the like may be used to lower the wellbore servicing apparatus 100 into the wellbore 114. It should be understood that the wellbore servicing apparatus 100 may alternatively be used in other operational environments, such as within an offshore wellbore operational environment.

[0034] Figure 1A illustrates a wellbore servicing apparatus 100 that may be used during production of the wellbore. As a result, the wellbore servicing apparatus 100 may remain in the well for extended periods of time while being removable for various servicing procedures as needed. The wellbore servicing apparatus 100 may comprise an upper end comprising a liner hanger 124 (such as a Halliburton VersaFlex® liner hanger), a lower end 128, and a tubing section 126 extending therebetween. The tubing section 126 may comprise a toe assembly 150 for selectively allowing fluid passage between flow passage 142 and annulus 138. The toe assembly 150 may comprise a float shoe 130, a float collar 132, a tubing conveyed device 134, and a polished bore receptacle 136 housed near the lower end 128. The components of toe assembly 150 (float shoe 130, float collar 132, tubing conveyed device 134, and polished bore receptacle 136) may actuated by hydraulic shifting or mechanical shifting as necessary to allow fluid communication between flow passage 142 and annulus 138. In alternative embodiments, a tubing section may further comprise a plurality of packers that function to isolate formation zones (e.g., zones 2, 4, 6, 8, 10, 12) from each other along the tubing section. The plurality of packers may be any suitable packers such as swellpackers, inflatable packers, squeeze packers, production packers, or combinations thereof.

[0035] The horizontal wellbore portion 118 and the tubing section 126 define an annulus 138 therebetween. The tubing section 126 comprises an interior wall 140 that defines a flow passage 142 therethrough. In some embodiments, an inner string may be disposed in the flow passage 142 and the inner string may extend therethrough so that an inner string lower end connects to toe assembly 150. The float shoe 130, the float collar 132, the tubing conveyed devices 134, and the polished bore receptacle 136 of toe assembly 150 may be actuated by mechanical shifting techniques using the inner string as necessary to allow fluid communication between fluid passage 142 and annulus 138.

[0036] By way of a non-limiting example, six service assemblies 148 are connected and disposed in-line along the tubing section 126, and are housed in the flow passage 142 of the tubing section 126. Each of the formation zones 2, 4, 6, 8, 10, and 12 has a separate and distinct one of the six service assemblies 148 associated therewith. Each service assembly 148 can be independently selectively actuated to expose different formation zones 2, 4, 6, 8, 10, and/or 12 for servicing, stimulation, and/or production (e.g., flow of a wellbore servicing fluid from the flow passage 142 of the work string 112 to the formation and/or flow of a production fluid to the flow passage 142 of the work string 112 from the formation) at different times. In this embodiment, the service assemblies 148 are ball drop actuated. In alternative embodiments, the service assemblies may be mechanical shift actuated, mechanically actuated, hydraulically actuated, electrically actuated, coiled tubing actuated, wireline actuated, or combinations thereof to increase or decrease a fluid path between the interior of service assemblies and the associated formation zones (e.g., by opening and/or closing a window or sliding sleeve). In alternative embodiments, the service assemblies may be any suitable service assemblies.

[0037] In an embodiment, the service assemblies 148 may each comprise a housing with one or more nozzles 200 associated therewith. The service assemblies 148 may be configured to be directly connected to or threaded into a tubing section such as tubing section 126 (or in alternative embodiments of a wellbore servicing apparatus, to other service assemblies). In some embodiments, the service assemblies 148 may comprise suitable structures (e.g., windows and/or sliding sleeves) for selective actuation of the service assembly.

[0038] In another embodiment shown in Figure IB, an assembly for servicing a well is illustrated in the lower portion of a wellbore. This assembly may be used to service a wellbore and may be removed prior to production of one or more fluids from the well. This assembly may be used in any of the operating environments described with respect to Figure 1A. In the embodiment shown in Figure IB, one end of the work string 1112 may be connected to one end of a tubular jet sub 1148. The jet sub 1148 may comprise a tubular housing that includes a longitudinal flow passage coupled to the flow passage 1142 extending through the length of the housing. The jet sub 1148 may have a plurality of openings 1154 machined through its wall that form nozzles as described in more detail below. Alternatively, a plurality of openings 1154 may be machined through the wall of the jet sub 1148 and may be adapted to receive one or more suitable nozzles as described in more detail below. The openings 1154 containing the nozzles may extend through the wall of the casing 1120 in one plane and can extend perpendicular to the axis of the casing 1120, at an acute angle to the axis of the casing 1120, and/or aligned with the axis.

[0039] The lower end of the jet sub 1148 may have one or more additional components coupled thereto. In an embodiment, a valve sub 1152 may be connected to the other end of the jet sub 1148 for use in controlling the flow of fluid through the work string 1112. The valve sub 1152 may normally be closed to cause flow of fluid to discharge from the jet sub 1148. The valve sub 1152 may be used to allow for emergency reverse circulation processes, such as during screenouts, equipment failures, etc. Additional suitable components may be coupled to the jet sub 1148 and/or the valve sub 1152 such as any other components that may be used in the wellbore servicing process including sensors, recorders, centralizers, and the like. In addition, it is understood that other conventional components, such as centering devices, blow out preventers, strippers, tubing valves, anchors, seals etc. can be associated with the work string 1112 of FIG. IB.

[0040] An annulus is formed between the inner surface of the casing 1120 and the outer surfaces of the work string 1112 and the jet sub 1148 and the valve sub 1152. Several different types of fluids may be pumped through the flow passage 1142 and out to the formation through the subs and the annulus. In order to treat the formation, the casing 1120 in the interval of interest must be either pre-perforated or perforated using conventional means; or it could be hydrajetted with sand using the jet sub 1148. Optionally, inside the casing section wire screens could be installed and packed with gravel in a manner well known in the art. The jet sub 1148 comprising the nozzles may then be activated by passing a fluid through the interior flow passage 1142 of the work string 1112, as described in more detail below.

[0041] Irrespective of the type of work string, assembly, and/or tool in which the nozzle 200 of Figure 2 is used, it will be appreciated that the nozzle 200 is configured to serve multiple functions. One function of the nozzle 200 is to increase the velocity of a fluid as it passes through the nozzle 200 to the formation. The nozzle 200 may be configured to restrict fluid flow and thus increase the fluid velocity (e.g., jetting the fluid) as the fluid passes through the nozzle 200. The jetted fluid may be jetted at a sufficient fluid velocity so that the jetted fluid can ablate and/or penetrate the lining (e.g., casing, cement, etc.) and/or the subterranean formation, thereby forming slots (e.g., eroded slots), perforation tunnels, micro-fractures, and/or extended fractures in the lining and/or subterranean formation. The jetted fluid may be flowed through the nozzle 200 for a jetting period to form a slot and/or perforation tunnel, micro-fractures, and/or extended fractures within the formation as described infra. Generally, the velocity of a jetted fluid is greater than 300 feet per second (ft/sec).

[0042] Referring to Figure 2, the nozzle 200 is shown in greater detail. The nozzle 200 may generally form a portion of a flow device such as a jetting device. The nozzle 200 comprises a generally cylindrical body 202 defining an interior flowpath 204. The nozzle comprises an outer end 206 that faces the formation zone of interest and an inner end 208 that faces the flow passage 142. The outer diameter of the body 202 is configured to complement and be received and held within a port in the service assembly housing. The thickness 210 of body 202 may be adjusted depending on the need of the process and may be determined by one of ordinary skill in the art with the aid of this disclosure. The outer end 206 of the body may be beveled for ease of insertion into the port in the housing. In an embodiment, the diameter of the body 202 may narrow between the inner end 208 and the outer end 206 so that the body has an overall wedge or conical shape. This shape may aid in maintaining the nozzle 200 within the port in the housing and/or maintaining sealing engagement of the nozzle 200 in the port to prevent channeling of fluid around the nozzle 200 upon the application of pressure to the flow passage 142 (as shown in Figure 1A).

[0043] The body 202 of the nozzle 200 may be constructed of any suitable materials. In an embodiment, the body 202 may be constructed of an abrasion and/or erosion resistant material. Suitable abrasion and/or erosion resistant materials may comprise matrix materials such as carbide particles in a metal matrix (e.g., tungsten carbide by itself or in a metallic binder, such as cobalt, tin, and/or nickel), ceramics, erosion resistant metals and alloys (e.g., tungsten carbide), and combinations thereof. In some embodiments, the nozzle 200 may only be needed for a limited time. In these embodiments, the body 202 may be constructed of a material that can be removed through degradation, abrasion, erosion, mechanical removal, etc. For example, the body 202 may be constructed of water soluble materials (e.g., water soluble aluminum, biodegradable polymer such as polylactic acid, etc.), acid soluble materials (e.g., aluminum, steel, etc.), thermally degradable materials (e.g., magnesium metal, thermoplastic materials, composite materials, etc.), or combinations thereof. The interior flowpath 204 is positioned within the body 202 to provide fluid communication between the flow passage 142 adjacent the inner end 208 and the formation adjacent the outer end 206. The interior flowpath 204 may be positioned concentrically within the body 202 and may be cylindrical in shape, however, in some embodiments, the shape of the interior flowpath may vary to some degree. The diameter of the interior flowpath 204 may be chosen to provide the desired fluid flow rate and fluid velocity at the appropriate operating conditions (e.g., pressure, temperature, etc.) and wellbore service fluid types (e.g., particulate type and/or concentration, fluid viscosity, fluid composition, etc.).

[0044] As shown in Figure 2, the body 202 may be configured to provide several distinct flow portions of the interior flowpath 204. For example, the interior flowpath 204 may comprise an inlet section 212, a flow section 214, and an expansion section 216. Nozzle 200 may be integrally formed from a single body 202 portion, although it will be appreciated by one of ordinary skill in the art that the various sections of the nozzle 200 may be contained in separate components that are coupled together. However, the nozzle 200 is constructed so that the interior flowpath 204 may provide fluid communication between the inner end 208 and the outer end 206 without any outlets, ports, or other fluid passageways to an exterior of the nozzle 200 in between. For example, the interior flowpath 204 may be defined by a continuous surface formed on the interior of the inlet section 212, the flow section 214, and the expansion section 216. Fluid flowing from the flow passage 142 may first flow through the inlet section 212, which is optional. The inlet section 212 may have a decreasing diameter 217 along its length 218 between the inner end 208 of the body 202 and the interface with the flow section 214. The diameter 217 may decrease gradually (e.g., over a curved surface) or may decrease in one or more steps, which may correspond to one or more sharp edges. In an embodiment, the diameter 220 of the flow section 214 may extend to the inner edge 208 of the nozzle 200, in which case the inlet section 212 may not be considered to be present. The flow section 214 may have a relatively uniform diameter 220 along its length 219. The diameter of the expansion section 216 is greater than the diameter 220 of the flow section 214 and may be relatively uniform along its length 222. The expansion section 216 extends to the outer edge 206 of the nozzle 200. In some embodiments, the diameter 220 of the flow section 214 may change diameter (e.g., slightly increase and/or slightly decrease) along its length.

[0045] The diameter 220 of the flow section 214 is less than the diameter 224 of the expansion section 216, thereby creating a shoulder 226 at the intersection of the flow section 214 and the expansion section 216. The shoulder 226 may be formed as an edge disposed perpendicular to the central longitudinal axis of the interior flowpath 204. In an embodiment, the shoulder may be formed of a generally flat edge that may be tilted up to about 30 degrees from a plane perpendicular to the longitudinal axis of the interior flowpath 204. In an embodiment, the shoulder 226 may comprise one or more rounded edges or surfaces to allow the shoulder to extend from the diameter 220 of the flow section 214 to the diameter 224 of the expansion section 216 over a short distance.

[0046] In an embodiment, the diameters and lengths of the inlet section 212, the flow section 214, and/or the expansion section 216 may vary depending on the particular application in which the nozzle 200 is used. In a wellbore servicing operation, the length 219 of the flow section 214 may be greater than about three times its diameter 220, alternatively greater than about four times its diameter 220. In some embodiments, length restrictions may exist and the length 219 of the flow section 214 may be less than three times its diameter 220. The diameter 220 of the flow section 214 may be measured as the minimum diameter of the flow section 214 when the diameter 220 varies over the length 219 of the flow section 214. The length 218 of the inlet section 212, if present, may be less than about 2 times the diameter 220 of the flow section 214. The length 222 of the expansion section 216 may range from about one half of the diameter 220 of the flow section 214 to about four times the diameter 220 of the flow section 214. In an embodiment, the diameter 224 of the expansion section 216 may be about 1.01 to about 1.5 times the diameter 220 of the flow section 214. In an embodiment, the overall length (i.e., the sum of lengths 218, 219, and 222) of the nozzle 200 may be about 0.5 inches to about 6 inches, alternatively about 0.75 to about 4 inches. The diameter of the flow section 214 may be about 0.05 inches to about 2 inches, alternatively about 0.2 inches to about 1 inch. Referring to Figures 2 through 3B, the fluid flow through interior flowpath 204 may expand into the expansion section 216 in a conical stream after passing through the flow section 214 over shoulder 226.

[0047] In some embodiments, the nozzle 200 may be designed to use the hydrostatic energy present at the downstream side of the nozzle to accelerate the fluid velocity of the fluid jet. This may allow the nozzle to use the downstream energy to perform a portion of the fluid acceleration, which may reduce the upstream pressure requirements (e.g., reducing a pressure differential requirement across the nozzle). Various factors that may be taken into consideration in designing the nozzle can include, but are not limited to, the nozzle geometry (e.g., the internal diameter, length, etc.), a pressure differential across the nozzle, and/or the density of the fluids passing through the nozzle. These properties may be expressed as a coefficient of discharge, C_d, of the jet nozzle. The coefficient of discharge is generally related to the ratio of the area of the vena contracta to the smallest flow area in the jet nozzle. Shaping the inlet section 212 may reduce or eliminate the presence of the vena contracta, and as a result, the coefficient of discharge may approach 1.0 in the limit of not having a vena contracta. In practice, average "shaped" nozzle coefficients of discharge may be about 0.95. In general, the Coefficient of Discharge (C_d) can be computed by the following relationship:

$$C_d = \frac{Q}{A\sqrt{\frac{2\Delta P}{\rho}}} \qquad \text{(Eq. 1)}$$

where Q is the fluid flow rate, A is the area of flow based upon the smallest inner diameter 220 of the nozzle, p is the fluid density, and ΔP is pressure differential across nozzle 200. In an embodiment, the use of the expansion section 216 may allow the nozzle 200 to achieve a coefficient of discharge of greater than 1.0, alternatively greater than about 1.1, alternatively greater than about 1.2, alternatively greater than about 1.3, alternatively greater than about 1.4, alternatively greater than about 1.5, or alternatively greater than about 1.6, as described in more detail herein.

[0048] A schematic diagram of the behavior of hydrajetting flow from a nozzle is shown in Figure 3A. When a substantially incompressible fluid jet (e.g., a liquid jet) is ejected into a gaseous atmosphere, the jet may only flare slightly due to the low viscosity of the gas in the atmosphere. Substantially incompressible fluids generally do not comprise a gas phase that may expand. The low viscosity of the gas may result in a relative small, if not negligible, friction force acting on the fluid exiting the nozzle. When a fluid having a viscosity on the same order as the fluid passing through the nozzle is present downstream of the nozzle, viscosity and/or fluid friction causes a rapid energy interchange between the jetted fluid and the fluid outside the nozzle. Assuming that flow line 201 represents the original, undisturbed jetted fluid, which may be in the middle of the energy mixing region, the stationary fluid outside the jet (e.g., outside flow line 201) may pull back the outside layer of fluid (e.g,. an outside "skin" of fluid). This may cause the fluid of the jet "skin" to slow down. Assuming that the flow rate of the jet flow is constant, the physical volume of the jet flow regime (often called the control volume) will increase. This may result in the apparent flaring of the fluid jet, as shown by flow lines 203. In other words, there is a fluid mixing between the two fluids. Even if the fluid in the jet and the fluid downstream of the jet were originally different fluids, they may become a homogeneous mixture between flow lines 203 and 205, at a lower velocity profile. As the jetted fluid flows away from the nozzle, the high-velocity portion of the jet (e.g., represented by the fluid within flow lines 205) may decrease in size and be replaced by a lower-velocity homogeneous fluid mixture. After the jet stabilizes, a "stable" torus may be formed around the jet as the fluid content becomes a stable mixture of the two fluids. In an embodiment, the fluid jet may comprise a compressible fluid that may expand when the jet is emitted from the nozzle. In this embodiment, the angular flaring of flow line 203 may be larger than that shown in Figure 3A.

[0049] Figure 3B illustrates the resulting velocity profile associated with the jetted fluid shown in Figure 3A. As can be seen, the inner core of high velocity fluid within flow lines 205 may have a velocity profile that drops off over the mixing region between flow lines 203 and 205. In this velocity profile, the peak velocity is seen to be in the center of the fluid jet. The velocity may then approach the bulk fluid velocity outside of the flared region shown by flow lines 203.

[0050] This hydrajetting flow may also be considered within a high pressure containment, which refers to a jet entering a volume of fluid having a greater than ambient pressure. When jetting in a high-pressure containment, the pressure upstream of the nozzle may be much higher than an ambient environment. For example, the pressure inside an oil well that is 6,000-ft deep may be approximately 4,000 psi. If a differential pressure of 4,000 psi is specified across the nozzle then surface pumping pressures may be increased to approximately 9,000 psi to 10,000 psi if friction is taken into account (e.g., when long coiled tubing is used, etc.). Using the nozzle described herein may allow the surface pressure requirements to be reduced by about 1,000 psi to about 2,000 psi, for example. This may allow a lower cost grade of pipe and lower-horsepower pumps to be used.

[0051] In order to reduce the overall pressure requirements, the ambient pressure within the wellbore may be taken into account. As shown in Figures 3A and 3B, the fluid outside of the jet tends to slow down the jetted fluid due to the viscous interactions. However, if the velocity in the area outside the jet is faster than the velocity of the primary jet itself, then instead of slowing down the high-velocity core, the jetted fluid could be accelerated. The nozzle design described herein may advantageously be used to create a high speed fluid that can accelerate the fluid jet.

[0052] A schematic illustration of the hydrajetting flow through a nozzle 200 having an expansion section 216 is shown in Figure 4A, and the corresponding velocity profile is shown in Figure 4B. The nozzle 200 has an expansion section 216 near the outer end 216. The expansion section 216 may create a chamber 402 after the enlargement having a reduced pressure relative to the fluid flowing through the nozzle 200 and the pressure downstream of the outer end 206 as a result of the Bernoulli effect in the area. The chamber 402 may be defined as an annular region about the inner circumference of the shoulder 226, the inner surface of the expansion section 216, and the fluid flowing through the nozzle 200. The resulting pressure reduction within the chamber 402 may result in flowback into the chamber 402 from the downstream region. Fluid that is pressurized by the hydrostatic pressure adjacent the outer end 206 may be pushing into the chamber 402. The fluid may then reverse flow direction to be directed outward. This inflow and outflow may carry the fluid flowing through the nozzle (e.g., fluid flowing along flow stream 307) outward at a greater speed as compared to a nozzle without any backflow. As a result of the reduced pressure within the chamber 402, the fluid entering and exiting the chamber 402 along flow line 207 may eventually meet the high downstream pressure, P_d (e.g., the pressure outside the outer end 206). The amount of fluid passing into the chamber 402 may be relatively small as compared to amount of fluid flowing through the nozzle 200. For example, the amount of fluid downstream of the outer edge 206 flowing back into the chamber 402 may be less than about 15%, less than about 10%, or less than about 5% of the amount of fluid flowing through nozzle 200.

[0053] Without intending to be limited by theory, it is believed that this flow exists due to the presence of a high-velocity "skin" or "sleeve" outside the original fluid jet. Further, it is believed that this flow is likely not stable, which may allow the energy balance to be satisfied. For example, in a stable or steady-state environment where the average pressure within the chamber 402, P_a, is low (e.g., caused by the high-velocity skin passing therethrough), the fluid flow through the nozzle 200 may accelerate because of the pressure differential between the upstream pressure, P_u, and the average pressure Pa, but would then likely be immediately followed by a deceleration due to the pressure differential between the average pressure, $\mathbf{P_a}$, and the downstream pressure, $\mathbf{P_d}$. This may negate any acceleration effects over an appreciable distance. It is therefore expected that a fluctuation in the cavity could exist that is tuned to its natural frequency. The fluctuation may be described by the equation:

$$P(t) \quad = \quad P_a + P_b \sin(\omega t) \qquad \text{(Eq. 2)}$$

[0054] where $\mathbf{P_a}$ is the average pressure within the chamber 402, $\mathbf{P}_b$ represents the amplitude of the pressure fluctuation and is a pressure where $\mathbf{P_a}$ + $\mathbf{P}_b$ is equal or somewhat less than the downhole pressure $\mathbf{P_d}$, and ω relates to the natural frequency n. The natural frequency n can be represented by the following equation:

$$n \quad = \quad \frac{i\,c}{4\,L} \qquad \text{(Eq. 3)}$$

where i is an odd number (1, 3, 5, etc.), c is the speed of sound in the fluid (e.g., for water, this is approximately 5,000 ft/sec), and L is the depth of the enlargement (e.g., one half of the difference between the inner diameter of the expansion section 216 and the inner diameter of the flow section 214).

[0055] The resulting velocity profile is shown in Figure 4B. The overall velocity profile of the fluid exiting the nozzle 200 may have an outer layer of fluid that has a higher velocity than a core region. Thus, the outer layer of fluid may accelerate the inner core to an even high velocity. In an embodiment, a fluid jet resulting from the nozzle described herein may demonstrate a velocity profile having an outer layer of fluid having a higher velocity than the core or central region of the fluid jet. In an embodiment, the outer layer of fluid may have a velocity that is at least about 10%, at least about 20%, at least about 30%, at least about 40%, at least about 50%, or at least about 60% greater than the lowest velocity in the core of the fluid jet leaving the nozzle 200. The relative velocity may refer at least to a peak velocity in the outer layer relative to a minimum velocity in the core of the fluid jet. In an embodiment, the velocity of the core fluid may be between about 400 ft/s and about 750 ft/s, and the velocity of the outer layer may be between about 1,200 ft/s and about 700 ft/s.

[0056] Without intending to be limited by theory, the resulting pressure change within the chamber 402 due to the backflow of fluid from downstream of the nozzle 200 may be thought of as a use of the downstream fluid energy to form and/or power the fluid stream flowing through the nozzle 200. The amount of pressure supplied to the chamber from the downstream environment may vary, and in an embodiment, may be at least about 10%, at least about 20%, at least about 30%, at least about 40%, or at least about 50% of the downstream ambient pressure. In an embodiment, the amount of pressure supplied to the chamber from the downstream environment may be less than about 80%, less than about 70%, or less than about 60% of the downstream ambient pressure. The design of the nozzle including the relative lengths and diameters of the flow section 214 and the expansion section 216 may be selected to provide the desired amount of backflow into the chamber 402, and thereby the amount of energy input based on the pressure input available from the ambient environment downstream of the nozzle 200.

[0057] As an example of the use of the equations, if a 3/16 in. nozzle has an enlargement that is 0.15 in. deep (e.g., L=0. 15 in), then n= 100,000 Hz for the first harmonics (e.g., for i=l). Based on these equations, the maximum efficiency of the system would generally occur when P_a and P_b are both equal to half of the downhole pressure P_d. Thus, assuming an efficiency coefficient C, where P_b = C P_{bMAX}, a list of C_dS at various values of C can be determined. The results are shown in Table I below.

Efficiency Coefficient (C)	Upstream Pressure (Pu)	Downstream Pressure (Pd)	Avg. Pressure (Pa)	Avg. Pressure Differential (Dp)	Discharge Coefficient(Cd)
1	10,000	8,000	4,000	6,000	1.732
0.9	10,000	8,000	4,400	5,600	1.673
0.8	10,000	8,000	4,800	5,200	1.612
0.7	10,000	8,000	5,200	4,800	1.549
0.6	10,000	8,000	5,600	4,400	1.483
0.5	10,000	8,000	6,000	4,000	1.414
0.4	10,000	8,000	6,400	3,600	1.342
0.3	10,000	8,000	6,800	3,200	1.265

[0058] In an embodiment, an efficiency coefficient can be selected between about 0.4 to about 0.8 to accounting for losses in the system. The resulting coefficient of discharge values achievable with the nozzle may then be between about 1.0 and about 1.8, or between about I.2 and about 1.7. It should be noted that the Cd will depend on the ambient pressure downstream of the nozzle. In a deep wellbore, the ambient pressure may be above 9,000 psi - I1,000 psi. In an embodiment, the high ambient pressure may result in the C_d approaching 2.0.

[0059] As noted above, the design of the nozzle 200 may result in the coefficient of discharge being above 1.0 during operation of the nozzle. The diameter of the expansion section 216 relative to the diameter of the flow section 214 may be selected to allow the fluid outside the outer end 206 to flow into and out of the chamber 402. Without intending to be limited by theory, it is believed that the diameter of the fluid stream passing through the expansion section 214 may be used to design the interior flow path diameter 224. For example, the inner diameter of the flow section 204 and/or the expansion section 216 may be selected so that the outer diameter of the fluid stream is slightly smaller than the inner diameter of the expansion section 216 when the fluid stream leaves the outer end 206. In an embodiment, the expansion section 216 diameter and length may be configured to ensure that the diameter is slightly larger than the diameter of the fluid stream at the outer end 206 of the nozzle 200As a result, a region of pressure below the pressure present outside of outer end 206 may be created in the chamber 402. The region of reduced pressure may pull fluid into it from fluid downstream of the outer edge 406.

[0060] Since the flowrate of the fluid stream through the nozzle 200 is based on the pressure differential across the nozzle 400, the resulting decrease in pressure due to the expansion section 216 may result in a higher fluid flowrate through the nozzle 400. Alternatively, a decreased pressure may be used to generate an equivalent fluid flowrate through the nozzle 200 as compared to a nozzle without the expansion section 216 as described herein. In an embodiment, any combination of increased flowrate and/or decreased pressure may be achieved through the use of the nozzle 200 having the expansion chamber.

[0061] In an embodiment, the use of an expansion section 216 in the nozzle 200 and a constant fluid supply pressure may result in an increased flowrate of fluid through the nozzle 200 of greater than about 10%, alternatively greater than about 20%, alternatively greater than about 30 %, or alternatively greater than about 40% as compared to a nozzle not comprising an expansion section 416. The corresponding decrease in pressure may allow smaller pumps and/or a reduced power input to the pumps to be used during a workover operation and/or a higher volume of fluid to be passed through the nozzles with the same pumping units. When used to provide a constant volumetric flow of fluid, the pump pressure can be reduced, which may reduce the fatigue associated with running the pump. In an embodiment, reducing a high pressure pump output pressure may increase the life of the pump by more than 50%, more than 100%, or more than 150%. For example, reducing a 15,000 psi pump output pressure by 15% may approximately double the pump fatigue life.

[0062] The flowrate increase through the nozzle may also be useful in performing a hydrajetting procedure. When the fluid jet strikes a surface adjacent the nozzle 200, the resulting pressure profile may be the same or similar to the velocity profile shown in Figure 4B. In general, the pressure and velocity are related according to the Bernoulli Principle, which indicates that the pressure of the fluid striking the surface will be greater as the velocity increases. Thus, the high pressure outer layer may have a higher impact pressure on the surface than the core of the jet. As compared to a fluid jet being emitted from a nozzle not having the expansion section, the velocity of the fluid jet exiting the nozzle 200 may have a higher velocity, and the pressure drop across the nozzle 200 may be lower than the pressure drop across a comparative nozzle not having the expansion section. When the jet strikes a surface such as the interior surface of a casing or the wellbore wall, the resulting pressure may therefore be greater than a jet being emitted from a comparative nozzle not having the expansion section. Still further, the gain in velocity obtained from receiving an energy input from the ambient fluid may allow the resulting pressure at the impact point to be higher than the pressure drop across the nozzle 200. For example, the velocity increase due to the ambient pressure input may allow the impact pressure at a surface to be a combination of the pressure drop across the nozzle plus the energy input from the ambient fluid minus the losses associated with friction and other turbulent effects. This may be useful in performing hydrajetting procedures as described in more detail herein. Referring to Figure 2, 4A, and 4B, the nozzle 200 may be operated by providing a fluid to the inner end 208 and allowing the fluid to flow through the interior flowpath 204 and exit the outer end 206. The fluid entering the nozzle 200 is at a higher pressure than the ambient pressure adjacent the outer edge 206 of the nozzle, thereby allowing the fluid to flow through the nozzle 200. Upon initiation of flow through the nozzle 200, the fluid may expand out of the flow section 214, past the shoulder 226, and flow into the expansion section 216. Due to the conical flow pattern almost touching the walls of the body 202 in the expansion section 216, a small stream of fluid from outside of the nozzle 200 is allowed to flow into the expansion section 216 in a fluctuating flow pattern. A chamber 302 may then be formed with a pressure below that of the ambient pressure outside the outer edge 206 of the nozzle 200. The resulting fluid flow through the nozzle 200 may experience a decreased pressure drop and/or an increased flowrate through the nozzle 200. Further, the skin velocity of the fluid jet may be higher than the velocity of the core of the fluid jet. Still further, the nozzle 200 may have a coefficient of discharge greater than 1.0.

[0063] In an embodiment, the nozzle 200 may be used in a service tool to service a wellbore 114. Generally, servicing a wellbore 114 may be carried out for a plurality of formation zones (as shown in Figure 1) starting from a formation zone in the furthest or lowermost end of the wellbore 114 (i.e., toe) and sequentially backward toward the closest or uppermost end of the wellbore 114 (i.e., heel). Referring to Figure 1, the wellbore servicing may begin by disposing a liner hanger comprising a float shoe and a float collar disposed near the toe, and a tubing section 126 comprising a plurality of service assemblies 148 comprising a nozzle 200 as described with respect to Figure 2. The service assembly 148 may be positioned adjacent the formation zone to be treated. While the orientation of the service assembly 148 is illustrated as being horizontal, in alternative methods of servicing a wellbore, the service assembly may be deviated, vertical, or angled, which can be selected based on the wellbore conditions. Prior to servicing of the wellbore, cementing of the wellbore may be performed via the float shoe and collar. In an embodiment, the service assembly 148 may initially be in a closed position wherein there is no fluid communication between the flow path 142 and the formation zone 12, and may be subsequently opened using any methods known to one of ordinary skill in the art with the aid of this disclosure. For example, the service assembly 148 may be actuated by hydraulically applying pressure, by mechanically, or electrically shifting a sleeve to move sleeve ports and the annular gap.

[0064] An abrasive wellbore servicing fluid (such as a fracturing fluid, a particle laden fluid, a cement slurry, etc.) may then be pumped down the wellbore 114 into the flow path 142 and through one or more nozzles 200. In an embodiment, the wellbore servicing fluid is an abrasive fluid comprising from about 0.5 to about 1.5 pounds of abrasives and/or proppant per gallon of the mixture (lbs/gal), alternatively from about 0.6 to about 1.4 lbs/gal, alternatively from about 0.7 to about 1.3 lbs/gal. As the abrasive wellbore servicing fluid is pumped down and passed through the interior flowpath 204 of the nozzle 200, a fluid jet is formed. Generally, the abrasive wellbore servicing fluid is pumped down at a sufficient flow rate and pressure to form a fluid jet through the nozzles 200 at a velocity of from about 50 to about 2700 feet per second (ft/s), alternatively about 300 to about 2000 ft/sec, alternatively from about 350 to about 1000 ft/sec, alternatively from about 400 to about 600 ft/sec for a period of from about 2 to about 10 minutes, alternatively from about 3 to about 9 minutes, alternatively from about 4 to about 8 minutes at a suitable original flow rate as needed by the service process. The pressure of the abrasive wellbore servicing fluid may be increased from about 2000 to about 5000 psig, alternatively from about 2500 to about 4500 psig, alternatively from about 3000 to about 4000 psig and the pumping down of the abrasive wellbore servicing fluid is continued at a constant pressure for a period of time. In an embodiment, the use of one or more nozzles 200 as described herein may reduce the pressure requirements by greater than about 10%, alternatively greater than about 20%, alternatively greater than about 30%, or alternatively greater than about 40%.

[0065] At the end of the jetting period, the fluid jets may have eroded the lining and/or formation zone to form slots and/or perforation tunnels (and optionally micro-fractures and/or extended fractures depending upon the treatment conditions and formation characteristics) within the lining and/or formation zone. If needed, the flow rate of the abrasive wellbore servicing fluid may be increased typically to less than about 4 to 5 times the original flow rate to form slots and/or perforation tunnels of a desirable size and/or geometry. The formation of slots and/or perforation tunnels may be desirable when compared to multiple fractures. Typically, slots and/or perforation tunnels lead to the formation of dominant/extended fractures, which provide less restriction to hydrocarbon flow than multiple fractures, and increase hydrocarbon production flow into the wellbore 114.

[0066] In an embodiment, the nozzle 200 and/or one or more additional components of the service tool may be removed. For example, the nozzle 200 and/or one more additional components may be removed by continued abrasion by flow of the abrasive wellbore servicing fluid and/or by degradation such as contacting the nozzle 200 and/or one or more additional components with an acid that degrades nozzle 200 and/or one or more additional components. The abrasive fluid and/or degradation fluid (e.g., acid) may be pumped down the flow path 142 for a sufficient time to completely (or partially) remove the nozzle 200 and/or one or more additional components. In alternative embodiments, the nozzle 200 and/or one or more additional components may be removed by any suitable method, for example, by mechanically removing the nozzle 200 and/or one or more additional components using coiled tubing or other devices or methods. Such actions may aid the wellbore service by increasing the area available for fluid flow through the tool and into the formation.

[0067] In an embodiment, the abrasive fluid may be displaced with another wellbore servicing fluid (for example, a proppant laden fracturing fluid that may or may not be similar to the abrasive wellbore servicing fluid) and the wellbore servicing fluid may be pumped through the nozzles 200 and/or additional apertures in the service assembly to form and extend dominant fractures in fluid communication with the slots and/or perforation tunnels. The dominant fractures may expand further and form micro-fractures in fluid communication with the dominant fractures. Generally, the dominant fractures expand and/or propagate from the slots and/or perforation tunnels within the formation zone to provide easier passage for production fluid (i.e., hydrocarbon) to the wellbore 114. Once the fractures are formed and extended, hydrocarbons can be produced by flowing the hydrocarbons from the micro-fractures (if present), to the dominant fractures, to the slots and/or perforation tunnels, and into the service assembly.

[0068] In an embodiment, a nozzle as shown in Figure 3A may be used in a Halliburton "SurgiFrac®" process. In this process, the impact or stagnation pressure of the fluid jet leaving the nozzle is used to initiate a fracture using the jetted fluid pressure. As described above, the total energy of the fluid jet should remain the same according to the Bernoulli Principle with losses due to friction and the like taken into account. In general, the total energy of the fluid jet is represented by the kinetic energy (i.e. the energy caused by velocity) and the potential energy, which can be represented by the pressure. In use, the high pressure, low velocity fluid in the tubing 1142 can be converted into a high velocity, lower pressure fluid jet by the nozzle - such as computed using the Equation 1. As the fluid jet impacts the wall of a perforation, or the "target," the fluid stops and turns back. This may cause the bottom of the perforation to be pressurized at a pressure similar to the pressure inside the tubing 1142. This pressure profile at the impact site could be represented by the profile shown in Figure 3B.

[0069] In some embodiments, the nozzle 200 having the expansion section can be used. In order to achieve the same flow rate as the comparative nozzle not having the expansion section, a lower tubing pressure is used due to the effect of the expansion section. The pressure profile may be similar to the velocity profile shown in Figure 4B. Since the average overall velocity in the fluid jets from the nozzle 200 and the comparative nozzle are approximately the same, the impact pressure at the bottom of the perforations are about the same. However, the pressure inside the tubing string upstream of the nozzle 200 is less. As a result, the pressurization of a perforation using nozzle 200 may occur with a lower tubing pressure as compared to a comparative nozzle not having the expansion section. Hence, the nozzle 200 may be effective in performing a SurgiFrac procedure at much lower pressures.

[0070] In an embodiment using the nozzle to perform a SurgiFrac procedure, a fracturing fluid may be pumped through the nozzles 200 once the slots and/or perforation tunnels have been generated in the presence of a fluid at pressures between the pressure of the pores of the formation and the fracture pressure. The pressure created at the impact location between the resulting fluid jet and the formation may be above the fracture pressure of the formation, which may result in the initiation of a fracture at the impact point. As described in more detail herein, the impact pressure may be based on the Bernoulli Principle that provides that the resulting pressure is based on the velocity of the incoming fluid. Once the fractures have been initiated in the desired locations, the pressure of the fluid may be increased above the fracture pressure to propagate the fractures into the formation. Without intending to be limited by theory, it is expected that the nozzle 200 may be used to create an impact pressure (e.g., a pressure at the impact point of the fluid jet with the formation) that is greater than the pressure drop across the nozzle 200. In an embodiment, the pressure drop across the nozzle may be at least about 1%, at least about 2%, at least about 5%, or at least about 10% less than the impact pressure based on an absolute pressure scale. This may be possible due to the energy input from the ambient fluid resulting from the use of the expansion section. This may allow for the generation of the fractures at the desired location with a lower pumping pressure.

[0071] The number of intervals or zones, the order in which the service assemblies comprising the nozzles described herein are used (e.g., partially and/or fully opened and/or closed), the service assemblies, the wellbore servicing fluid, etc. shown herein may be used in any suitable number and/or combination and the configurations shown herein are not intended to be limiting and are shown only for example purposes. Any desired number of formation zones may be treated or produced in any order.

[0072] In another embodiment, the work string 1112 of Figure IB may be used to service a wellbore. In connection with formations in which the wellbores extend for relatively long distances, either vertically, horizontally, or angularly, the jet sub 1148, the valve sub 1152, and the workstring 1112 can be initially placed at the toe section (i.e., the farthest section from the ground surface) of the well. Treatment of the subterranean formation 1102 using one or more servicing fluids may be carried out in intervals and repeated numerous times throughout the wellbore section (e.g., such as every 100 to 200 feet).

[0073] Referring to Figure IB, the wellbore servicing may begin by disposing the work string 1112 comprising the valve sub 1152 and the jet sub 1148, which comprises a nozzle 200 as described with respect to Figures 2 and 3. The jet sub 1148 may be positioned adjacent the formation zone to be treated. While the orientation of the work string 1112 is illustrated as being horizontal, in alternative methods of servicing a wellbore, the work string 1112 may be deviated, vertical, or angled, which can be selected based on the wellbore conditions. In an embodiment, the valve sub 1152 may initially be in an open position so that fluid flow is directed out of the work string 1112 rather than through the nozzle 200. The valve sub 1152 may be subsequently closed using any methods known to one of ordinary skill in the art with the aid of this disclosure. For example, a ball or dart may be dropped into the work string 1112, pass through the jet sub 1148, and seat on a shoulder within the valve sub 1152. One or more servicing fluids may be pumped down the work string 1112 to form a jet through the nozzle 200 for treating the subterranean formation 1102. For example, the various fluids may comprise a preflush fluid, a servicing or stimulation fluid, an afterflush fluid, and/or a diversion fluid. In some embodiments, the servicing fluid may comprise a foamed fluid and/or the servicing fluid may be foamed through the introduction of gas through the work string 1112.

[0074] In some embodiments, an initial fluid comprising an abrasive material may be used to form one or more passages in the casing 1120 and/or the subterranean formation 1102 to allow the other fluids to reach the subterranean formation 1102. In an embodiment, the fluid may comprise an abrasive fluid comprising from about 0.5 to about 1.5 pounds of abrasives and/or proppants per gallon of the mixture (lbs/gal), alternatively from about 0.6 to about 1.4 lbs/gal, alternatively from about 0.7 to about 1.3 lbs/gal. As the abrasive wellbore servicing fluid is pumped down and passed through the jet sub 1148 and the nozzle 200, a fluid jet is formed. Generally, the abrasive wellbore servicing fluid is pumped down at a sufficient flow rate and pressure to form a fluid jet through the nozzles 200 at a velocity of from about 50 to about 2700 feet per second (ft/s), alternatively about 300 to about 2000 ft/sec, alternatively from about 350 to about 1000 ft/sec, alternatively from about 400 to about 600 ft/sec for a period of from about 2 to about 10 minutes, alternatively from about 3 to about 9 minutes, alternatively from about 4 to about 8 minutes at a suitable original flow rate as needed by the service process. The pressure of the abrasive wellbore servicing fluid may be increased from about 30 to 50,000 psig, alternatively from about 2000 to about 10,000 psig, alternatively from about 2500 to about 5000 psig, alternatively from about 3000 to about 4000 psig and the pumping down of the abrasive wellbore servicing fluid is continued at a constant pressure for a period of time. At the end of the jetting period, the fluid jets may have eroded one or more passages in the casing 1120.

[0075] In an embodiment, a preflush fluid may be pumped down the work string 1112 and/or the annulus at pressures between the pressure of the pores of the formation and the fracture pressure. The preflush fluid can be non-acidic, acidic, or both. The preflush fluid may pass through the jet sub 1148 to form a fluid jet directed at the subterranean formation 1102.

[0076] A stimulation fluid may then pumped through the work string 1112 at pressures between the pore pressure and the fracture pressure. In some embodiments, the stimulation fluid may be pumped through the work string 1112 and the nozzle 200 at pressures above the fracture pressure of the formation. The stimulation fluid may comprise a conventional acid that is used in squeezing or matrix acidizing, along with various additives that are well known in the art. Typical acids may include, but are not limited to, mineral or organic acids, such as hydrochloric acid, hydrofluoric acid, formic acid, or acetic acid, or a blend thereof. The stimulation fluid may react with the subterranean formation 1102 to cause fracturing and squeezing, in a conventional manner.

[0077] Generally, the servicing fluids may be pumped down the work string 1112 at a sufficient flow rate and pressure to form a fluid jet through the nozzle 200. For example, the stimulation fluid may be pumped through the work string 1112 and out of the nozzle 200 in the jet sub 1148 to form a jet with a velocity of from about 50 to about 2700 feet per second (ft/s), alternatively about 300 to about 2000 ft/sec, alternatively from about 350 to about 1000 ft/sec, alternatively from about 400 to about 600 ft/sec. The stimulation fluid may be pumped out of the nozzles for a period sufficient to treat the interval of interest. In an embodiment, a suitable treatment period may range from about 2 to about 20 minutes, alternatively from about 3 to about 15 minutes, alternatively from about 4 to about 8 minutes at a suitable original flow rate as needed by the service process.

[0078] An afterflush fluid may then pumped down the work string 1112 and/or annulus to sweep the stimulation fluid out of the wellbore. This afterflush fluid is generally non-acidic. After a predetermined pumping of the afterflush fluid, a diversion stage may be initiated to insure that the fluid is spread over a relative large surface area of the subterranean formation 1102. Once the desired treatment of an interval is accomplished, the above steps may be repeated in another interval. The work string 1112 may then be removed from the wellbore and fluid can be recovered from the well. The fluid may comprise both the servicing fluid and hydrocarbons from the subterranean formation 1102.

[0079] While the nozzle 200 has been described herein in the context of a subterranean formation and a well, the design of the nozzle 200 may be applied to a variety of industrial settings where a high velocity fluid stream is desired with a reduced pressure or pumping requirements and/or improved flowrate or fluid velocity requirements. For example, a similar design to the nozzle 200 may be used in a valve seat (e.g., a ball valve seat), a pump valve, an exhaust pipe, a launch tube (e.g., a firearm barrel, submarine launch tube, etc.), an aircraft engine, a jetting device (e.g., in with an apparatus for industrial cleaning such as the industrial cleaning of hydrocarbon production equipment, car washes, yard work, etc.), power boosters (e.g., compressors, turbochargers, etc.), jet steering/propulsion devices in boats and/or ships, and the like.

[0080] In an embodiment as shown in Figure 5, a valve seat 500 for a ball valve is illustrated. As illustrated, the valve seat 500 is configured similarly to the nozzle 200. The valve seat 500 comprises a body 502 defining an interior flowpath 504. The valve seat 500 comprises a first end 508 and a second end 506, wherein the first end 508 may be configured to receive a sealing element such as a ball 509. The first end 508 may comprise one or more seats for engaging and forming a sealing engagement with the ball 509. In general, the ball 509 may comprise a fluid pathway 515 disposed therethrough, and the ball 509 may be rotated to align or misalign the fluid pathway through the ball 509 with the interior flowpath 504 through the valve seat, thereby opening or closing the valve, respectively. While described in terms of a ball 509 engaging a seat, it will be appreciated that the valve seat 500 may be configured to engage other valve or sealing elements such as flapper elements in flapper type valves and/or valve gates in gate valves.

[0081] The interior flowpath 504 through the valve seat 500 may comprise several distinct flow portions including, but not limited to, a flow section 514 and an expansion section 516. The valve seat 500 may be integrally formed from a single body 502 portion, although it will be appreciated by one of ordinary skill in the art that the various sections of the valve seat 500 may be contained in separate components that are coupled together. Fluid flowing through the ball 509 and into the flow passage 504 may first flow through the first end 508. The flow section 514 may have a relatively uniform diameter 520 along its length 519. The diameter 524 of the expansion section 516 is greater than the diameter 520 of the flow section 514 and may be relatively uniform along its length 522. The expansion section 516 extends to the second end 506 of the valve seat 500. The diameter 520 of the flow section 514 is less than the diameter 524 of the expansion section 516, thereby creating a shoulder 526 at the intersection of the flow section 514 and the expansion section 516. The shoulder 526 may be formed in any of the configurations described above with respect to the shoulder 226 of the nozzle 200. The diameters and lengths of the flow section 514, and/or the expansion section 516 may vary depending on the particular application in which the valve seat 500 is used, and may be the same as or similar to those described above with respect to the nozzle 200.

[0082] The valve may be operated in several configurations. When the valve is closed, fluid may be present on both sides of the valve. When the ball 509 is rotated to align the fluid pathway 515 through the ball 509 with the interior flowpath 504, fluid may begin to flow towards the valve body 500. When the fluid pressure on the first end 508 of the valve body 500 exceeds the fluid pressure on the second end 506 of the valve seat 500, the fluid may flow through the valve body 500 from the first end 508 to the second end 506. Upon initiation of flow through the valve seat 500, the fluid may expand out of the flow section 514, past the shoulder 526, and flow into the expansion section 516. A chamber (e.g., like chamber 402 shown in Figure 4A) may then be formed with a pressure below that of the ambient pressure adjacent the second end 506 of the valve seat 500. In an embodiment, some amount of backflow may be allowed into the expansion section 516 of the valve seat 500 (e.g., into a chamber in the expansion section 516) to affect the pressure in the chamber. The amount of pressure supplied to the chamber from the ambient environment adjacent the second end 506 may vary, and in an embodiment, may be in any of the ranges described herein with respect to the nozzle 200. The resulting fluid flow through the valve seat 500 from the first end 508 to the second end 506 may experience a decreased pressure drop and/or an increased flowrate through the valve seat 500. This may be advantageous in reducing the pressure losses past the valve seat 500.

[0083] In an embodiment as shown in Figures 6A and 6B, a pump discharge valve 600 is illustrated. In general, a pump discharge valve 600 is used at the outlet of a pump to allow fluid to flow through the valve (e.g., exit the pump), while preventing reverse flow through the valve (e.g., prevent fluid from entering the pump). The pump discharge valve 600 generally comprises a body 602 and a poppet 603 configured to engage the body 602. The poppet may be retained in engagement with the body by a biasing member. When a pressure within a chamber 605 adjacent the poppet 603 exceeds the pressure on the opposite side of the poppet 603 and overcomes the biasing force from the biasing member, the poppet 603 may translate out of engagement with the body 602 to thereby allow fluid to flow between the body 602 and the poppet 603. A pressure differential on the opposite side of the poppet 603 that is greater than the pressure within the chamber 605 may further bias the poppet 603 into sealing engagement with the body 602, thereby preventing reverse flow into the chamber 605. While described as a pump discharge valve 600, any of a variety of one-way or check valves may operate in a similar manner and the principles described herein may apply to any suitable one-way or check valve. In an embodiment, the poppet 603 may comprise a shoulder 626 formed on an outer diameter thereof. In some embodiments, the shoulder may alternatively or additionally be present on the inner surface of the body 602.

[0084] As illustrated in Figures 6A and 6B, when the poppet 603 is separated from the body 602, a fluid pathway 604 is formed that may be configured similarly to the nozzle 200 described herein. The fluid pathway 604 may be formed on one side by the inner diameter of the body 602 and on a second side by the outer diameter of the poppet 603. The fluid pathway 604 may comprise a first end 608 (e.g., fluid inlet) and a second end 606 (e.g., fluid discharge). The fluid pathway 604 through the pump discharge valve 600 may comprise several distinct flow portions including, but not limited to, a flow section 614 and an expansion section 616. Fluid flowing through the pump discharge valve 600 may first flow through the first end 608. The fluid pathway 604 may have a relatively uniform annular opening 620 along its length 619. The diameter 624 of the expansion section 616 is greater than the annular opening 620 of the flow section 614 and may be relatively uniform along its length 622. The expansion section 616 extends to the second end 606 of the fluid pathway 604. The annular opening 620 of the flow section 614 is less than the annular opening 624 of the expansion section 616, thereby creating a shoulder 626 at the intersection of the flow section 614 and the expansion section 616. The shoulder 626 may be formed in any of the configurations described above with respect to the shoulder 226 of the nozzle 200. In an embodiment, the diameters and lengths of the flow section 614 and/or the expansion section 616 may vary depending on the particular application in which the pump discharge valve 600 is used, and may be the same as or similar to those described above with respect to the nozzle 200.

[0085] The pump discharge valve 600 may be operated in several configurations. A pump element may provide a fluid to the chamber 605, which may exert a pressure on the poppet 603. When the pressure provides a sufficient force to overcome any pressure on the opposite side of the poppet as well as a biasing force from a biasing element on the poppet 603, the poppet 603 may disengage from the body 602 and form a fluid pathway 604 between the body 602 and the poppet 603. The shoulder 626 on the poppet 603 may be disposed along the fluid pathway 604, thereby forming the flow section 614 and the expansion section 616. As the fluid pathway 604 is formed, fluid may begin to flow from the first end 608 of the fluid pathway 604 to the second end 606 of the fluid pathway 604. Upon initiation of fluid flow through the fluid pathway 604, the fluid may expand out of the flow section 614, past the shoulder 626, and flow into the expansion section 616. A chamber (e.g., like chamber 402 of Figure 4A) may then be formed with a pressure below that of the ambient pressure adjacent the second end 606 of the fluid pathway 604. In an, some amount of backflow may be allowed into the expansion section 616 of the fluid pathway 604 (e.g., into a chamber in the expansion section 616) to affect the pressure in the chamber. The amount of pressure supplied to the chamber from the downstream environment may vary, and in an embodiment, may be in any of the ranges described herein with respect to the nozzle 200. The resulting fluid flow through the fluid pathway 604 from the first end 608 to the second end 606 may experience a decreased pressure drop and/or an increased flowrate through the fluid pathway 604 in the pump discharge valve 600. This may be advantageous in reducing the horsepower requirements for the pump. In an embodiment, the horsepower requirements for a pump utilizing the pump discharge valve design described herein may have a power consumption between about 1% and about 5% less than a comparative pump that does not comprise the shoulder 626 and resulting flow sections 614, 616 but is otherwise the same.

[0086] In an embodiment as shown in Figure 7, an exhaust pipe 700 is illustrated. As illustrated, the exhaust pipe 700 is configured similarly to the nozzle 200, except that the expansion section may increase in diameter towards the outer end to take into account the compressibility of the gasses passing through the exhaust pipe 700. The exhaust pipe 700 comprises a body 702 defining an interior flowpath 704. The exhaust pipe 700 comprises a first portion 708 and a second end 706. The first portion 708 comprises a fluid conduit coupled to any of a number of process units. In an embodiment, the first portion may be in fluid communication with an engine (e.g., automobile engine, industrial engine, etc.), a vent line or vent tank, a combustion source, a safety discharge line, or the like. The interior flowpath 704 through the exhaust pipe 700 may comprise several distinct flow portions including, but not limited to, a flow section 714 through the first portion 708 and an expansion section 716. The exhaust pipe 700 may be integrally formed from a single body 702 portion. It will be appreciated by one of ordinary skill in the art that the various sections (e.g., the expansion section 716) may be contained in separate components that are coupled together, for example the expansion section 716 may be an add-on component to an existing exhaust pipe (e.g., an automobile tail pipe, truck exhaust stack, etc.).

[0087] Fluid generally flows from the exhaust pipe 700 to the ambient environment past the second end 706. In this flow configuration, fluid may first flow through the first portion 708. The flow section 714 may have a relatively uniform diameter 720. The length of the flow section 714 may be selected to allow for fluid communication with a desired processing unit. The diameter 724 of the expansion section 716 is greater than the diameter 720 of the flow section 714 and may be relatively uniform along its length 722. The expansion section

716 extends to the second end 706 of the exhaust pipe 700. The diameter 720 of the flow section 714 is less than the diameter 724 of the expansion section 716, thereby creating a shoulder 726 at the intersection of the flow section 714 and the expansion section 716. The shoulder 726 may be formed in any of the configurations described above with respect to the shoulder 226 of the nozzle 200. In an embodiment, the diameters and lengths of the flow section 714 and/or the expansion section 716 may vary depending on the particular application in which the exhaust pipe 700 is used, and may be the same as or similar to those described above with respect to the nozzle 200.

[0088] In an embodiment, the fluid flowing through the exhaust pipe 700 may be a gas. When the fluid is a gas, the diameter 724 of the expansion section 716 may expand along the length 722 of the expansion section 716 so that the diameter 724 increases starting at the shoulder 726 and moving to the second end 706. In an embodiment, the expansion section 716 may have a conical, frusto-conical, or trapezoidal cross-section. The expansion may be configured to provide for the expansion of the gas stream as the pressure drops along the length 722 of the expansion section 716. The increase in diameter 724 may occur gradually (e.g., at a constant slope) and/or a in series of steps (e.g., sharp, rounded, or curved shoulders).

[0089] When the fluid pressure within the first portion 708 of the exhaust pipe 700 exceeds the fluid pressure (e.g., atmospheric pressure) beyond the second end 706 of the exhaust pipe 700, the fluid may flow through the exhaust pipe 700 from the first portion 708 to the second end 706. As fluid flows through the exhaust pipe 700, the fluid may expand out of the flow section 714, past the shoulder 726, and flow into the expansion section 716. A chamber 701 (e.g., like chamber 402 of Figure 4A) may then be formed with a pressure below that of the ambient pressure adjacent the second end 706 of the exhaust pipe 700. In an embodiment, some amount of backflow may be allowed into the expansion section 716 of the exhaust pipe 700 (e.g., into a chamber 701 in the expansion section 716) to affect the pressure in the chamber 701. The amount of pressure supplied to the chamber 701 from the downstream environment may vary, and in an embodiment, may be in any of the ranges described herein with respect to the nozzle 200. The resulting fluid flow through the exhaust pipe 700 from the first portion 708 to the second end 706 may experience a decreased pressure drop and/or an increased flowrate through the exhaust pipe 700. In some embodiments, this may be advantageous in reducing the pressure losses in exhaust pipe 700. The resulting decrease in back pressure may improve the efficiency of various upstream processes such an internal combustion engine. In some embodiments, an engine coupled upstream of the exhaust pipe 700 may experience an increase in fuel efficiency between about 2% to about 10%, or about 5% to about 7% as compared to the same engine that is not coupled to an exhaust pipe 700 comprising the shoulder 726 and resulting flow sections 714, 716 (e.g., in contrast to a a constant diameter exhaust pipe).

[0090] In an embodiment as shown in Figure 8, a launch tube 800 is illustrated. As illustrated, the launch tube 800 is configured similarly to the nozzle 200. The launch tube 800 may be configured to contain and/or propel an object to be launched, fired, or propelled out of the launch tube 800. In an embodiment, the launch tube 800 comprises a gun barrel for firing a bullet or other ballistic component. In some embodiments, the launch tube 800 comprises a submarine launch tube for various projectiles, which may comprise self-propelled projectile (e.g., torpedoes). In still other embodiments, the launch tube 800 may comprise a missile launch tube, which may be used in air and/or in a liquid environment (e.g., underwater). In general, the launch tube 800 may comprise a projectile 803 disposed in the launch tube 800 and a fluid disposed in an interior flowpath 804 comprising a fluid. Upon launching the projectile 803, the fluid in the interior flowpath 804 may be required to be displaced to allow the projectile 803 to exit the launch tube 800. Typically, the fluid must be displaced quickly, thereby creating a high fluid flowrate out of the launch tube 800 during the launch process and an increased pressure in the fluid due to the driving force behind the projectile. The flow configuration illustrated in Figure 8 may be used to reduce the pressure drop and/or energy loss due to displacing the fluid within the interior flowpath 804.

[0091] As illustrated in Figure 8, the launch tube 800 comprises a body 802 defining the interior flowpath 804 therethrough. The launch tube 800 comprises a first end 808 wherein the projectile 803 may be disposed prior to initiating the launch. The launch tube 800 also comprises a second end 806 adjacent an ambient environment. The interior flowpath 804 through the launch tube 800 may comprise several distinct flow portions including, but not limited to, a launch section 814 and an expansion section 816. The launch tube 800 may be integrally formed from a single body 802 portion, although it will be appreciated by one of ordinary skill in the art that the various sections of the launch tube 800 may be contained in separate components that are coupled together. The launch section 814 may have a relatively uniform diameter 820 along its length 819. The diameter 824 of the expansion section 816 is greater than the diameter 820 of the launch section 814 and may be relatively uniform along its length 822. The expansion section 816 extends to the second end 806 of the launch tube 800. The diameter 820 of the launch section 814 is less than the diameter 824 of the expansion section 816, thereby creating a shoulder 826 at the intersection of the launch section 814 and the expansion section 816. The shoulder 826 may be formed in any of the configurations described above with respect to the shoulder 226 of the nozzle 200. In an embodiment, the diameters and lengths of the flow section launch section 814 and/or the expansion section 816 may vary depending on the particular application in which the launch tube 800 is used, and may be the same as or similar to those described above with respect to the nozzle 200. Since the effect is primarily dependent upon the pressure downstream of the launch tube, the deeper the location of the tube in water, the higher the efficiency due to the increased hydrostatic pressure.

[0092] In an embodiment, the fluid within the launch tube 800 may be a gas, and during the launch or firing of the projectile 803, the gas may be displaced from the launch tube 800. When the fluid is a gas, the diameter 820 of the expansion section 816 may expand along the length 822 of the expansion section 816 so that the diameter 824 increases starting at the shoulder 826 and moving to the second end 806. In an embodiment, the expansion section 816 may have a conical, frusto-conical, or trapezoidal cross-section. The expansion may be configured to provide for the expansion of the gas stream as the pressure drops along the length 822 of the expansion section 816. The increase in diameter 824 may occur gradually (e.g., at a constants slope) and/or a in series of steps (e.g., sharp, rounded, or curved shoulders).

[0093] The launch tube 800 may be operated by first positioning the projectile 803 within the launch tube. In general, the projectile 803 may be stationary within the launch tube so that the fluid within the interior flowpath 804 is also stationary prior to initiating the launching or firing of the projectile 803. Upon the launching or firing of the projectile 803, the projectile may begin to move towards the second end 806, thereby displacing the fluid within the interior flowpath 804 towards the ambient environment. As the fluid is accelerated through the interior flowpath 804, the fluid may expand out of the launch section 814, past the shoulder 826, and flow into the expansion section 816. A chamber 801 (e.g., like chamber 402 of Figure 4A) may then be formed with a pressure below that of the ambient pressure adjacent the second end 806 of the launch tube 800. In an embodiment, some amount of backflow may be allowed into the expansion section 816 of the launch tube 800 (e.g., into a chamber 801 in the expansion section 816) to affect the pressure in the chamber 801. The fluid flowing into the chamber 801 may come from the ambient environment adjacent the second end 806 and/or from the fluid flowing out of the expansion section 816 such that a portion of the fluid may turn and enter the chamber

801. The amount of pressure supplied to the chamber from the ambient environment may vary, and in an embodiment, may be in any of the ranges described herein with respect to the nozzle 200. The resulting fluid flow out of the launch tube 800 ahead of the projectile 803 may experience a decreased pressure drop and/or present a decreased resistance to the movement of the projectile 803 out of the launch tube 800. This may be advantageous in allowing the projectile to retain energy, thus traveling further and/or faster. For example, a bullet may have an increased speed for a longer ballistic flight, a torpedo may accelerate out of a launch tube with an increased velocity to strike a target sooner, or a missile may launch with a decreased fuel consumption to allow for a longer flight range. The effectiveness of the feature in the case of the bullet is air may be limited by the air pressure (e.g., an atmospheric pressure of about 14.7 psia). However, the velocity of the of the bullet may generate a relatively large pressure within the launch tube and/or barrel, and the resulting increase in the back pressure due to the sudden acceleration of the bullet may be key to the performance improvement. In an embodiment, the use of the launch tube as described herein may result in an increased velocity of a projectile leaving the launch tube of between about 1% and about 20% for a projectile launched in a gas (e.g., in air), or between about 5% and about 40% for a projectile launched in a liquid (e.g., a subsea launch).

[0094] In an embodiment as shown in Figure 9, a turbine engine 900 (e.g., an aircraft engine, a turbine generator, etc.) is illustrated. As illustrated, portions of the turbine engine 900 are configured similarly to the nozzle 200. In general, the engine 900 comprises a body 902 comprising a first interior flowpath 904 upstream of a combustion section 903 and a second interior flowpath 905 downstream of the combustion section 903. In general, the combustion section may comprise one or more sets of turbine blades 935 upstream and/or downstream of a combustion chamber. The combustion section 903 may be configured to contact fuel with at least a portion of the incoming air, combust the fuel to increase the temperature of the mixture, and pass the mixture through one or more downstream sets of turbines that power the upstream one or more sets of turbines. In some embodiments, the one or more sets of turbines may be coupled by a shaft to a generator to produce shaft work for generating electricity. The net effect of the turbine engine 900 is to produce thrust for an aircraft and/or shaft work for generating electricity, running a compressor, running a mechanical unit, or the like. The turbine engine 900 comprises a first end 908 and a second end 906. The first interior flowpath 904 upstream of the combustion section 903 may comprise several distinct flow portions including, but not limited to, an inlet flow section 914 and an expansion section 916. The second interior flowpath 905 downstream of the combustion section 903 may comprise several distinct flow portions including, but not limited to, a flow section 915 and an outlet expansion section 917. It will be appreciated by one of ordinary skill in the art that the various sections and components of the turbine engine 900 may be contained in separate components that are coupled together. In some embodiments, the body 902 may be integrally formed from a single body 902 portion.

[0095] Fluid (e.g., air, air/fuel, etc.) generally flows from the ambient environment upstream of the turbine engine into the inlet 908, through the turbine engine 900 and exits the turbine engine 900 at the exhaust 906. The fluid flowing through the turbine engine 900 may generally pass through the first interior flowpath 904, then the combustion section 903, followed by the second interior flowpath 905. The first interior flowpath 904 may generally comprise the inlet flow section 914 and the expansion section 916. The inlet flow section 914 may have a relatively uniform diameter 920 along its length 919. The diameter 924 of the expansion section 916 is greater than the diameter 920 of the flow section 914 and may be relatively uniform along its length 922. The expansion section 916 extends to the combustion section 903. The diameter 920 of the flow section 914 is less than the diameter 924 of the expansion section 916, thereby creating a shoulder 926 at the intersection of the flow section 914 and the expansion section 916. The shoulder 926 may be formed in any of the configurations described above with respect to the shoulder 226 of the nozzle 200. In an embodiment, the diameters and lengths of the inlet flow section 914 and/or the expansion section 916 may vary depending on the particular application in which the turbine engine 900 is used, and may be the same as or similar to those described above with respect to the nozzle 200.

[0096] Similarly, the second interior flowpath 905 may generally comprise the flow section 915 and the outlet expansion section 917. The flow section 915 may have a relatively uniform diameter 930 along its length 929. The diameter 934 of the outlet expansion section 917 is greater than the diameter 930 of the flow section 915 and may be relatively uniform along its length 932. The outlet expansion section 917 extends to the outlet 906. The diameter 930 of the flow section 915 is less than the diameter 934 of the outlet expansion section 917, thereby creating a shoulder 927 at the intersection of the flow section 915 and the outlet expansion section 917. The shoulder 927 may be formed in any of the configurations described above with respect to the shoulder 226 of the nozzle 200. In an embodiment, the diameters and lengths of the flow section 915 and/or the outlet expansion section 917 may vary depending on the particular application in which the turbine engine is used, and may be the same as or similar to those described above with respect to the nozzle 200.

[0097] In an embodiment, the fluid flowing through the first interior flowpath 904 and/or the second interior flowpath 905 may be a gas. When the fluid is a gas, the diameter 924 of the expansion section 916 and/or the diameter 934 of the outlet expansion section 917 may expand along the length 922, 932, respectively, from the upstream end to the downstream end. In an embodiment, the expansion section 916 and/or the outlet expansion section 917 may have a conical, frusto-conical, or trapezoidal cross-section. The expansion may be configured to provide for the expansion of the gas stream as the pressure drops along the length of the expansion section 916 and/or the outlet expansion section 917. The increase in diameter may occur gradually (e.g., at a constant slope) and/or a in series of steps (e.g., sharp, rounded, or curved shoulders).

[0098] In use, a fluid may be moving through the turbine engine 900 due to the action of the one or more sets of turbines and the combustion section 903. The turbine engine 900 may be moving, for example on an airplane, or stationary, for example when used with power generation. In either case, the fluid may flow into the inlet 908, through the first interior flowpath 904, through the combustion section 903, through the second interior flowpath 905, and out the exhaust 906.

[0099] As fluid flows through the first interior flowpath, the fluid may expand out of the inlet flow section 914, past the shoulder 926, and flow into the expansion section 916. A chamber 901 (e.g., like chamber 402 of Figure 4A) may then be formed with a pressure below that of the ambient pressure in the combustion section 903. In an embodiment, some amount of backflow may be allowed into the expansion section 916 of the first interior flowpath 904 (e.g., into a chamber 901 in the expansion section 916) to affect the pressure in the chamber 901. The amount of pressure supplied to the chamber from the combustion section 903 may vary, and in an embodiment, may be in any of the ranges described herein with respect to the nozzle 200. The resulting fluid flow through the first interior flowpath 904 may experience a decreased pressure drop and/or an increased flowrate through the first interior flowpath 904.

[00100] Similarly as fluid flows through the second interior flowpath 905, the fluid may expand out of the flow section 915, past the shoulder 927, and flow into the outlet expansion section 917. A chamber 931 (e.g., like chamber 402 of Figure 4A) may then be formed with a pressure below that of the ambient pressure in the ambient environment adjacent the exhaust 906. In an embodiment, some amount of backflow may be allowed into the expansion section

917 of the second interior flowpath 905 (e.g., into a chamber 931 in the outlet expansion section 917) to affect the pressure in the chamber 931. The amount of pressure supplied to the chamber 931 from the ambient environment may vary, and in an embodiment, may be in any of the ranges described herein with respect to the nozzle 200. The resulting fluid flow through the second interior flowpath 905 may experience a decreased pressure drop and/or an increased flowrate.

[00101] In some embodiments, the use of a flow section and expansion section adjacent the inlet 908 and/or the outlet 906 may be advantageous in reducing the pressure losses and/or achieving a higher fluid flowrate in turbine engine 900. The resulting decrease in back pressure may improve the efficiency, horsepower, and/or electrical output of the turbine engine 900. In some embodiments, a turbine engine 900 may experience an increase in fuel efficiency between about 2% to about 10%, or about 5% to about 7% as compared to the same engine not having the shoulder 926 and/or shoulder 927 and resulting flow sections 914, 916 and/or flow sections 915, 917, respectively.

[00102] In an embodiment as shown in Figure 10, a blower assembly 1000 is illustrated. As illustrated, the blower assembly 1000 is configured similarly to the nozzle 200. The blower assembly 1000 may be used to move a fluid such as air. In some embodiments, the blower assembly 1000 may be used to accelerate a small portion of air in a fan or larger blower assembly configured to create drag and induce movement in a larger portion of air. In this embodiment, the small portion of air, as represented by flow arrows 1025, can be accelerated and used to create a bulk flow of a larger portion of the air. Such a configuration may also be used to create a bulk flow of a liquid.

[00103] As illustrated in Figure 10, the blower assembly 1000 comprises a body 1002 defining an interior flowpath 1004. The blower assembly 1000 comprises an inlet 1008 and an exhaust 1006. The interior flowpath 1004 through the blower assembly 1000 may comprise several distinct flow portions including, but not limited to, a flow section 1014 and an expansion section 1016. The blower assembly 1000 may be integrally formed from a single body 1002 portion. It will be appreciated by one of ordinary skill in the art that the various sections (e.g., the expansion section 1016) may be contained in separate components that are coupled together.

[00104] A pressurized fluid is generally introduced into the inlet 1008 and flows through the interior flowpath 1004 to the outlet 1006. In this flow configuration, fluid may first flow through the flow section 1014. The flow section 1014 may have a relatively uniform diameter 1020 along its length 1019, though the diameter 1020 may change along the length 1019. The diameter 1024 of the expansion section 1016 is greater than the diameter 1020 of the flow section 1014 and may be relatively uniform along its length 1022. The expansion section 1016 extends to the end of the exhaust 1006. The diameter 1020 of the flow section 1014 is less than the diameter 1024 of the expansion section 1016, thereby creating one or more shoulders 1025, 1026 along the length 1022 of the expansion section 1016. The shoulders 1025, 1026 may be formed in any of the configurations described above with respect to the shoulder 226 of the nozzle 200. In an embodiment, the diameters and lengths of the flow section 1014 and/or the expansion section 1016 may vary depending on the particular application in which the blower assembly 1000 is used, and may be the same as or similar to those described above with respect to the nozzle 200.

[00105] In an embodiment, the fluid flowing through the blower assembly 1000 may be a gas. When the fluid is a gas, the diameter 1024 of the expansion section 1016 may expand along the length 1022 of the expansion section 1016 so that the diameter 1024 increases starting at the shoulder 1025 and moving to the exhaust 1006. In an embodiment, the expansion section 1016 may have a conical, frusto-conical, stepped, or trapezoidal cross-section. The expansion may be configured to provide for the expansion of the gas stream as the pressure drops along the length 1022 of the expansion section 1016. The increase in diameter 1024 may occur gradually (e.g., at a constant slope) and/or a in series of steps (e.g., sharp, rounded, or curved shoulders) such as those formed by shoulder 1025. 10 10 10

[00106] When the fluid pressure upstream of the inlet 1008 of the blower assembly 1000 exceeds the fluid pressure (e.g., atmospheric pressure) beyond the exhaust 1006, the fluid may flow through the blower assembly 1000 from the inlet 1008 to the exhaust 1006. As fluid flows through the blower assembly 1000, the fluid may expand out of the flow section 1014, past the shoulder 1025 and shoulder 1026, and flow into the expansion section 1016. A chamber 1001 (e.g., like chamber 402 of Figure 4A) may then be formed with a pressure below that of the ambient pressure adjacent the exhaust 1006 end of the blower assembly 1000. In an embodiment, some amount of backflow may be allowed into the expansion section 1016 (e.g., into the chamber 1001 in the expansion section 1016) to affect the pressure in the chamber 1001. The amount of pressure supplied to the chamber 1001 from the downstream environment may vary, and in an embodiment, may be in any of the ranges described herein with respect to the nozzle 200. The resulting fluid flow through the blower assembly 1000 from the inlet 1008 to the exhaust 1006 may experience a decreased pressure drop and/or an increased flowrate through the blower assembly 1000. In some embodiments, this may be advantageous in reducing the pressure losses in blower assembly 1000.

[00107] In some embodiments, the blower assembly 1000 may comprise a portion of a larger inducted flow blower assembly. The blower assembly 1000 may be an elongated structure having the cross-section illustrated in Figure 10. The interior flowpath 1004 may comprise a slot or other such structure. In some embodiments, the blower assembly 1000 may form an enclosed, elongated structure such that the elongated interior flowpath 1004 (e.g., a slot-like interior flowpath 1004) forms a continuous path. For example, the enclosed, elongated structure may form a circular, oval, rectangular, triangular, oblong, elliptical, or other closed structure having a slot like exhaust 1006. The resulting fluid flow out of the exhaust 1006 may form a sheet like fluid flow conforming to the shape of the enclosed, elongated structure (e.g., a circular structure would form a hollow tube like fluid flow, etc.). When the blower assembly 1000 forms an enclosed, elongated structure, the fluid stream formed by the blower assembly 1000 may also form a closed fluid stream defining a volume of fluid within the closed area. Based on fluid dynamics, the fluid within the closed area is subjected to drag based on the moving fluid stream exiting the exhaust, and the fluid within the closed area can be accelerated and entrained with the closed fluid stream. Such a configuration may be used to generate or induce a bulk fluid flow within the closed area based on the fluid stream exiting the blower assembly 1000. As the use of the blower assembly 1000 design disclosed herein may generate a higher fluid flow velocity and/or a greater flowrate out of the exhaust 1006, the blower assembly 1000 may also be used to induce a greater bulk flowrate out of the blower assembly 1000.

[00108] Returning to Figures 2 and 3, the nozzle may be used in various other industries. For example, the nozzle 200 may be used in a blower assembly for use in moving air for landscaping. A typical landscape blower may generate approximately 30 psia to about 50 psia. In some embodiments, some amount of backflow may be allowed into the expansion section 216 (e.g., into a chamber 302 in the expansion section 216) to affect the pressure in the chamber. Based on atmospheric pressure, between about 2 psia and about 12 psia, or between about 5 psia and about 9 psia may be introduced into the chamber 302 to reduce the resulting drag on the air stream passing through the blower assembly. Thus, the air being emitted from the blower assembly may have a higher velocity and/or a greater amount of air may be emitted as compared to a similar nozzle not comprising the shoulder 226 and flow sections 214, 216. Similarly, the design of the nozzle in Figures 2 and 3 may be used in a jet propulsion device. In these devices, a fluid is pressurized and passed out of the nozzle. The resulting thrust out of the nozzle is used to propel various device such as floating boats, subsea vessels (submarines, Remote Operated Vehicles, personal watercraft, etc.). In general, the deeper the location of the underwater propulsion device comprising the nozzle as described herein, the greater the increase in efficiency of the nozzle design. The use of the design of the nozzle 200 may allow the fluid to be emitted with a higher velocity and/or a greater amount of fluid may be emitted as compared to a similar nozzle not comprising the shoulder 226 and flow sections 214, 216.

[00109] As these embodiments demonstrate, the design of the nozzle may be used in a variety of settings and device in various industries. While initially described in terms of a nozzle, the use of device comprising a fluid pathway having a plurality of flow sections separated by a shoulder may be applicable to any number of devices other than nozzles.

EXAMPLES

[00110] The disclosure having been generally described, the following examples are given as particular embodiments of the disclosure and to demonstrate the practice and advantages thereof. It is understood that the examples are given by way of illustration and are not intended to limit the specification or the claims in any manner.

EXAMPLE 1

[00111] In order to illustrate the benefits of the nozzles as described herein, several comparative examples have been prepared. The nozzle of the present disclosure has been compared to a conventional jet nozzle (e.g., commercially available as jetting tools from a variety of vendors worldwide), and a HydraJet nozzle (e.g., commercially available from Halliburton Energy Service, Inc., of Houston, Texas), which do not comprise expansion chambers as described herein. In order to aid in comparison between the different nozzles, the same dimensions are used for the jets in each example unless otherwise noted (i.e. the internal diameters are the same). The conventional jetting tools generally have a C_d of around 0.7 (based on published data). The Halliburton HydraJet nozzle has a C_d of approximately 0.95 based upon test data. The "Current Nozzle" has an expansion chamber as described herein, and a C_d of 1.3 was selected for discussion in this example.

[00112] Calculation of the flow rates was made using Eq. 1 as described in more detail above. First, the conventional nozzle example uses a pressure differential across the nozzle of 4500 pounds per square inch (psi). Based upon Eq.l, the flow rate is 2.0189 BPM. Using the Halliburton jet nozzle at the same pressure produces a flow rate of 2.7399 BPM. The Current nozzle has a flowrate of 3.7493 BPM at the same pressure differential. In order to pump at approximately the same flow rate as the Halliburton nozzle (i.e., 2.7399 BPM), the pressure requirement for the new jet would be 2403.1 psi. Further, to pump at the same horsepower level as the Halliburton jet nozzle case, then, using the Current nozzle, the pressure differential would be 3651 psi, thereby producing a flowrate of about 3.377 BPM. The results of the nozzle calculations are shown in Table 1.

TABLE 1

Nozzle Calculation Results

	C_d	Jet Nozzle Diameter (in.)	Pressure (psig)	Fluid Density (lb/gal)	Flow Rate (Barrels /minute)
Conventional Jet Nozzle	0.7	0.25	4500	8.9	2.0189
Halliburton Jet Nozzle	0.95	0.25	4500	8.9	2.7399
Current Nozzle	1.3	0.25	4500	8.9	3.7493
Current Nozzle	1.3	0.25	2403.1	8.9	2.7399
Current Nozzle	0.25	1.3	3651	8.9	3.3773

[00113] The results of the calculations indicate that the use of the expansion section with the nozzle as described herein allows for the nozzle to have a coefficient of discharge of 1.3. The resulting flow rate increase represents about an 85.7% increase over the convention jet nozzle and a 36.8% increase of the Halliburton jet nozzle using approximately the same input pressure. Alternatively, the use of the nozzle as described herein resulted in a 46.6% decrease in the pressure required to pass the same volume of fluid through the nozzle as compared to the Halliburton jet nozzle with a coefficient of discharge of 0.95. Accordingly, the nozzle comprising the expansion section illustrates an improvement over comparable nozzles not comprising an expansion section.

EXAMPLE 2

[00114] As an example, a computational fluid dynamics (CFD) simulation was performed using a 0.1875-in. jet nozzle, with upstream and downstream pressures set at: P_u = 6,000 psi, and P_d = 4,000 psi. The velocity in the jet flow would normally be around 145 to 157 m/s, or approximately 475 to 516 ft/sec. The output of the simulation is shown in Figures 11A and 11B. As evidenced in Figures 11A and 11B, on the left, at near the boundary of the nozzle before entering the enlargement, the velocity exceeds 190 m/s or 623 ft/sec. This "skin" velocity continues to increase toward the right at 254 m/s or 833 ft/sec, more than 60% greater than an ideally formed conventional nozzle, which should have a velocity of 516 ft/sec. These high-velocity pulses can pull the jet flow along with them, pushing the jet flow out of the nozzle. In addition, the vacuum at the bottom of the cavity also helps provide a "pseudo low pressure" for the jet nozzle. Note that the "pseudo low pressure" helps accelerate the fluid inside the nozzle but, without the pull effect from the high-velocity pulses, the fluid simply slows down again.

EXAMPLE 3

[00115] Another CFD simulation was performed to study the effects of the size of the diameter expansion in the expansion section. Figures 12A-12C demonstrates the effect of greater enlargements in the expansion section. The results were obtained using the CFD model with a 3/16-in. ID nozzle and a pressure differential across the nozzle of approximately 2,000 psi. The velocity vectors of the outer skin of fluid can be seen from figures. As shown in Figure 12A, the pull velocity provided by a 0.040-in. enlargement is 254 m/sec or 833 ft/sec. When this cavity diameter is increased to 0.1 in., the pull velocity decreases to 177 m/sec or 580 ft/sec as shown in FIG. 12B. For a 0.16-in. cavity diameter increase, the velocity slightly increases to 181 m/s or 593 ft/sec as shown in Figure 12C. The small velocity increase between the 0.1 in expansion section increase and the 0.16 in expansion section increase may be assumed to be "the same" within the margin of the simulation software. These results can lead to the conclusion that smaller cavities (e.g., smaller increases in diameter from the flow section to the expansion section) may result in a higher restriction for the annulus flow into the nozzle enlargement, thus causing a high vacuum in the chamber formed in the enlargement. This combination would generate a higher C_d factor.

EXAMPLE 4

[00116] Another CFD simulation was performed to study the effects of the pressure differential across the nozzle. Figures 13A-13D demonstrates the effect of different pressure changes across the nozzle while maintaining a constant expansion section diameter. For this simulation, the effect of pressure was studied using flow through a 0.25-in. nozzle with a 0.04-in. enlargement. The results indicate that the higher the pressure differential, the faster the flow rate or velocity, even when dealing with conventional jets. Again, from the figures, it can be observed that the pressure differentials (ΔP) of 4,000 psi, 3,000 psi, 2,000 psi, and 1,500 psi, which should have respective ideal velocities of 729 ft/sec, 632 ft/sec, 516 ft/sec, and 446 ft/sec, respectively (or 222 m/s, 192 m/s, 157 m/s, and 136 m/s, respectively), did reach these velocities at the core of the jet flows. Skin velocities, again are high, showing 1,181 ft/sec, 984 ft/sec, 833 ft/sec, and 692 ft/sec, respectively (or 360 m/s, 300 m/s, 254 m/s, and 211 m/s, respectively). These equate to an approximately 55% to 62% velocity improvement at the skin. Another result from the simulation indicates that the two slower rates (Figures 13C and 13D) are dominated by the first harmonics only, while the higher-velocity conditions are dominated by higher harmonics.

EXAMPLE 5

[00117] A simulation was performed to demonstrate the difference between the nozzle having the expansion section and a conventional nozzle not having an expansion section. Figure 14 illustrates a simulated flow velocity pattern for a nozzle having an expansion section. Observing the velocity distribution in the flow stream before hitting the target, Figure 14 shows that the flow is dominated by the high-velocity fluid that originated from the potential energy provided by the hydrostatic pressure in the annulus region. As discussed previously, this high-velocity "object" carries with it the fluid originating from the jet. And, similar to a conventional jet, it loses energy fast as it moves toward the target on the right. Note that this "object" or "feature" collapses into a smaller, high-velocity feature, as can be seen on the right side, as it hits the target. In comparison, a conventional jet is illustrated in Figure 15, and it can be seen that the "skin" loses velocity as it penetrates the fluid.

[00118] Returning to Figure 14, a "window" shows a region where the specific fluid activities occur during the jetting process. As the different features move across the window, they are captured in Figures 16A-16F, which is presented as two series—one on the left (Figures 16A-16C) and the other on the right (Figures 16D-16F). In each window, the time stamp is shown in steps of 1/10,000 sec.

[00119] In the first frame shown in Figure 16A, at 0.0001 sec, the annulus fluid is being accelerated and "sucked" into the fast jet stream. A circular, counterclockwise flow is shown in this frame (and all other frames). The annular fluid that was accelerated in the jet cavity is then pulled in by the slower jet fluid in the center. This results in the accelerated fluid being slowed down, while the outside of the jetted fluid is accelerated by it. This part of the annular fluid collapses, as can be seen in the next frame (Figure 16B at 0.0002 sec). Similarly, in Figures 16D and 16E (from 0.0010 sec to 0.0012 sec), the annular fluid accelerates, and it collapses in Figure 16F (at 0.0013 sec).

EXAMPLE 6

[00120] A laboratory test was performed to valid the results of the simulations. The laboratory setup is schematically illustrated in Figure 17. As shown, two nozzles—a conventional nozzle 1701 and a nozzle 1702 comprising an expansion section as described herein—were placed in series so that the flow rates through the two nozzles would be the same. A pump 1703 provided pressure to the circuit and a choke 1704 was used to maintain a back pressure in the system. Pressures were recorded across each nozzle. Both nozzles 1701, 1702 were forced to jet into a large chamber 1705, 1706 to avoid a situation in which the jets could damage equipment during the job and also to eliminate axial fluid velocity differences above the jets. Both nozzles had the same 0.25-in. inner diameters.

[00121] The fluid used was a gel containing 2 lb/gal sand. Both pressure differentials across the two nozzles were recorded and plotted in Figure 18. The pressure in the downstream tank 1706 (ambient local pressure for the current nozzle 1702) was maintained at 4,000 psi using a variable choke 1704. At the initial state, Figure 18 shows that the pressure above the currently described nozzle 1702 was a mere 6,200 psi, meaning that it was only 2,100 psi above the downstream pressure. The conventional nozzle 1701 had a 4,000-psi pressure differential; thus, the pump pressure was 10,100 psi. The C_d factor of the conventional nozzle 1701 was known to be close to 1.0, and based on Equation (1), the C_d of the new nozzle 1702 was approximately 1.38. Note that the conventional nozzle 1701 lost pressure as it was eroded by the jet stream. In contrast, the new nozzle 1702 behaved oppositely; it actually increased pressure as it was eroded. This was a result of the "feature" (e.g., the shoulder and resulting chamber) being eroded away, meaning the C_d factor decreased as the feature eroded. It is predicted that the pressure drops of the two nozzles would become equal at a later time when that occurred.

[00122] Figure 18 also shows a C_d plot. Repeating the tests three times showed C_dS fluctuating between 1.36 to 1.39. The C_dS dropped to 1.2 when the jet nozzles were worn out (excessively eroded). It is anticipated (see dotted line in Figure 18) that pressures of the two nozzles will eventually converge to a value at which C_dS are approximately equal to 1.0.

[00123] The test was repeated using the same gel, but without the addition of sand. Results using the same flow rate (2.5 bbl/min) were recorded at a pressure differential of 3,550 psi across the conventional nozzle 1701 (note that the density of the fluid was now much lower; see Equation 1), while the pressure differential across the new nozzle 1702 was recorded at 1,850 psi. This means that the C_d factor of the new nozzle was approximately 1.385. Because a clean gel was used, the nozzles did not erode at all, so the numbers were "constant," though they did rapidly fluctuate at a very high frequency.

[00124] These tests demonstrate the validity of Equation 2, which allows several conclusions to be drawn. Note that $\mathbf{P_a} - \mathbf{P_b}$ cannot be less than zero, and, therefore, $\mathbf{P_b}$ cannot be greater than $\mathbf{P_d/2}$. Hence, at a 100% efficiency, the potential energy increase is limited by 50% of the ambient (or downstream) pressure $\mathbf{P_d}$. This means that pressure savings can be higher at higher ambient pressure; yet, logically, it cannot be higher than 50% of the pressure differential.

[00125] Having described the systems and methods, various embodiments may include, but are not limited to:

[00126] In a first embodiment, a method of jetting comprises providing a pressurized fluid to an interior flow path disposed in a nozzle body, wherein the nozzle body comprises a flow section and an expansion section, wherein the expansion section is disposed downstream from the flow section; passing the pressurized fluid through the flow section in the interior flow path and into the expansion section in the interior flow path; and passing a fluid jet out of the nozzle body from the expansion section, wherein the nozzle operates with a coefficient of discharge between about 1.0 and about **1.7.**

[00127] A second embodiment may include the method of the first embodiment, wherein the expansion section has a diameter 1.01 to 1.5 times greater than a diameter of the flow section.

[00128] A third embodiment may include the method of the first or second embodiment, wherein a length of the flow section is greater than about three times the diameter of the flow section.

[00129] A fourth embodiment may include the method of any of the first to third embodiments, wherein a length of the expansion section is between about one half of a diameter of the flow section and about four times the diameter of the flow section.

[00130] A fifth embodiment may include the method of any of the first to fourth embodiments, wherein the nozzle body further comprises a shoulder formed at an intersection of the flow section and the expansion section, wherein a length and diameter of the expansion section are configured to control the amount of backflow of fluid into the expansion section when a fluid is flowing through the nozzle.

[00131] A sixth embodiment may include the method of any of the first to fifth embodiments, wherein the fluid jet comprises a first portion of fluid in an outer layer of the fluid jet and a second portion of fluid in a core of the fluid jet, and wherein a fluid velocity of the first portion of fluid is higher than a fluid velocity of the second portion of fluid.

[00132] In a seventh embodiment, a method of jetting comprises: providing a pressurized fluid to an interior flow path disposed in a nozzle body, wherein the nozzle body comprises a flow section and an expansion section, wherein the expansion section is disposed downstream from the flow section; passing the pressurized fluid through the flow section in the interior flow path and into the expansion section in the interior flow path; and passing a fluid jet out of the nozzle body from the expansion section, wherein the fluid jet comprises a first portion of fluid in an outer layer of the fluid jet and a second portion of fluid in a core of the fluid jet, and wherein a fluid velocity of the first portion of fluid is higher than a fluid velocity of the second portion of fluid.

[00133] An eighth embodiment may include the method of the seventh embodiment, wherein the fluid velocity of the second portion of fluid in the core of the fluid jet is in the range of from about 300 feet per second to about 1,000 feet per second.

[00134] A ninth embodiment may include the method of the seventh or eighth embodiment, wherein the fluid velocity of the first portion of fluid in the outer layer of the fluid jet is in the range of from about 600 feet per second to about 2,000 feet per second.

[00135] A tenth embodiment may include the method of any of the seventh to ninth embodiments, wherein the fluid velocity of the first portion of fluid is at least 10% higher than the fluid velocity of the second portion of fluid.

[00136] An eleventh embodiment may include the method of any of the seventh to tenth embodiments, further comprising: receiving an ambient fluid from downstream of the nozzle to enter into the expansion section; accelerating the ambient fluid out of the expansion section; and accelerating the outer layer of the fluid jet using the ambient fluid that is accelerated out of the expansion section.

[00137] A twelfth embodiment may include the method of the eleventh embodiment, wherein receiving the ambient fluid and accelerating the ambient fluid occur as a cyclic process.

[00138] A thirteenth embodiment may include the method of any of the seventh to twelfth embodiments, wherein the nozzle body has a coefficient of discharge greater than 1.0 during the jetting.

[00139] A fourteenth embodiment may include the method of any of the seventh to thirteenth embodiments, wherein the expansion section has a diameter about 1.01 to about 1.5 times greater than a diameter of the flow section.

[00140] In a fifteenth embodiment, a method of hydrajetting comprises pressurizing a fluid using a pump to create a pressurized fluid; providing the pressurized fluid to a nozzle at an inlet pressure, wherein the nozzle is disposed in a wellbore in a subterranean formation, and wherein the nozzle comprises a flow section adjacent to an expansion section; passing the pressurized fluid through the flow section to the expansion section; passing the pressurized fluid out of the expansion section to create a fluid jet at an outlet pressure; directing the fluid jet towards a surface of the wellbore; and creating a stagnation pressure within the wellbore in response to directing the fluid jet towards the surface of the wellbore, wherein a pressure drop between the inlet pressure and the outlet pressure is less than the stagnation pressure.

[00141] A sixteenth embodiment may include the method of the fifteenth embodiment, wherein the pressurized fluid comprises an abrasive wellbore servicing fluid.

[00142] A seventeenth embodiment may include the method of the fifteenth or sixteenth embodiment, wherein the pressure drop is at least 1% less than the stagnation pressure.

[00143] An eighteenth embodiment may include the method of any of the fifteenth to seventeenth embodiments, further comprising: forming a slot or a perforation tunnel in the subterranean formation with the fluid jet.

[00144] A nineteenth embodiment may include the method of the eighteenth embodiment, further comprising: introducing a second pressurized fluid into the subterranean formation at a pressure sufficient to form one or more fractures in fluid communication with the slot or the perforation tunnel.

[00145] A twentieth embodiment may include the method of the nineteenth embodiment, further comprising: allowing one or more hydrocarbons to flow from the one or more fractures through the slot or the perforation tunnel and into the wellbore.

[00146] At least one embodiment is disclosed and variations, combinations, and/or modifications of the embodiment(s) and/or features of the embodiment(s) made by a person having ordinary skill in the art are within the scope of the disclosure. Alternative embodiments that result from combining, integrating, and/or omitting features of the embodiment(s) are also within the scope of the disclosure. Where numerical ranges or limitations are expressly stated, such express ranges or limitations should be understood to include iterative ranges or limitations of like magnitude falling within the expressly stated ranges or limitations (e.g., from about 1 to about 10 includes, 2, 3, 4, etc.; greater than 0.10 includes 0.11, 0.12, 0.13, etc.). For example, whenever a numerical range with a lower limit, Ri, and an upper limit, R_u, is disclosed, any number falling within the range is specifically disclosed. In particular, the following numbers within the range are specifically disclosed: $R=Ri+k*(R_u-Ri)$, wherein k is a variable ranging from 1 percent to 100 percent with a 1 percent increment, i.e., k is 1 percent, 2 percent, 3 percent, 4 percent, 5 percent, ... 50 percent, 51 percent, 52 percent, ..., 95 percent, 96 percent, 97 percent, 98 percent, 99 percent, or 100 percent. Moreover, any numerical range defined by two R numbers as defined in the above is also specifically disclosed. Use of the term "optionally" with respect to any element of a claim means that the element is required, or alternatively, the element is not required, both alternatives being within the scope of the claim. Use of broader terms such as comprises, includes, and having should be understood to provide support for narrower terms such as consisting of, consisting essentially of, and comprised substantially of. Accordingly, the scope of protection is not limited by the description set out above but is defined by the claims that follow, that scope including all equivalents of the subject matter of the claims. Each and every claim is incorporated as further disclosure into the specification and the claims are embodiment(s) of the present invention.

CLAIMS

What is claimed is:

1. A method of jetting comprising:

providing a pressurized fluid to an interior flow path disposed in a nozzle body, wherein the nozzle body comprises a flow section and an expansion section, wherein the expansion section is disposed downstream from the flow section;

passing the pressurized fluid through the flow section in the interior flow path and into the expansion section in the interior flow path; and

passing a fluid jet out of the nozzle body from the expansion section, wherein the nozzle operates with a coefficient of discharge between about 1.0 and about 1.7.

2. The method of claim 1, wherein the expansion section has a diameter 1.01 to 1.5 times greater than a diameter of the flow section.

3. The method of claim 1, wherein a length of the flow section is greater than about three times the diameter of the flow section.

4. The method of claim 1, wherein a length of the expansion section is between about one half of a diameter of the flow section and about four times the diameter of the flow section.

5. The method of claim 1, wherein the nozzle body further comprises a shoulder formed at an intersection of the flow section and the expansion section, wherein a length and diameter of the expansion section are configured to control the amount of backflow of fluid into the expansion section when a fluid is flowing through the nozzle.

6. The method of claim 1, wherein the fluid jet comprises a first portion of fluid in an outer layer of the fluid jet and a second portion of fluid in a core of the fluid jet, and wherein a fluid velocity of the first portion of fluid is higher than a fluid velocity of the second portion of fluid.

7. A method of jetting comprising:

providing a pressurized fluid to an interior flow path disposed in a nozzle body, wherein the nozzle body comprises a flow section and an expansion section, wherein the expansion section is disposed downstream from the flow section;

passing the pressurized fluid through the flow section in the interior flow path and into the expansion section in the interior flow path; and

passing a fluid jet out of the nozzle body from the expansion section, wherein the fluid jet comprises a first portion of fluid in an outer layer of the fluid jet and a second portion of fluid in a core of the fluid jet, and wherein a fluid velocity of the first portion of fluid is higher than a fluid velocity of the second portion of fluid.

8. The method of claim 7, wherein the fluid velocity of the second portion of fluid in the core of the fluid jet is in the range of from about 300 feet per second to about 1,000 feet per second.

9. The method of claim 7, wherein the fluid velocity of the first portion of fluid in the outer layer of the fluid jet is in the range of from about 600 feet per second to about 2,000 feet per second.

10. The method of claim 7, wherein the fluid velocity of the first portion of fluid is at least 10% higher than the fluid velocity of the second portion of fluid.

11. The method of claim 7, further comprising:

receiving an ambient fluid from downstream of the nozzle to enter into the expansion section;

accelerating the ambient fluid out of the expansion section; and

accelerating the outer layer of the fluid jet using the ambient fluid that is accelerated out of the expansion section.

12. The method of claim 11, wherein receiving the ambient fluid and accelerating the ambient fluid occur as a cyclic process.

13. The method of claim 7, wherein the nozzle body has a coefficient of discharge greater than 1.0 during the jetting.

14. The method of claim 7, wherein the expansion section has a diameter about 1.01 to about 1.5 times greater than a diameter of the flow section.

15. A method of hydrajetting comprising :

pressurizing a fluid using a pump to create a pressurized fluid;

providing the pressurized fluid to a nozzle at an inlet pressure, wherein the nozzle is disposed in a wellbore in a subterranean formation, and wherein the nozzle comprises a flow section adjacent to an expansion section;

passing the pressurized fluid through the flow section to the expansion section;

passing the pressurized fluid out of the expansion section to create a fluid jet at an outlet pressure;

directing the fluid jet towards a surface of the wellbore; and

creating a stagnation pressure within the wellbore in response to directing the fluid jet towards the surface of the wellbore, wherein a pressure drop between the inlet pressure and the outlet pressure is less than the stagnation pressure.

16. The method of claim 15, wherein the pressurized fluid comprises an abrasive wellbore servicing fluid.

17. The method of claim 15, wherein the pressure drop is at least 1% less than the stagnation pressure.

18. The method of claim 15, further comprising: forming a slot or a perforation tunnel in the subterranean formation with the fluid jet.

19. The method of claim 18, further comprising: introducing a second pressurized fluid into the subterranean formation at a pressure sufficient to form one or more fractures in fluid communication with the slot or the perforation tunnel.

20. The method of claim 19, further comprising: allowing one or more hydrocarbons to flow from the one or more fractures through the slot or the perforation tunnel and into the wellbore.

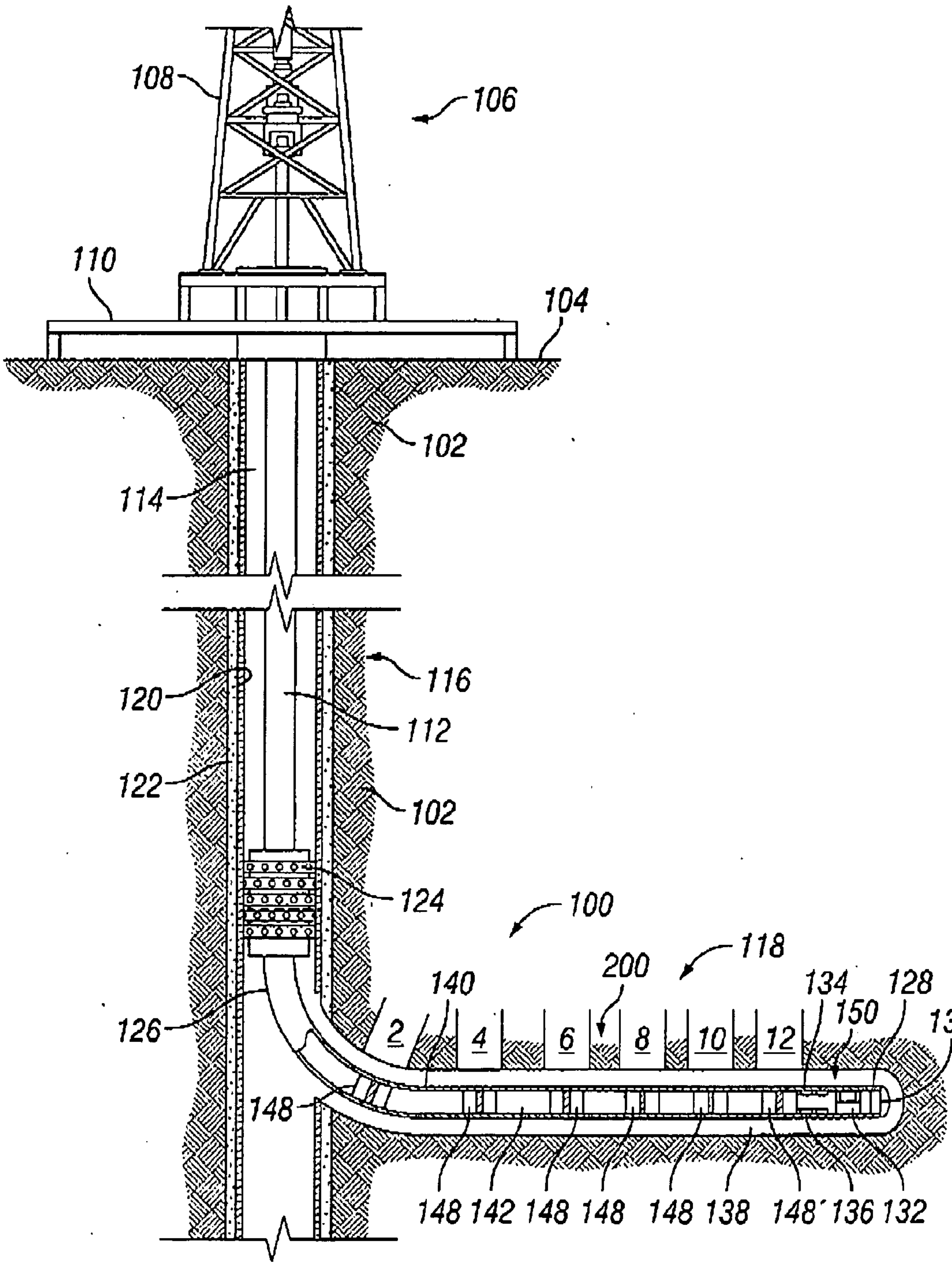

108
106
110
104
102
114
116
120
112
122
102
124
100
118
200
140
134
128
150
130
2
4
6
8
10
12
126
148
148 142 148 148 148 138 148' 136 132

FIG. 1A

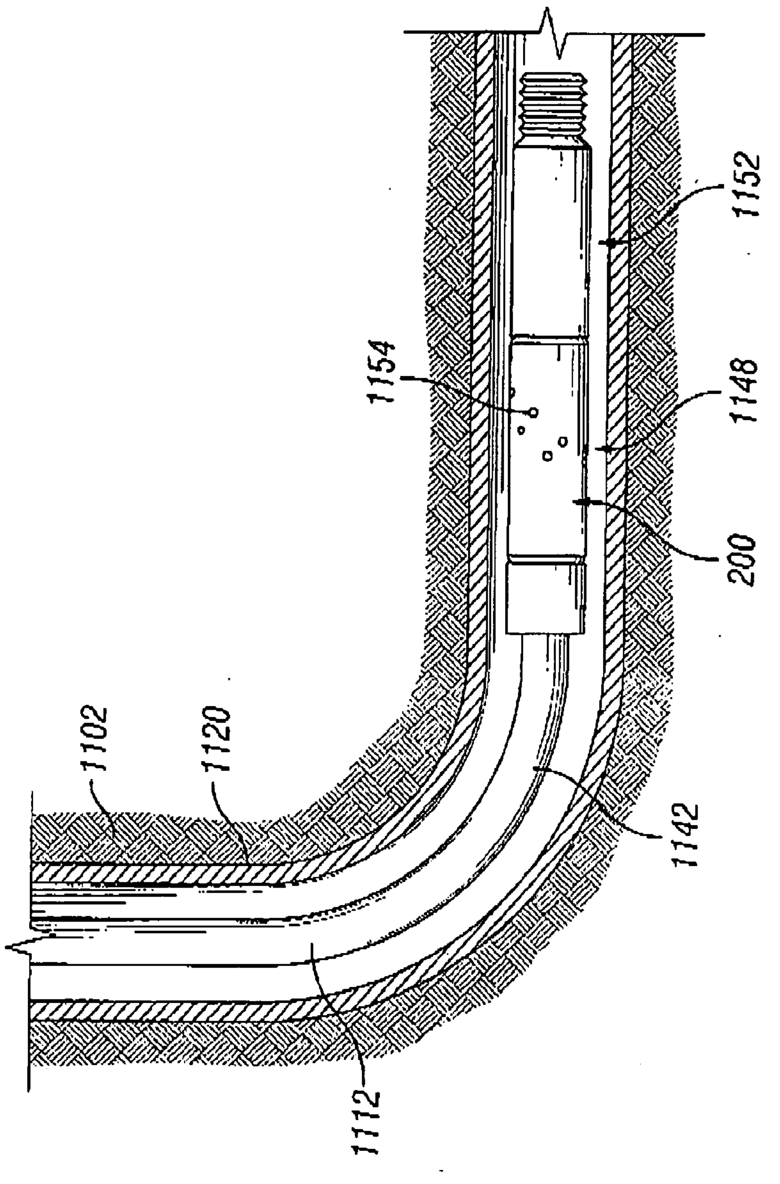


FIG. 1B

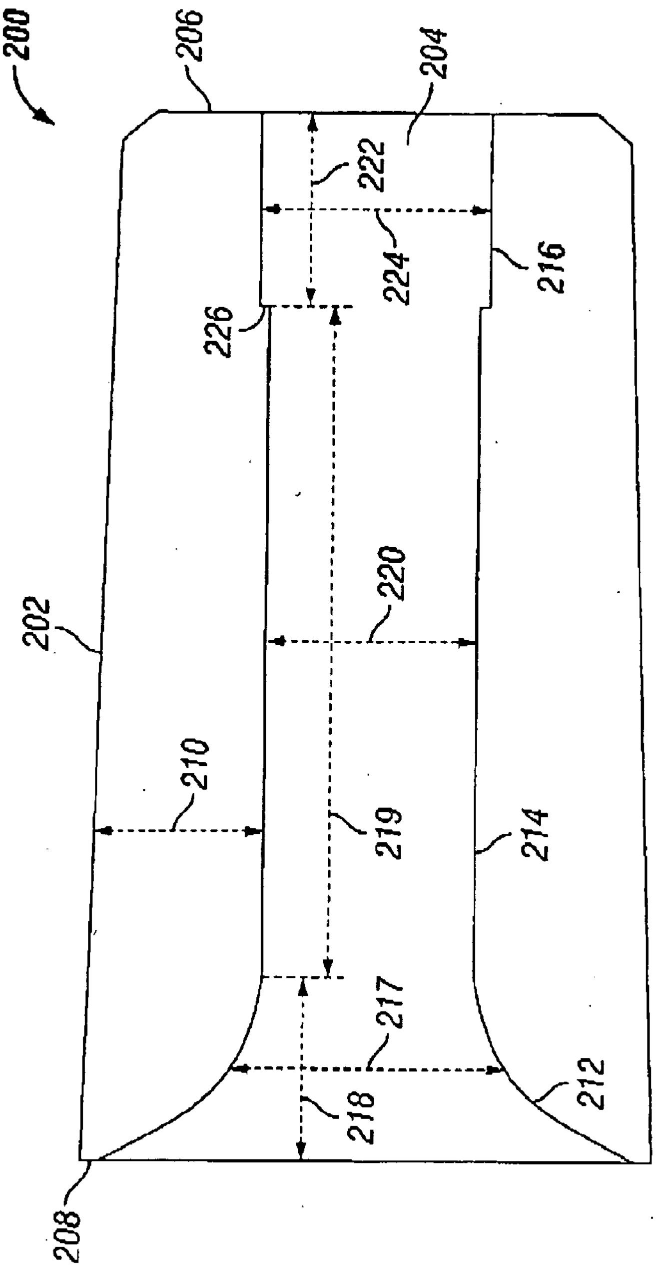


FIG. 2

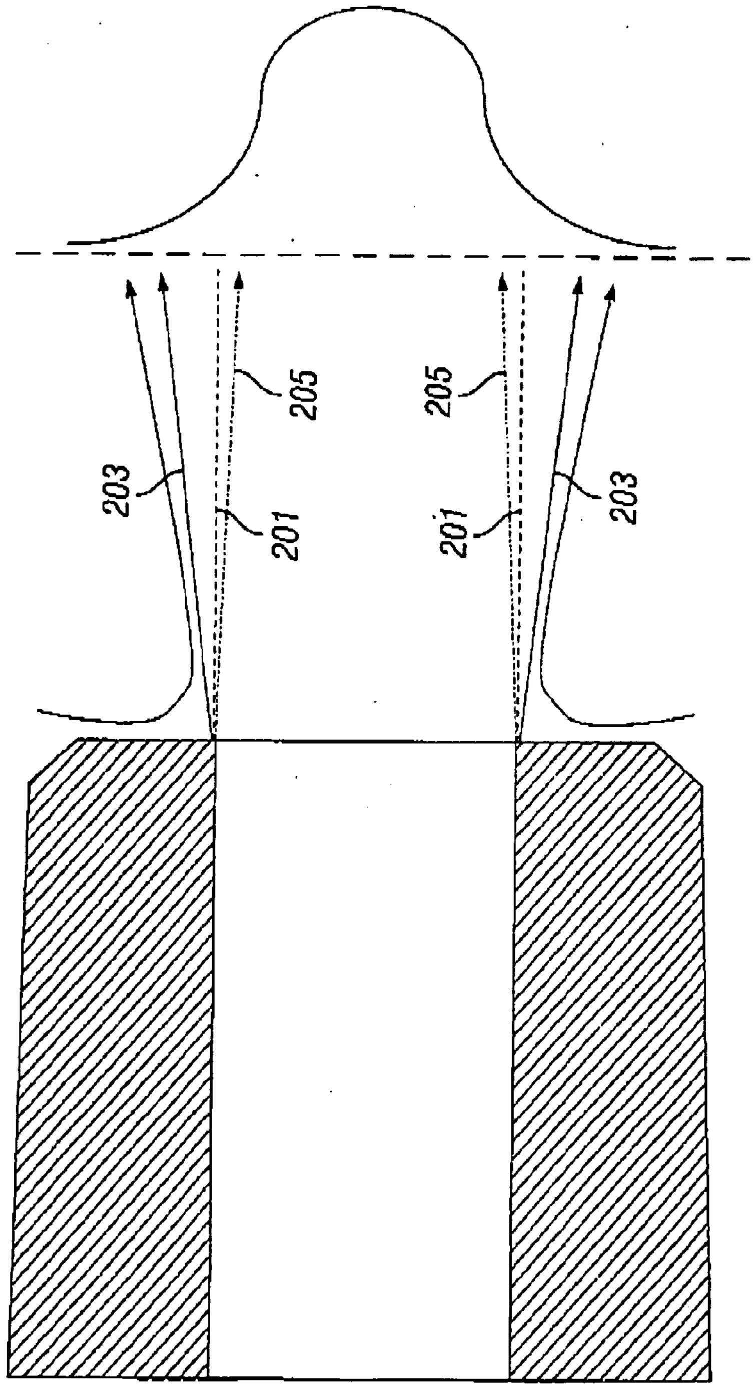


FIG. 3B

FIG. 3A

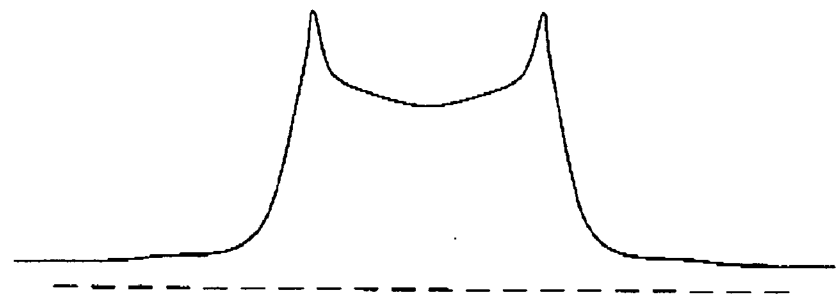


FIG. 4B

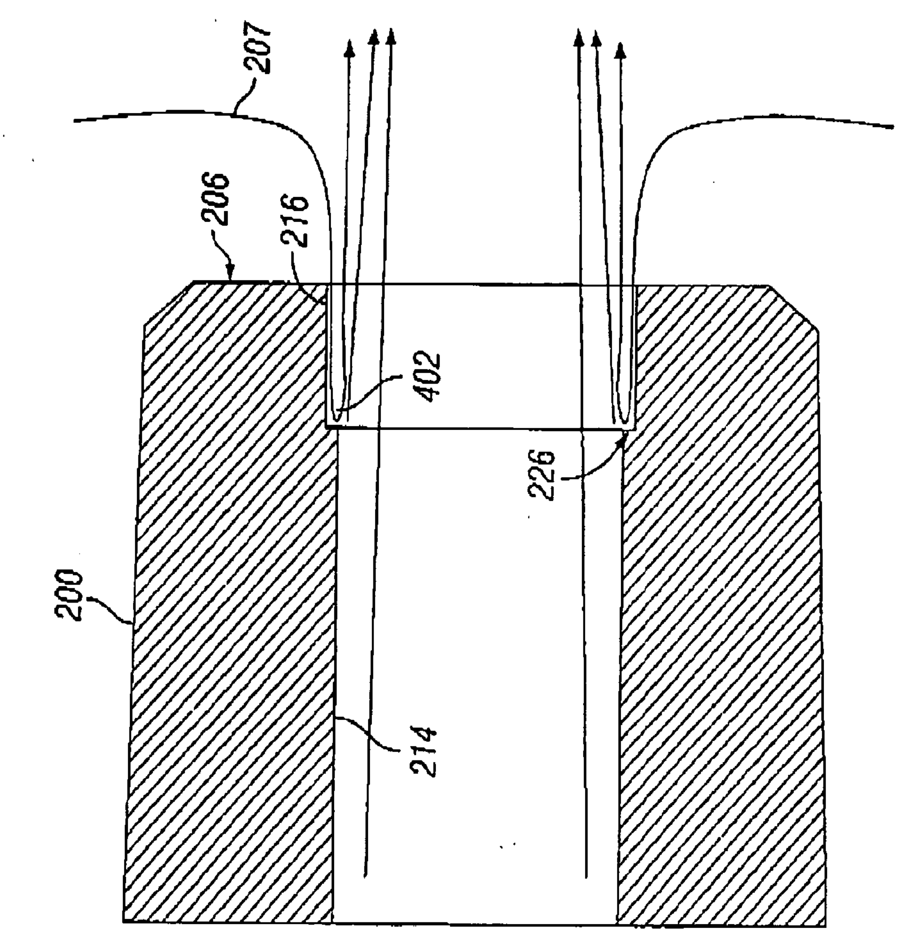


FIG. 4A

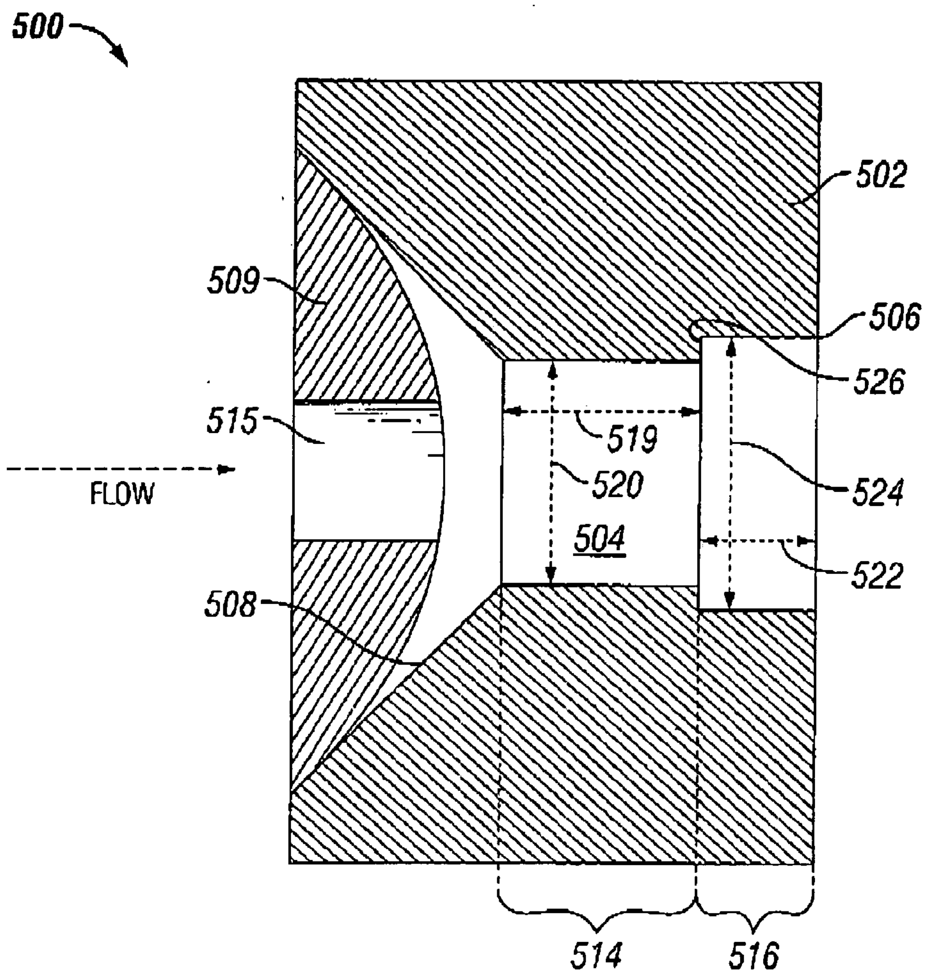


FIG. 5

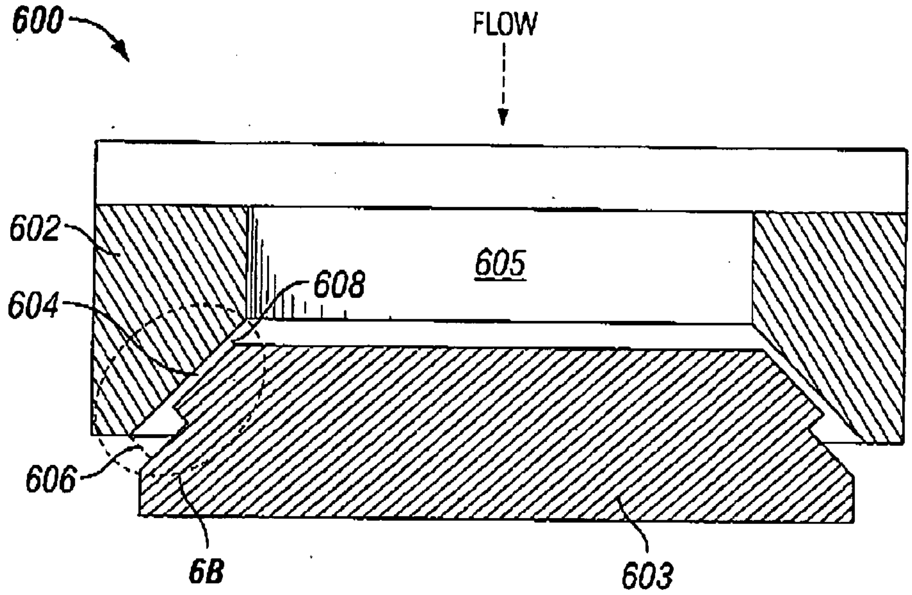

600
FLOW
602
604
605
608
606
6B
603

FIG. 6A

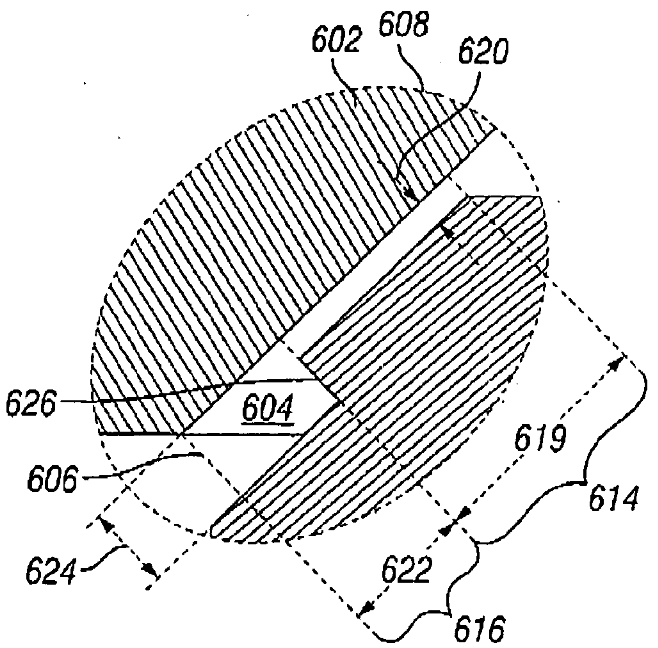

602
608
620
626
604
606
619
614
624
622
616

FIG. 6B

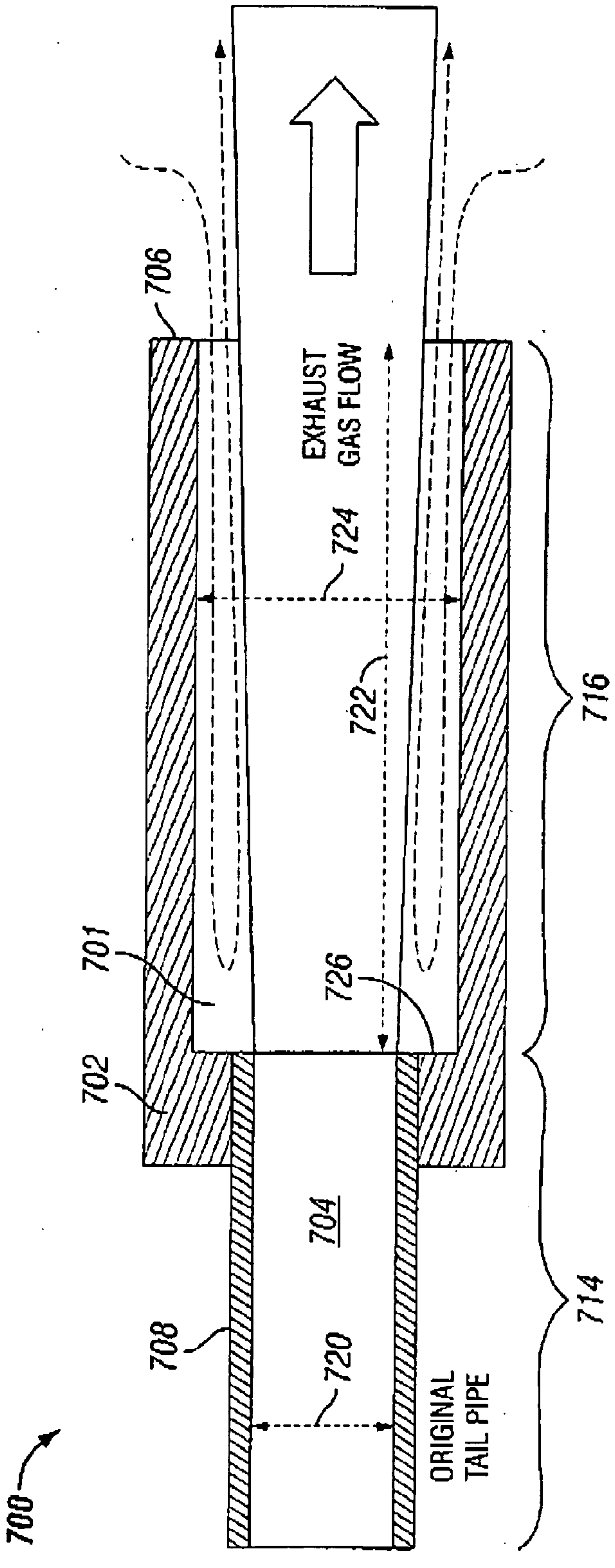

EXHAUST GAS FLOW
706
724
722
716
701
726
702
704
714
708
720
ORIGINAL TAIL PIPE
700

FIG. 7

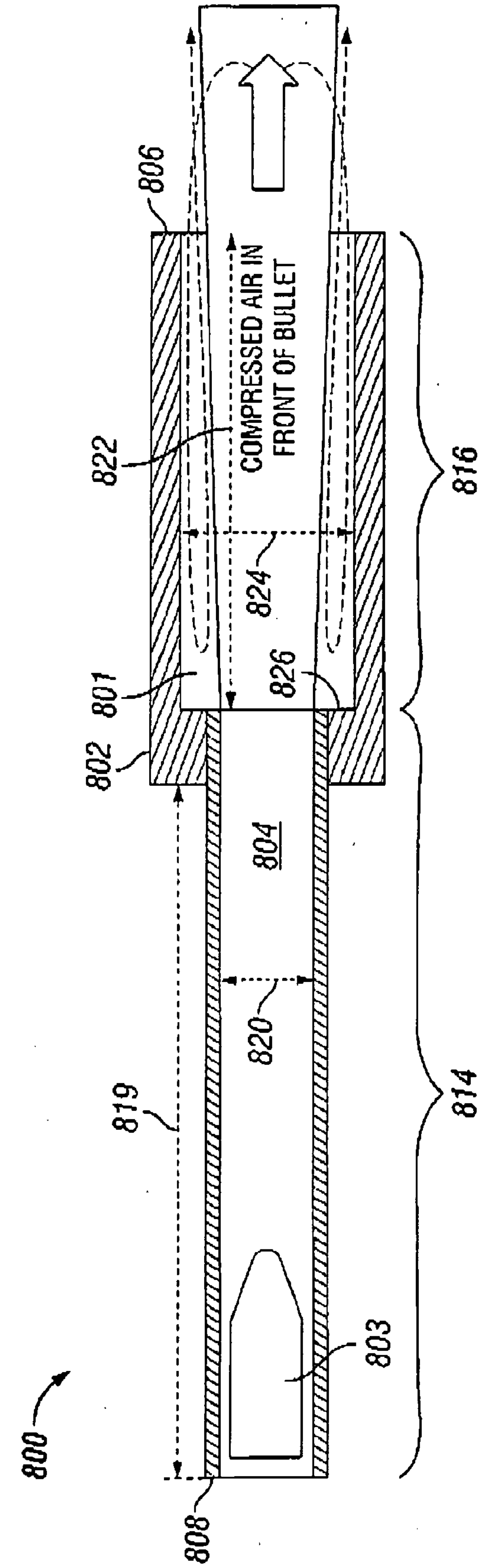

806
COMPRESSED AIR IN FRONT OF BULLET
822
816
824
801
826
802
804
820
819
814
803
800
808

FIG. 8

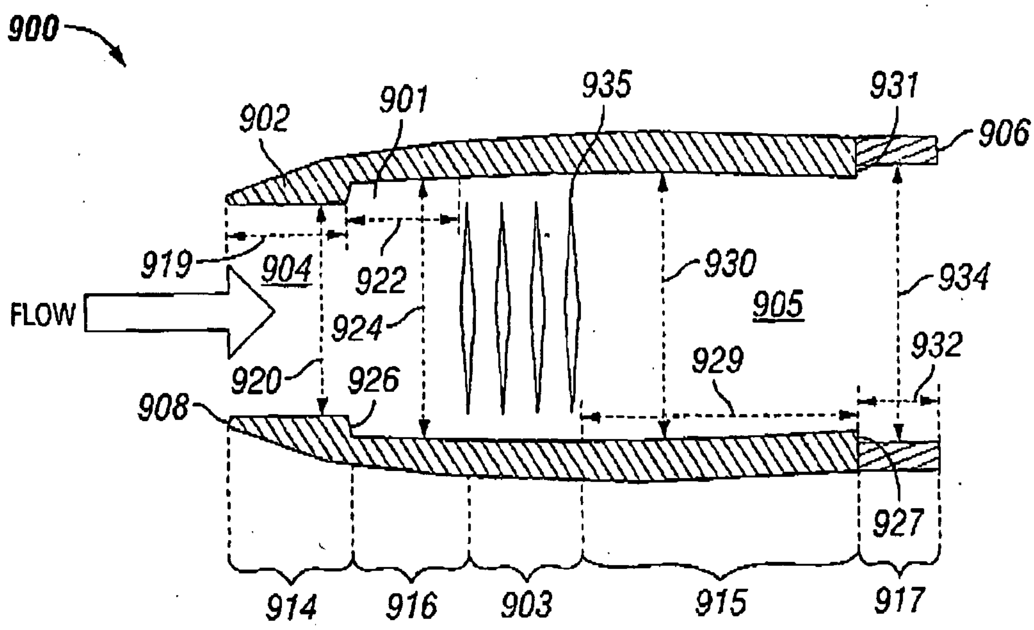

900
902
901
935
931
906
919
904
922
930
934
FLOW
924
905
920
926
929
932
908
927
914
916
903
915
917

FIG. 9

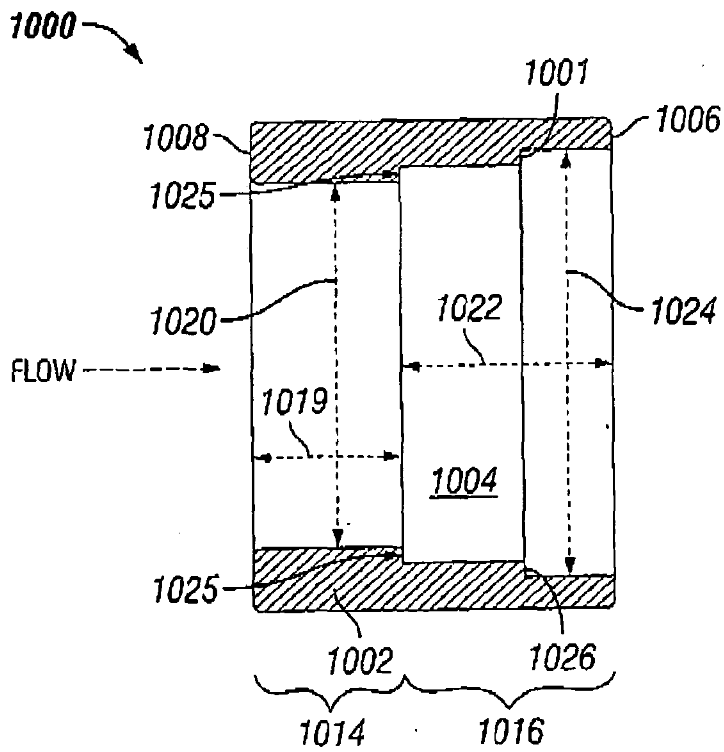
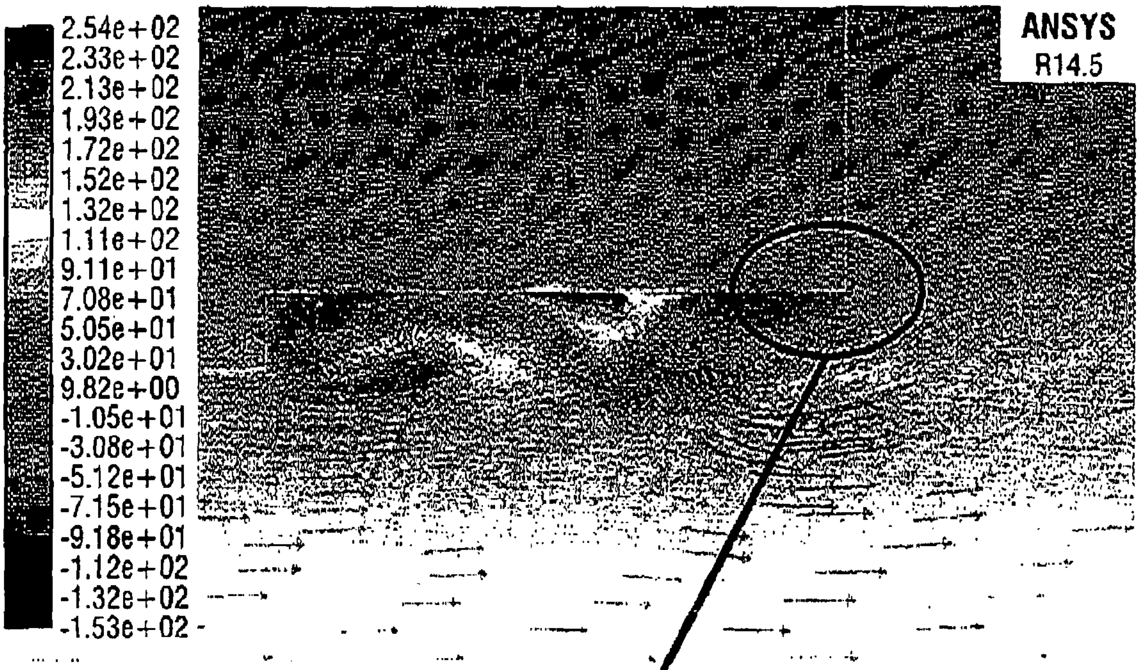

1000
1001
1008
1006
1025
1020
1022
1024
FLOW
1019
1004
1025
1002
1026
1014
1016

FIG. 10



Vector Colored by Axial velocity (m/s)

FIG. 11A

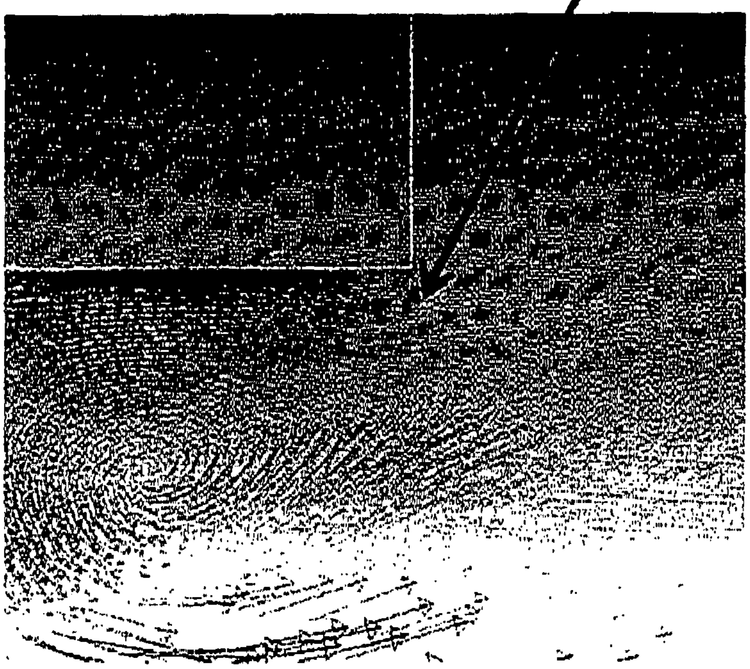
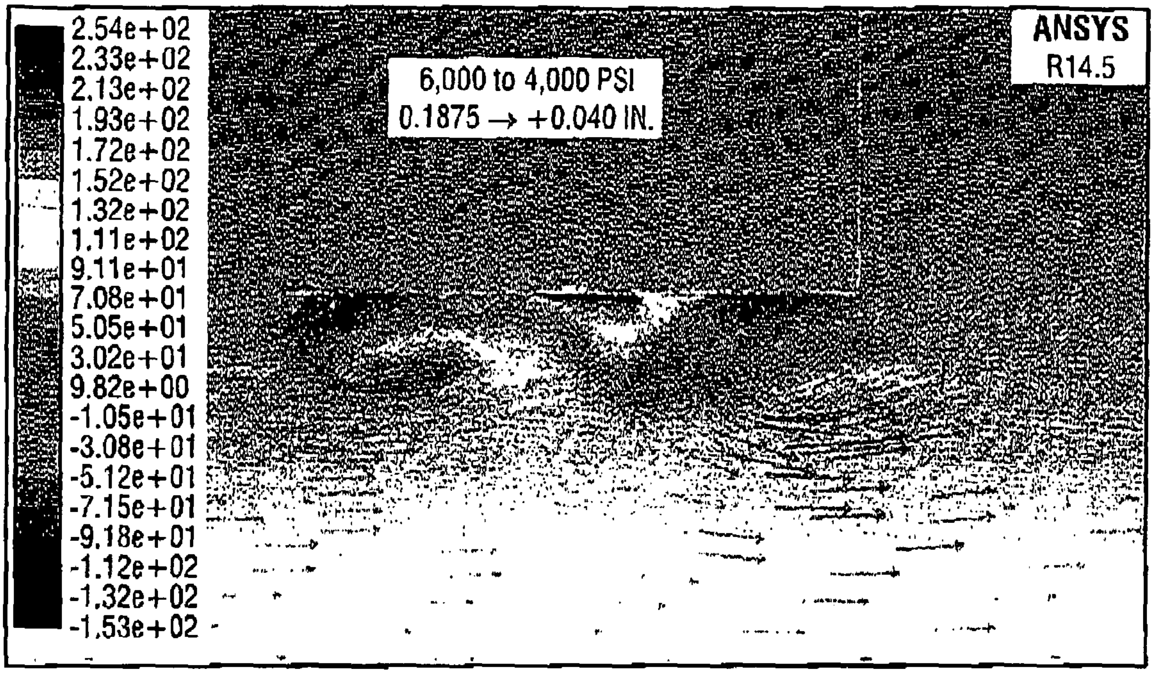
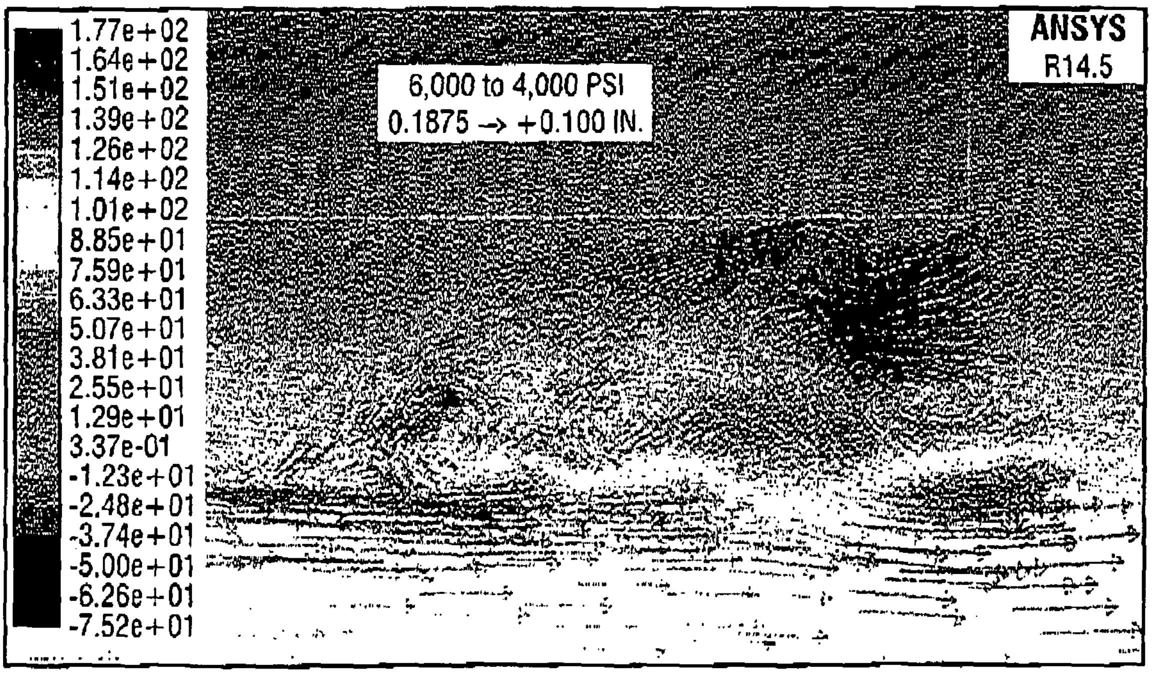


FIG. 11B



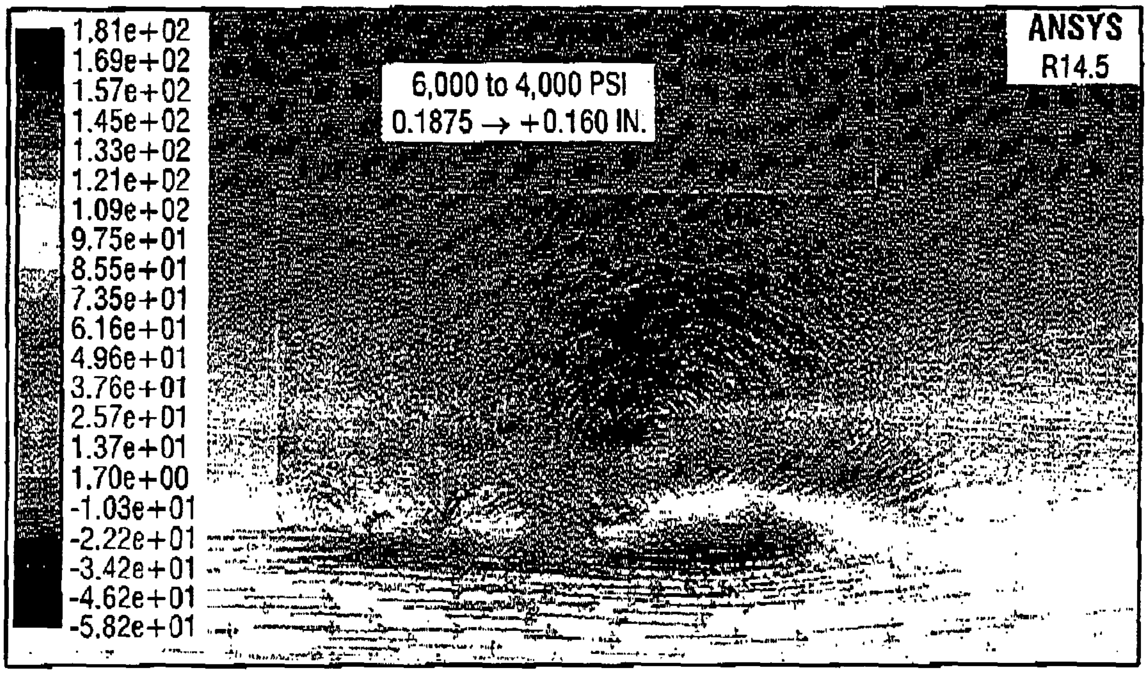
Vector Colored by Axial velocity (m/s)

FIG. 12A



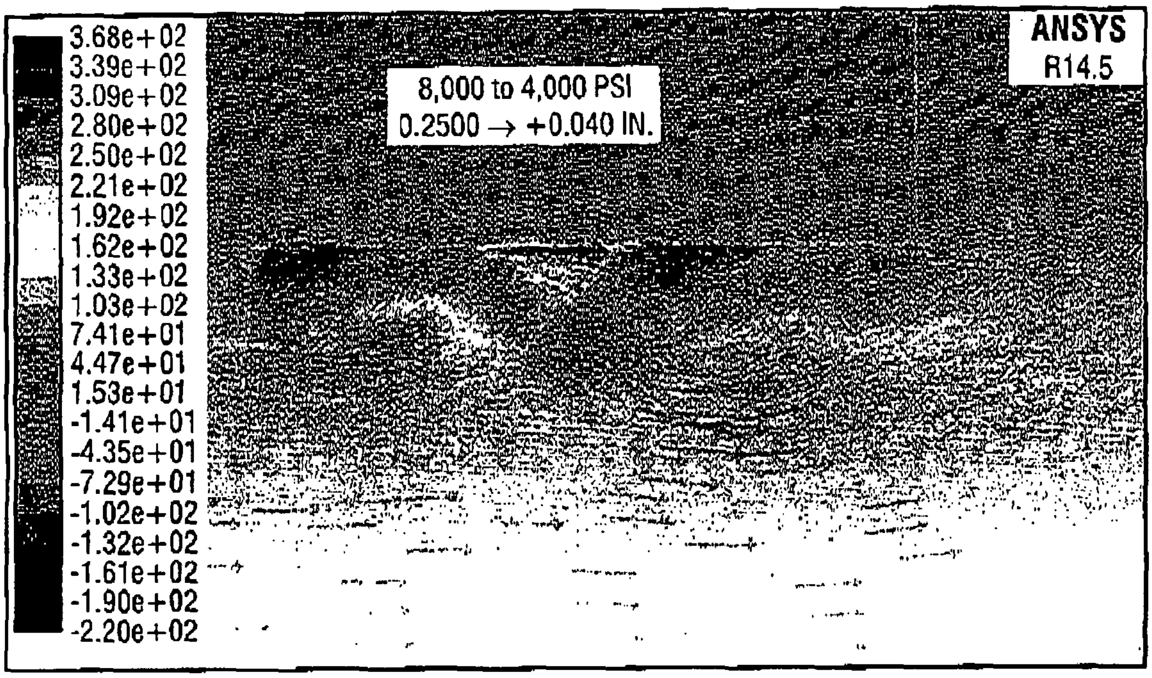
Vector Colored by Axial velocity (m/s)

FIG. 12B



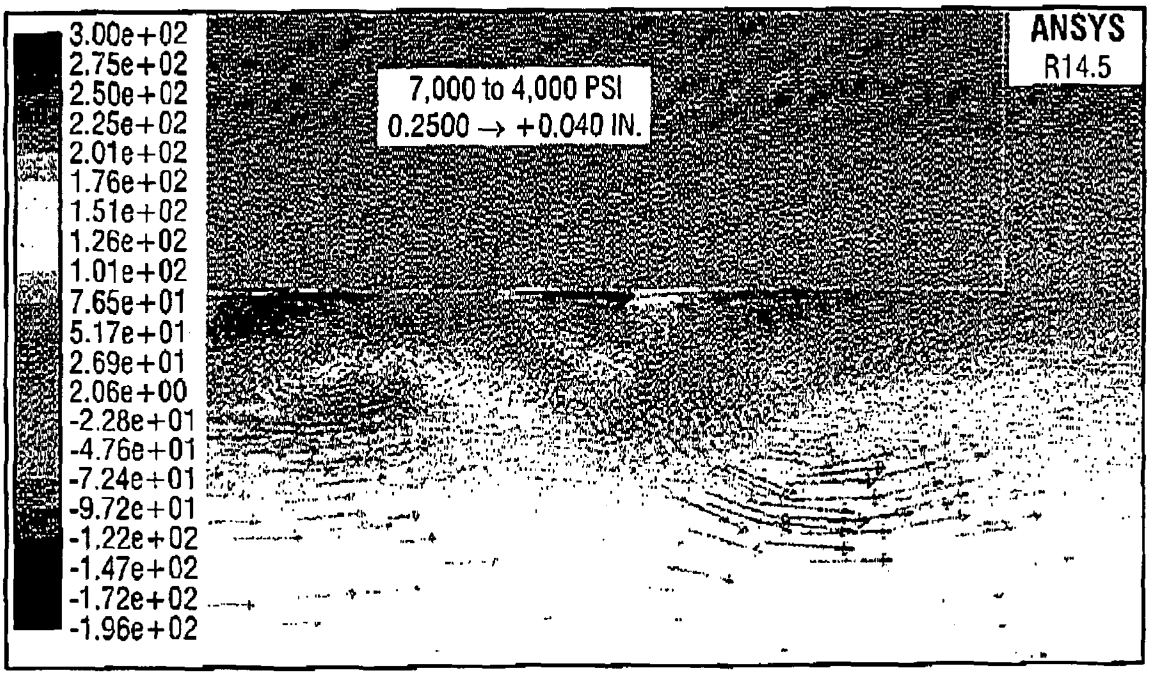
Vector Colored by Axial velocity (m/s)

FIG. 12C



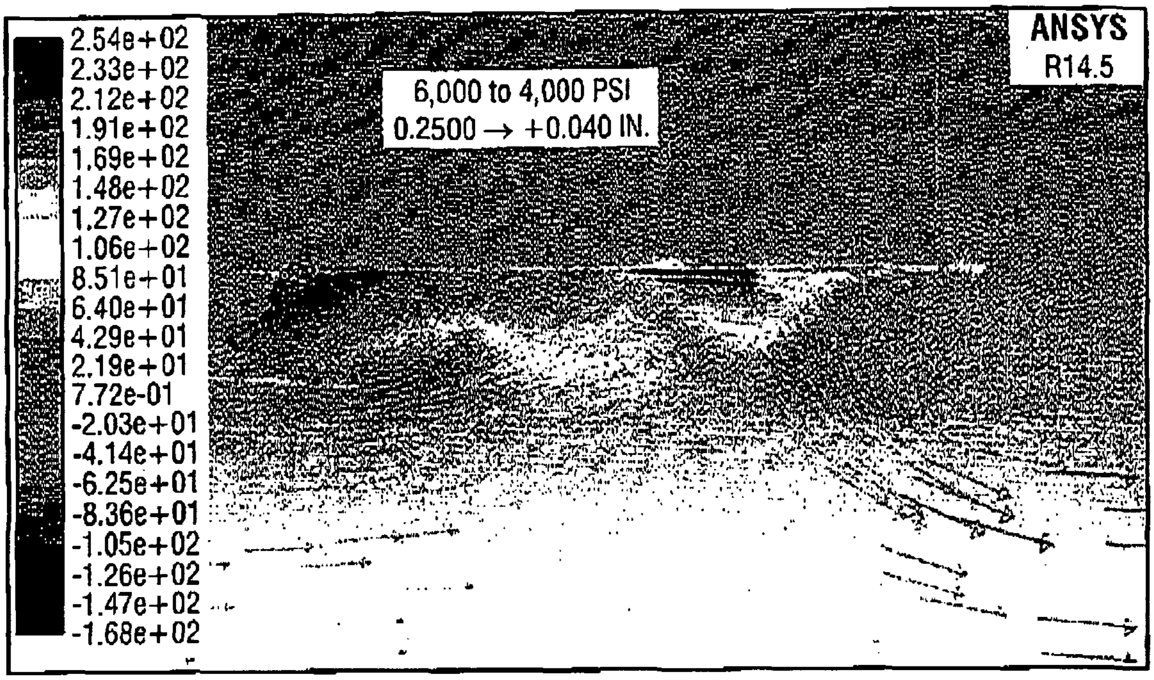
Vector Colored by Axial velocity (m/s)

FIG. 13A



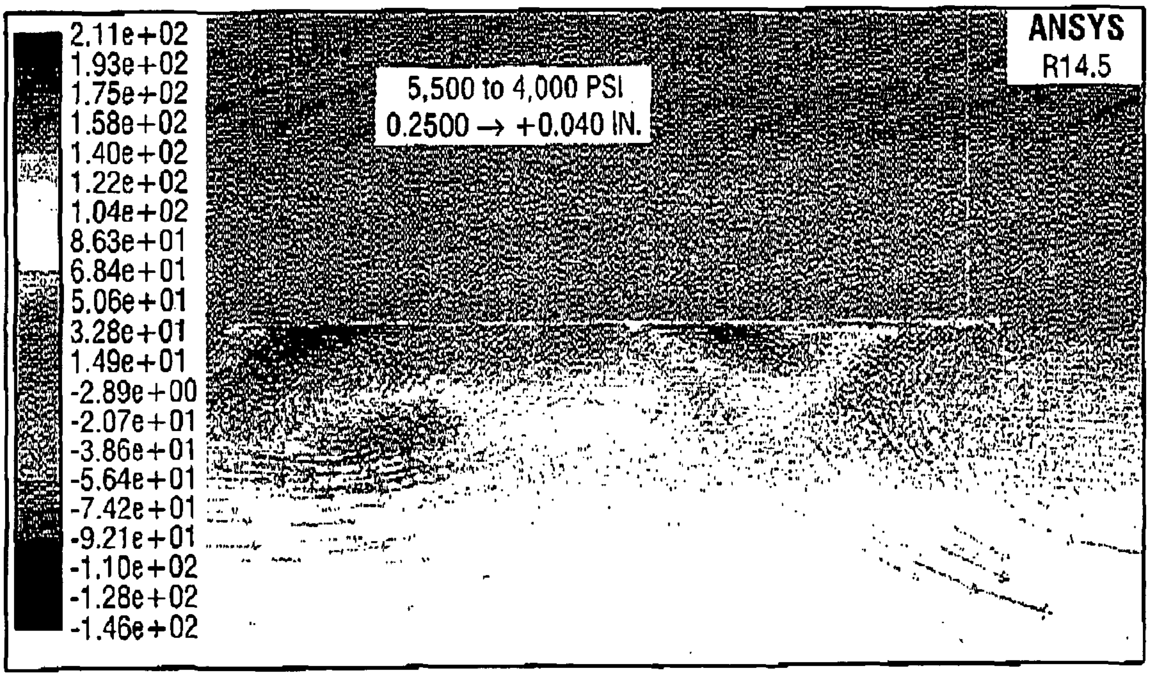
Vector Colored by Axial velocity (m/s)

FIG. 13B



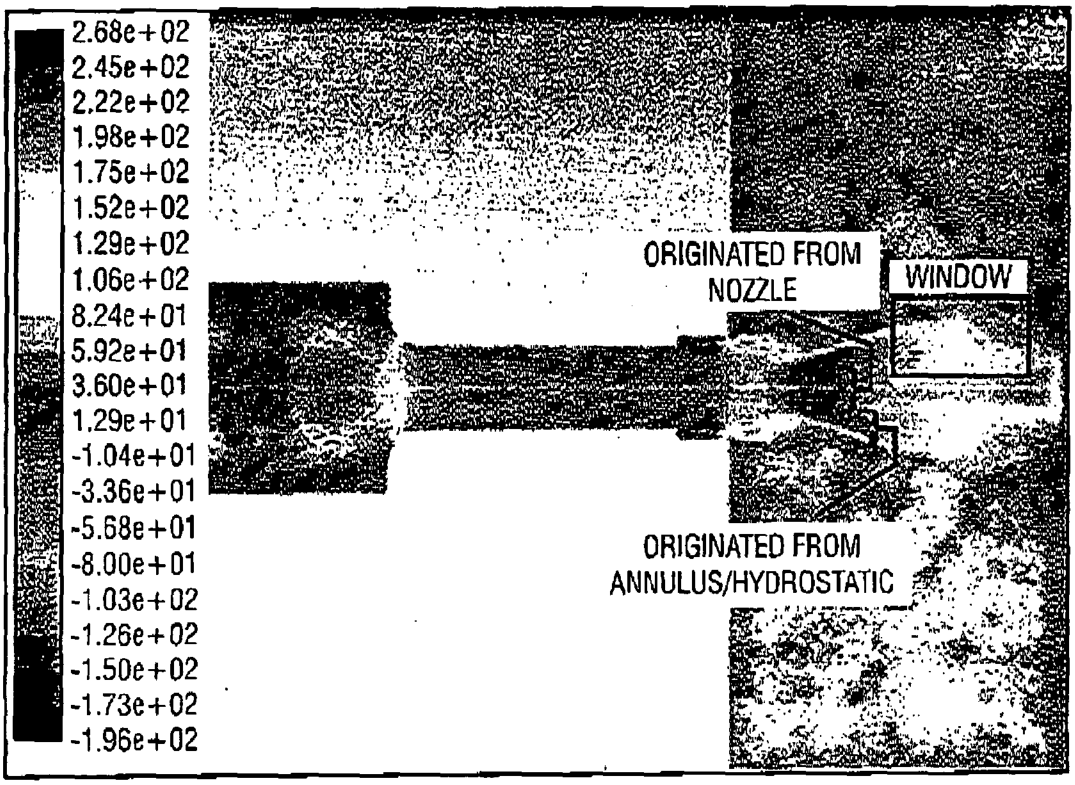
Vector Colored by Axial velocity (m/s)

FIG. 13C



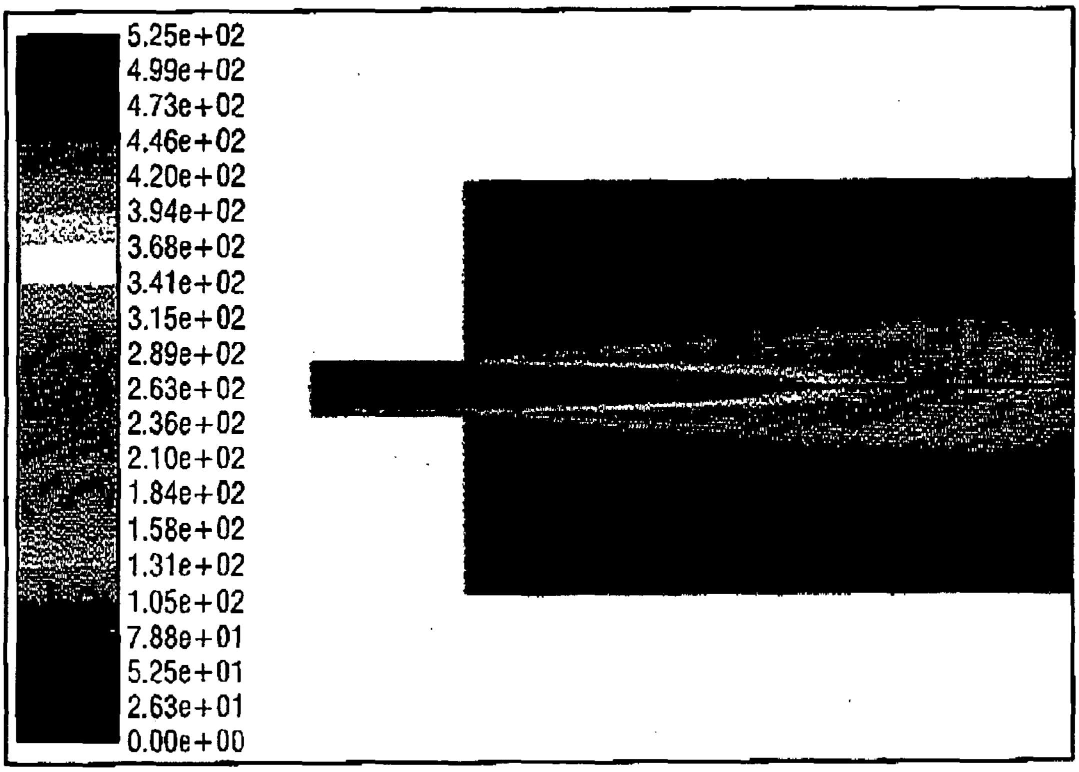
Vector Colored by Axial velocity (m/s)

FIG. 13D



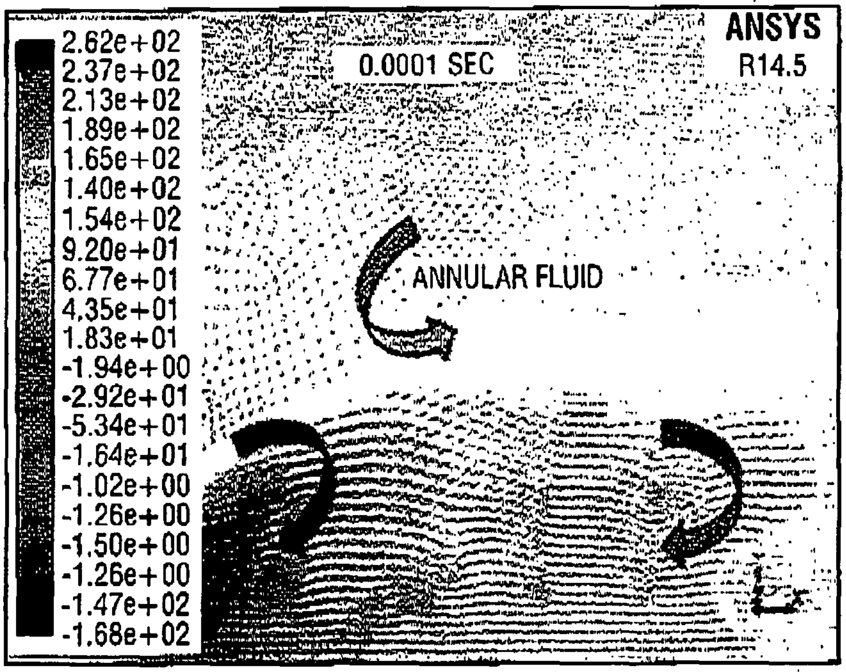
Vector Colored by Axial velocity (m/s)

FIG. 14



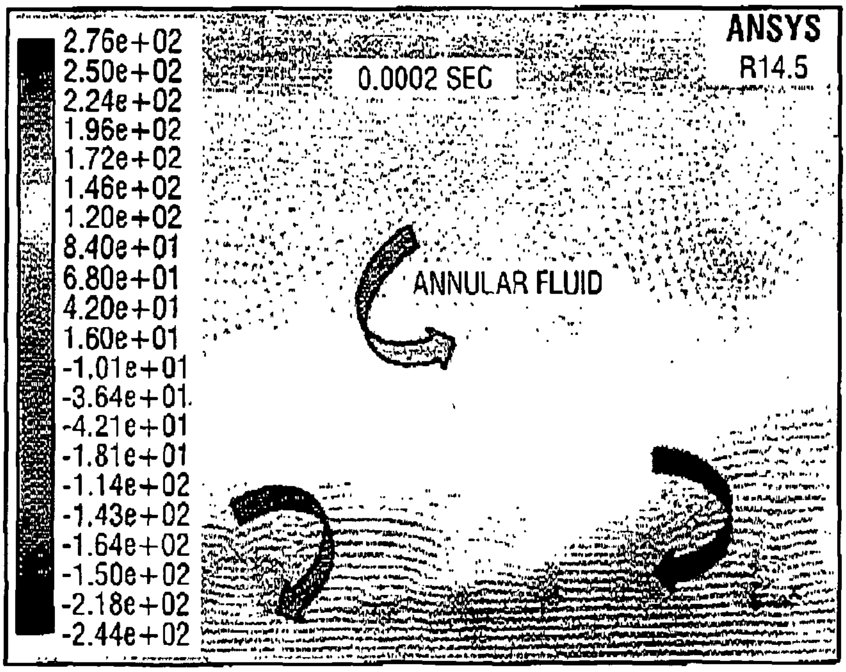
Vector Colored by Axial velocity (m/s)

FIG. 15



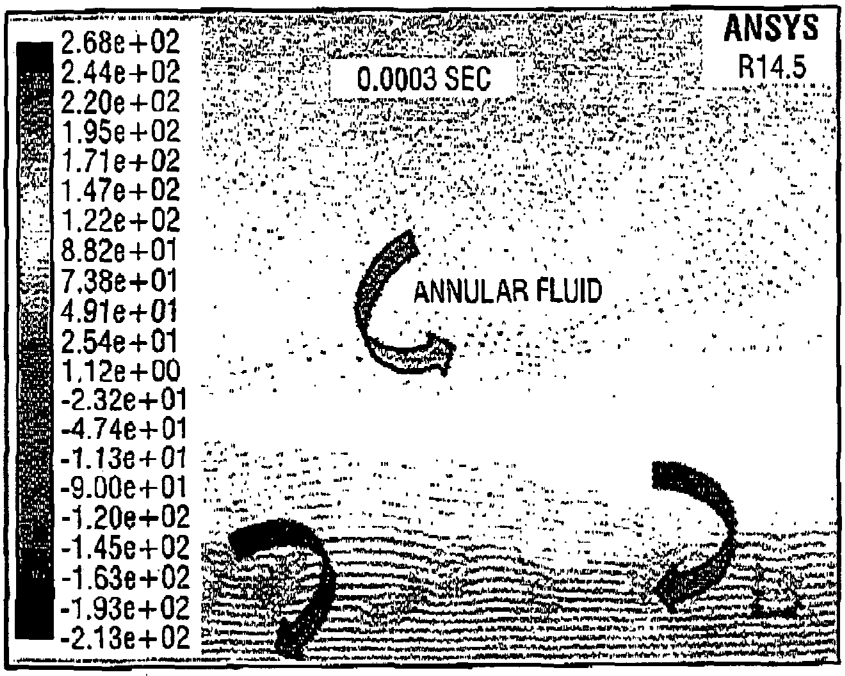
Vector Colored by Axial velocity (m/s)

FIG. 16A



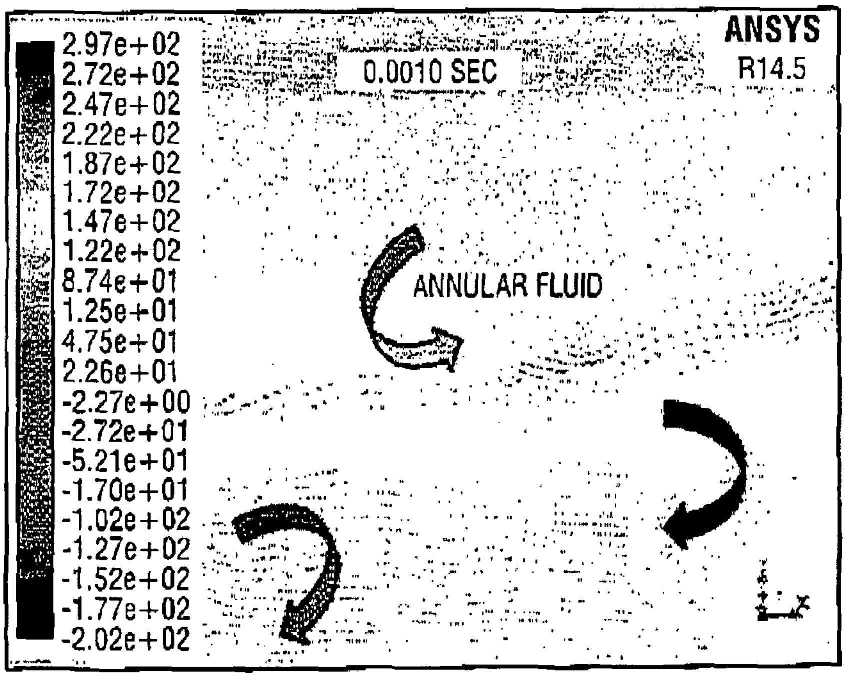
Vector Colored by Axial velocity (m/s)

FIG. 16B



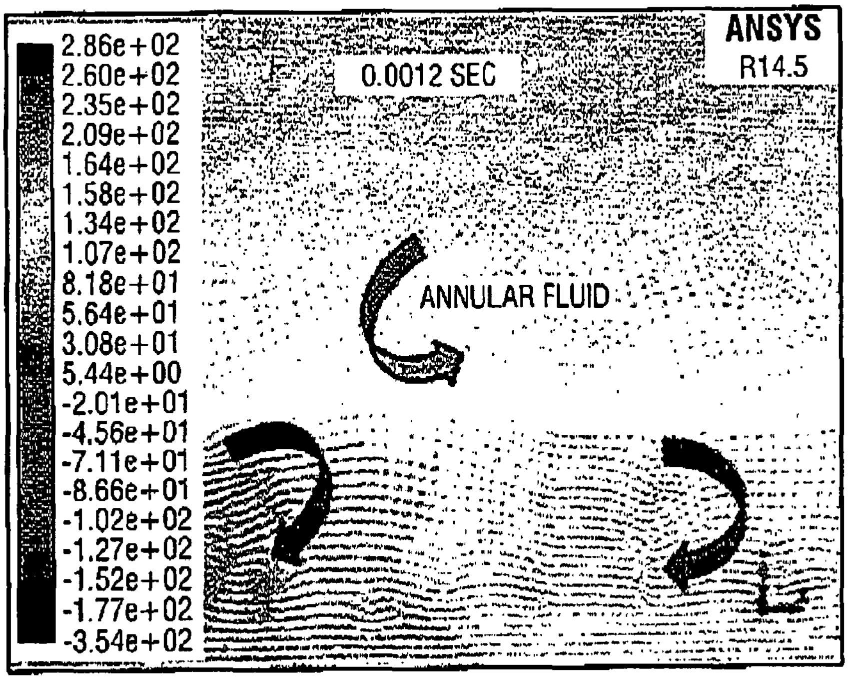
Vector Colored by Axial velocity (m/s)

FIG. 16C



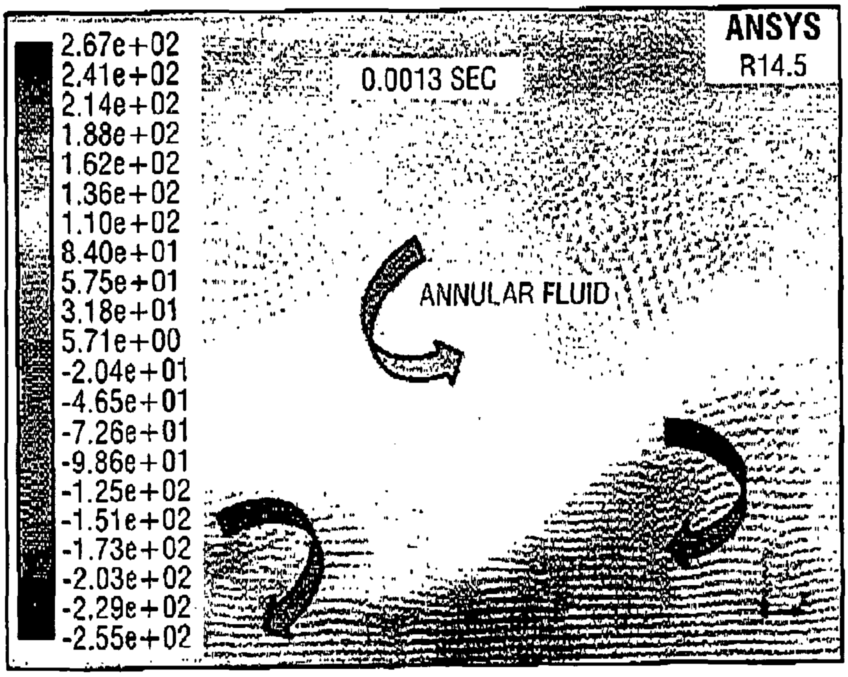
Vector Colored by Axial velocity (m/s)

FIG. 16D



Vector Colored by Axial velocity (m/s)

FIG. 16E



Vector Colored by Axial velocity (m/s)

FIG. 16F

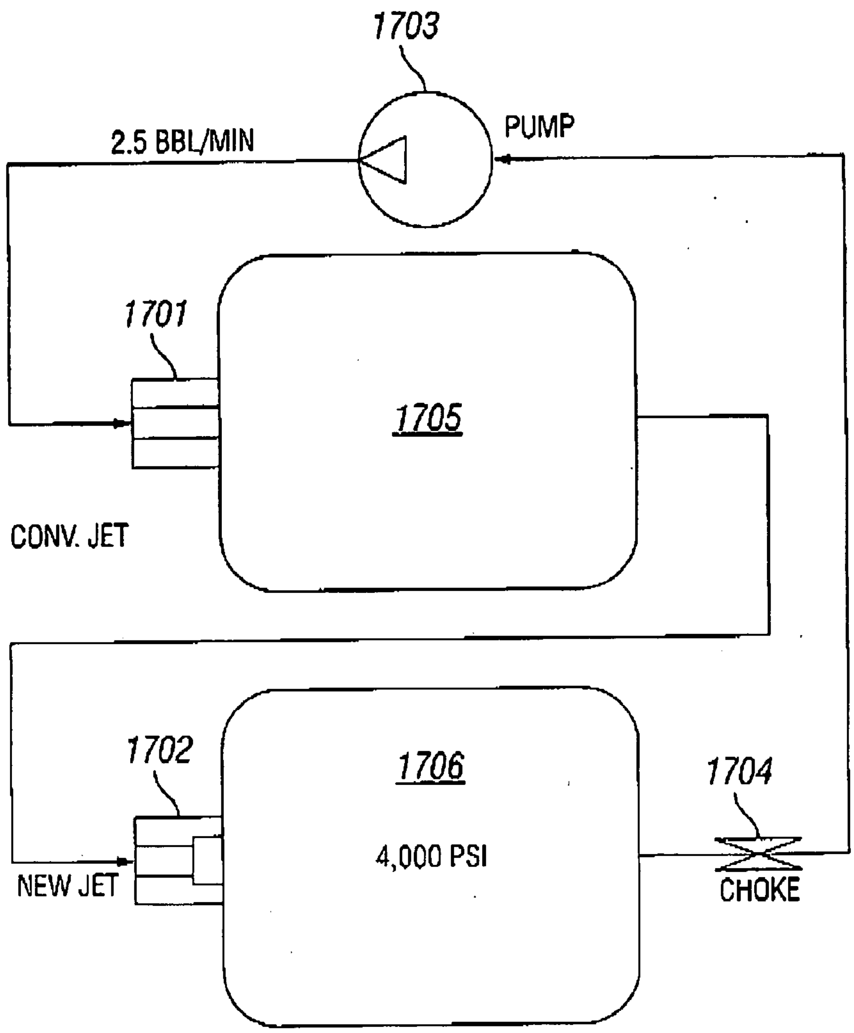

1703
PUMP
2.5 BBL/MIN
1701
1705
CONV. JET
1702
1706
4,000 PSI
1704
NEW JET
CHOKE

FIG. 17

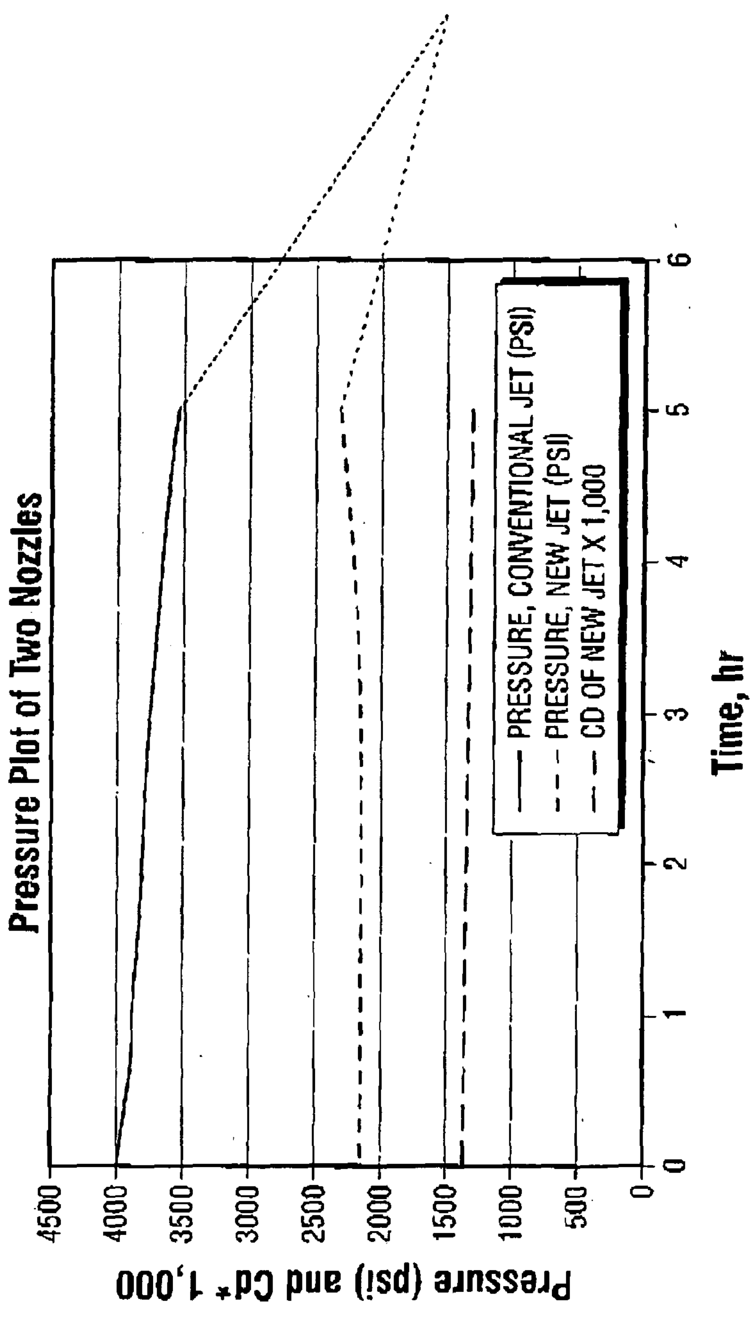

Pressure Plot of Two Nozzles
Pressure (psi) and Cd* 1,000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
1
2
3
4
5
6
Time, hr
PRESSURE, CONVENTIONAL JET (PSI)
PRESSURE, NEW JET (PSI)
CD OF NEW JET X 1,000

FIG. 18