**Title:** DYNAMIC SOLIDS CONCENTRATION VARIATION VIA PRESSURE EXCHANGE DEVICE

(57) Abstract: Apparatus and methods for dynamically varying well treatment fluid solids concentration utilizing a mixer and a pressure exchange device. The mixing device mixes a solids-free fluid and a solid material to form a substantially continuous supply of a solids-laden fluid having a predetermined solids concentration and a first pressure. The pressure exchanger receives the substantially continuous supply of solids-laden fluid at the first pressure and a substantially continuous supply of pressurized fluid at a second pressure, and pressurizes the substantially continuous supply of solids-laden fluid to a third pressure utilizing the substantially continuous supply of pressurized fluid at the second pressure. The second and third pressures are substantially greater than the first pressure.

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Dynamic Solids Concentration Variation Via Pressure Exchange Device

Cross-Reference to Related Applications

[0001] This application claims priority to and the benefit of U.S. Provisional Application No. 62/155,525, titled "USE OF PRESSURE EXCHANGE DEVICES IN CONJUNCTION WITH DYNAMIC SOLIDS CONCENTRATION VARIATION," filed May 1, 2015, the entire disclosure of which is hereby incorporated herein by reference.

Background of the Disclosure

[0002] A variety of fluids are used in oil and gas operations. Fluids may be pumped into the subterranean formation through the use of one or more high pressure pumps. Abrasive fluids, such as solids-laden fluids containing insoluble solid particles, can reduce functional life and increase maintenance of the high pressure pumps.

Summary of the Disclosure

[0003] This summary is provided to introduce a selection of concepts that are further described below in the detailed description. This summary is not intended to identify indispensable features of the claimed subject matter, nor is it intended for use as an aid in limiting the scope of the claimed subject matter.

[0004] The present disclosure introduces a method that includes forming a substantially continuous stream of fluid having a varying solids concentration, pressurizing the substantially continuous stream of fluid with a pressure exchanger, and injecting the pressurized substantially continuous stream of fluid into a wellbore during a subterranean well treatment operation.

[0005] The present disclosure also introduces a method that includes pressurizing, with a first pressure exchanger, a first substantially continuous stream of fluid having a first solids concentration. The method also includes pressurizing, with a second pressure exchanger, a second substantially continuous stream of fluid having a second solids concentration that is substantially less than the first solids concentration. The method also includes combining the pressurized first and second substantially continuous streams of fluid to form a third substantially continuous stream of fluid having a third solids concentration, and injecting the third
substantially continuous stream of fluid into a wellbore during a subterranean well treatment operation.

[0006] The present disclosure also introduces a system that includes a mixing device operable to receive and mix a solids-free fluid and a solid material to form a substantially continuous supply of a solids-laden fluid having a predetermined solids concentration and a first pressure. The system also includes a pressure exchanger operable to receive the substantially continuous supply of solids-laden fluid at the first pressure, receive a substantially continuous supply of pressurized fluid at a second pressure, and pressurize the substantially continuous supply of solids-laden fluid to a third pressure utilizing the substantially continuous supply of pressurized fluid at the second pressure. The second and third pressures are substantially greater than the first pressure.

[0007] These and additional aspects of the present disclosure are set forth in the description that follows, and/or may be learned by a person having ordinary skill in the art by reading the materials herein and/or practicing the principles described herein. At least some aspects of the present disclosure may be achieved via means recited in the attached claims.

Brief Description of the Drawings

[0008] The present disclosure is understood from the following detailed description when read with the accompanying figures. It is emphasized that, in accordance with the standard practice in the industry, various features are not drawn to scale. In fact, the dimensions of the various features may be arbitrarily increased or reduced for clarity of discussion.

[0009] FIG. 1 is a schematic view of at least a portion of an example implementation of apparatus according to one or more aspects of the present disclosure.

[0010] FIG. 2 is a schematic view of the apparatus shown in FIG. 1 in an operational stage according to one or more aspects of the present disclosure.

[0011] FIG. 3 is a schematic view of the apparatus shown in FIG. 2 in another operational stage according to one or more aspects of the present disclosure.

[0012] FIG. 4 is a schematic view of the apparatus shown in FIGS. 2 and 3 in another operational stage according to one or more aspects of the present disclosure.

[0013] FIG. 5 is a schematic view of at least a portion of an example implementation of apparatus according to one or more aspects of the present disclosure.
FIG. 6 is a sectional view of the apparatus shown in FIG. 5.

FIG. 7 is another view of the apparatus shown in FIG. 6 in a different stage of operation.

FIG. 8 is a schematic view of at least a portion of an example implementation of apparatus according to one or more aspects of the present disclosure.

FIG. 9 is a schematic view of at least a portion of an example implementation of apparatus according to one or more aspects of the present disclosure.

FIG. 10 is a schematic view of at least a portion of an example implementation of apparatus according to one or more aspects of the present disclosure.

FIG. 11 is a schematic view of at least a portion of an example implementation of apparatus according to one or more aspects of the present disclosure.

FIG. 12 is a schematic view of at least a portion of an example implementation of apparatus according to one or more aspects of the present disclosure.

FIG. 13 is a schematic view of at least a portion of an example implementation of apparatus according to one or more aspects of the present disclosure.

FIG. 14 is a schematic view of at least a portion of an example implementation of apparatus according to one or more aspects of the present disclosure.

FIGS. 15 and 16 are graphs related to one or more aspects of the present disclosure.

FIG. 17 is a schematic view of at least a portion of an example implementation of apparatus according to one or more aspects of the present disclosure.

FIGS. 18-20 are graphs related to one or more aspects of the present disclosure.

FIG. 21 is a schematic view of at least a portion of an example implementation of apparatus according to one or more aspects of the present disclosure.

FIG. 22 is a flow-chart diagram of at least a portion of an example implementation of a method according to one or more aspects of the present disclosure.

FIG. 23 is a flow-chart diagram of at least a portion of an example implementation of another method according to one or more aspects of the present disclosure.

**Detailed Description**

It is to be understood that the following disclosure provides many different embodiments, or examples, for implementing different features of various embodiments.
Specific examples of components and arrangements are described below to simplify the present disclosure. These are, of course, merely examples and are not intended to be limiting. In addition, the present disclosure may repeat reference numerals and/or letters in the various examples. This repetition is for simplicity and clarity, and does not in itself dictate a relationship between the various embodiments and/or configurations discussed. Moreover, the formation of a first feature over or on a second feature in the description that follows may include embodiments in which the first and second features are formed in direct contact, and may also include embodiments in which additional features may be formed interposing the first and second features, such that the first and second features may not be in direct contact. It should also be understood that the terms "first," "second," "third," etc., are arbitrarily assigned, are merely intended to differentiate between two or more parts, fluids, etc., and do not indicate a particular orientation or sequence.

[0030] The present disclosure introduces one or more aspects related to utilizing one or more pressure exchangers to divert abrasive fluids away from high-pressure pumps, instead of pumping solids-laden fluid with the high-pressure pumps. A non-abrasive solids-free fluid may be pressurized by the high-pressure pumps, while the pressure exchangers, located downstream from the high pressure pumps, transfer the pressure from the pressurized solids-free fluid to a low pressure solids-laden fluid. Such use of pressure exchangers may facilitate improved fluid control during well treatment operations and/or increase functional life of the high-pressure pumps and other wellsite equipment fluidly coupled between the high-pressure pumps and the pressure exchangers.

[0031] As used herein, a "fluid" is a substance that can flow and conform to the outline of its container when the substance is tested at a temperature of 71 °F (22 °C) and a pressure of one atmosphere (atm) (0.1 megapascals (MPa)). A fluid may be liquid, gas, or both. A fluid may be water based or oil based. A fluid may have just one phase or more than one distinct phase. A fluid may be a heterogeneous fluid having more than one distinct phase. Example heterogeneous fluids within the scope of the present disclosure include a solids-laden fluid or slurry (such as may comprise a continuous liquid phase and undissolved solid particles as a dispersed phase), an emulsion (such as may comprise a continuous liquid phase and at least one dispersed phase of immiscible liquid droplets), a foam (such as may comprise a continuous liquid phase and a dispersed gas phase), and mist (such as may comprise a continuous gas phase and a dispersed
liquid droplet phase), among other examples also within the scope of the present disclosure. A heterogeneous fluid may comprise more than one dispersed phase. Moreover, one or more of the phases of a heterogeneous fluid may be or comprise a mixture having multiple components, such as fluids containing dissolved materials and/or undissolved solids.

[0032] Plunger pumps may be employed in high-pressure oilfield pumping applications, such as for hydraulic fracturing applications. Plunger pumps are often referred to as positive displacement pumps, intermittent duty pumps, triplex pumps, quintuplex pumps, or frac pumps. Multiple plunger pumps may be employed simultaneously in large-scale operations where tens of thousands of gallons of fluid are pumped into a wellbore. These pumps are linked to each other using a manifold, which is plumbed to collect the output of the multiple pumps and direct it to the wellbore.

[0033] As described above, some fluids (e.g., fracturing fluid) may contain ingredients that are abrasive to the internal components of a pump. For example, a fracturing fluid generally contains proppant or other solid particulate material, which is insoluble in a base fluid. To create fractures, the fracturing fluid is generally pumped at high pressures, sometimes in the range of 5,000 to 15,000 pounds force per square inch (psi) or more. The proppant may initiate the fractures and/or keep the fractures propped open. The propped fractures provide highly permeable flow paths for oil and gas to flow from the subterranean formation, thereby enhancing the production of a well. However, the abrasive fracturing fluid may accelerate wear of the internal components of the pumps. Consequently, the repair, replacement, and maintenance expenses of the pumps can be quite high, and life expectancy can be low.

[0034] Example implementations of apparatus described herein relate generally to a fluid system for forming and pressurizing a solids-laden fluid (e.g., fracturing fluid) having predetermined concentrations of solid material for injection into a wellbore during well treatment operations. The fluid system may include a blending or mixing device for receiving and mixing a solids-free carrying fluid or gel and a solid material to form the solids-laden fluid. The fluid system may also include a fluid pressure exchanger for increasing pressure or otherwise energizing of the solids-laden fluid formed by the mixing device prior to being injected into the wellbore. The fluid pressure exchanger may be utilized to pressurize the solids-laden fluid by facilitating or permitting pressure from a pressurized solids-free fluid to be transferred to a low-pressure solids-laden fluid, among other uses. The fluid pressure exchanger may comprise one
or more chambers into which the low-pressure solids-laden fluid and the pressurized solids-free fluid are conducted. The solids-free fluid may be conducted into the chamber at a higher pressure than the solids-laden fluid, and may thus be utilized to pressurize the solids-laden fluid. The pressurized solids-laden fluid is then conducted from the chamber to a wellhead for injection into the wellbore. By pumping just the solids-free fluid with the pumps and utilizing the pressure exchanger to increase the pressure of the solids-laden fluid, the useful life of the pumps may be increased. Example implementations of methods described herein relate generally to utilizing the fluid system to form and pressure the solids-laden fluid having the predetermined concentrations of solid material for injection into the wellbore during well treatment operations. For clarity and ease of understanding, the solids-laden fluid may be referred to hereinafter simply as a "dirty fluid" and the solids-free fluid may be referred to hereinafter simply as a "clean fluid."

[0035] FIG. 1 is a schematic view of an example implementation of a chamber 100 of a fluid pressure exchanger for pressurizing a dirty fluid with a clean fluid according to one or more aspects of the present disclosure. The chamber 100 includes a first end 101 and a second end 102. The chamber 100 may include a border or boundary 103 between the dirty and clean fluids defining a first volume 104 and a second volume 105 within the chamber 100. The boundary 103 may be a membrane that is impermeable or semi-permeable to a fluid, such as a gas. The membrane may be an impermeable membrane in implementations in which the dirty and clean fluids are incompatible fluids, or when mixing of the dirty and clean fluids is to be substantially prevented, such as to recycle the clean fluid absent contamination by the dirty fluid. The boundary 103 may be a semi-permeable membrane in implementations permitting some mixing of the clean fluid with the dirty fluid, such as to foam the dirty fluid when the clean fluid comprises a gas. The boundary 103 may also be a floating piston slidably disposed along the chamber 100. The floating piston may physically isolate the dirty and clean fluids and be movable via pressure differential between the dirty and clean fluids. The boundary 103 may be a mixing zone in which the dirty and clean fluids mix or otherwise interact during pressurizing operations. The boundary 103 may also not exist, such that the first and second volumes 104 and 105 form a continuous volume within the chamber 100. A first inlet valve 106 is operable to conduct the dirty fluid into the first volume 104 of the chamber 100, and a second inlet valve 107 is operable to conduct the clean fluid into the second volume 105 of the chamber 100.
For example, FIG. 2 is a schematic view of the chamber 100 shown in FIG. 1 in an operational stage according to one or more aspects of the present disclosure, during which the dirty fluid 110 has been conducted into the chamber 100 through the first inlet valve 106 at the first end 101, such as via one or more fluid conduits 108. Consequently, the dirty fluid 110 may move the boundary 103 within the chamber 100 along a direction substantially parallel to the longitudinal axis 111 of the chamber 100, thereby increasing the first volume 104 and decreasing the second volume 105. The first inlet valve 106 may be closed after entry of the dirty fluid 110 into the chamber 100.

FIG. 3 is a schematic view of the chamber 100 shown in FIG. 2 in a subsequent operational stage according to one or more aspects of the present disclosure, during which a clean fluid 120 is being conducted into the chamber 100 through the second inlet valve 107 at the second end 102, such as via one or more fluid conduits 109. The clean fluid 120 may be conducted into the chamber 100 at a higher pressure compared to the pressure of the dirty fluid 110. Consequently, the higher-pressure clean fluid 120 may move the boundary 103 and the dirty fluid 110 within the chamber 100 back towards the first end 101, thereby reducing the volume of the first volume 104 and thereby pressurizing or otherwise energizing the dirty fluid 110. The clean fluid 120 may be a combustible or cryogenic gas that, upon combustion or heating, acts to pressurize the dirty fluid 110, whether instead of or in addition to the higher pressure of the clean fluid 120 acting to pressurize the dirty fluid 110. The boundary 103 and/or other components may include one or more burst discs to protect against overpressure from the clean fluid 120.

As shown in FIG. 4, the boundary 103 may continue to reduce the first volume 104 as the pressurized dirty fluid 110 is conducted from the chamber 100 to a wellhead (not shown) at a higher pressure than when the dirty fluid 110 entered the chamber 100, such as via a first exit valve 112 and one or more conduits 113. The second inlet valve 107 may then be closed, for example, in response to pressure sensed by a pressure transducer within the chamber 100 and/or along one or more of the conduits and/or inlet valves.

After the pressurized dirty fluid 110 is discharged from the chamber 100, the clean fluid 120 may be drained via an exit valve 114 at the second end 102 of the chamber 100 and one or more conduits 116. The discharged clean fluid 120 may be stored as waste fluid or reused during subsequent iterations of the fluid pressurizing process. For example, additional quantities
of the dirty and clean fluids 110, 120 may then be introduced into the chamber 100 to repeat the pressurizing process to achieve a substantially continuous supply of pressurized dirty fluid 110.

[0040] The valves 106, 107, 112, and 114 may each be or comprise a needle valve, a metering valve, a butterfly valve, a globe valve, and/or other valves. The valves 106, 107, 112, and 114 may also or instead each be or comprise a check valve, including in implementations not utilizing a rotor or other rotating device as described below.

[0041] A fluid pressure exchanger comprising the apparatus shown in FIGS. 1-4 and/or others within the scope of the present disclosure may also comprise more than one of the example chambers 100 described above. For example, FIG. 5 is a schematic view of an example fluid pressure exchanger 200 containing multiple chambers 150 circumferentially spaced about a perimeter of a rotor 201 according to one or more aspects of the present disclosure.

[0042] The rotor 201 is slidably disposed within a housing 210 between opposing end caps 202, 203 in a manner permitting relative rotation between the rotor 201 and the housing 210 and end caps 202, 203. For example, the end caps 202, 203 may be positionally set on each side of the housing 210, and the rotor 201 may rotate around its longitudinal axis 211, relative to the end caps 202, 203 and the housing 210, or the end caps 202, 203 and the housing 210 may rotate around the longitudinal axis 211 relative to the rotor 201. Such rotation may be via a motor (not shown) operably connected to the rotor 201 or at least one of the end caps 202, 203 and the housing 210. Rotation may also be achieved by the longitudinal shape of the chambers 150 as they extend through the rotor 201, such as in a helical manner, such that rotation of the rotor 201 is induced by fluid flow through the chambers 150. The rotation of the rotor 201 about the longitudinal axis 211 is depicted in FIG. 5 by arrow 220.

[0043] The end caps 202, 203 may functionally replace the valves 106, 107, 112, and 114 depicted in FIGS. 1-4. For example, the first end cap 202 may be substantially disc-shaped, or may comprise a substantially disc-shaped portion, through which an inlet passage 204 and an exit passage 205 extend. The inlet passage 204 may act as the first inlet valve 106 shown in FIGS. 1-4, and the exit passage 205 may act as the first exit valve 112 shown in FIGS. 1-4. Similarly, the second end cap 203 may be substantially disc-shaped, or may comprise a substantially disc-shaped portion, through which an inlet passage 206 and an exit passage 207 extend. The inlet passage 206 may act as the second inlet valve 107 shown in FIGS. 1-4, and the exit passage 207 may act as the second exit valve 114 shown in FIGS. 1-4. The passages 204-
207 may have a variety of dimensions and shapes. For example, as in the example implementation depicted in FIG. 5, the passages 204-207 may each have dimensions and shapes substantially corresponding to the cross-sectional dimensions and shapes of the openings of each chamber 150 at the opposing ends of the rotor 201. However, other implementations are also within the scope of the present disclosure, provided that the chambers 150 may each be sealed against the end caps 202, 203 in a manner preventing or minimizing fluid leaks. For example, the surfaces of the end caps 202, 203 that mate with the corresponding ends of the rotor 201 may comprise face seals and/or other sealing means. Particles in the dirty and/or clean fluids may also be utilized to aid in sealing between the relatively rotating portions of the rotor 201 and the end caps 202, 203 and housing 210.

[0044] In the example implementation depicted in FIG. 5, the rotor 201 comprises eight chambers 150. However, other implementations within the scope of the present disclosure may comprise as few as two chambers 150, or as many as several dozen. The rotational speed may also vary and may be timed as per the velocity of the boundary 103 between the dirty and clean fluids and the length 221 of the chambers 150 so that the timing of the valves 204-207 are adjusted in order to facilitate proper functioning as described herein. The rotational speed may be based on the intended flow rate of the pressurized dirty fluid exiting the chambers 150 collectively, the amount of pressure differential between the dirty and clean fluids, and/or the dimensions of the chambers 150. For example, larger dimensions of the chambers 150 and greater rotational speed of the rotor 201 relative to the end caps 202, 203 and housing 210 will increase the discharge volume of the pressurized dirty fluid.

[0045] The size and number of instances of the fluid pressure exchanger 200 utilized at a wellsite in oil and gas operations may depend on the location of the fluid pressure exchanger 200 within the process flow stream at the wellsite. For example, some oil and gas operations at a wellsite may utilize multiple pumps (such as the pumps 306 shown in FIG. 8) that each receive low-pressure dirty fluid from a common manifold (such as the manifold 308 shown in FIG. 8) and then pressurize the dirty fluid for return to the manifold. For such operations, an instance of the fluid pressure exchanger 200 may be utilized between each pump and the manifold, and/or one or more instances of the fluid pressure exchanger 200 may replace one or more of the pumps. In such implementations, the rotor 201 may have a length 221 ranging between about 25 centimeters (cm) and about 150 cm, and a diameter 222 ranging between about 10 cm and about
30 cm, the cross-sectional area (flow area) of each chamber 150 may range between about 5 cm² and about 20 cm², and/or the volume of each chamber 150 may range between about 75 cubic cm (cc) and about 2500 cc, although other dimensions are also within the scope of the present disclosure.

[0046] In other implementations, the pumps may each receive low-pressure clean fluid from the manifold (such as may be received at the manifold from a secondary fluid source) and then pressurize the clean fluid for return to the manifold. The pressurized clean fluid may then be conducted from the manifold to one or more instances of the fluid pressure exchanger 200 to be utilized to pressurize low-pressure dirty fluid received from a gel maker, proppant blender, and/or other low-pressure processing device, and the pressurized dirty fluid discharged from the fluid pressure exchanger(s) 200 may be conducted towards a well. Examples of such operations include those shown in FIGS. 9-12, among other examples within the scope of the present disclosure. In such implementations, the length 221 of the rotor 201, the diameter 222 of the rotor 201, the flow area of each chamber 150, the volume of each chamber 150, and/or the number of chambers 150 may be much larger than as described above.

[0047] FIG. 6 is a cross-sectional view of the apparatus shown in FIG. 5 during an operational stage in which two of the chambers are substantially aligned with the passages 204, 205 of the first end cap 202 but not with the passages 206, 207 of the second end cap 203. Thus, the inlet passage 204 fluidly connects one of the depicted chambers 150, designated by reference number 250 in FIG. 6, with the one or more conduits 108 supplying the non-pressurized dirty fluid, such that the non-pressurized dirty fluid may be conducted into the chamber 250. At the same time, the exit passage 205 fluidly connects another of the depicted chambers 150, designated by reference number 251 in FIG. 6, with the one or more conduits 113 conducting previously pressurized dirty fluid out of the chamber 251, such as for conduction into a wellbore (not shown). As the rotor 201 rotates relative to the end caps 202, 203, the chambers 250, 251 will rotate out of alignment with the passages 204, 205, thus preventing fluid communication between the chambers 250, 251 and the respective conduits 108, 113.

[0048] FIG. 7 is another view of the apparatus shown in FIG. 6 during another operational stage in which the chambers 250, 251 are substantially aligned with the passages 206, 207 of the second end cap 203 but not with the passages 204, 205 of the first end cap 202. Thus, the inlet passage 206 fluidly connects the chamber 250 with the one or more conduits 109 supplying the
pressurizing or energizing clean fluid, such that the clean fluid may be conducted into the chamber 250. At the same time, the exit passage 207 fluidly connects the other chamber 251 with the one or more conduits 116 conducting previously used pressurizing clean fluid out of the chamber 251, such as for recirculation to the clean fluid source (not shown). As the rotor 201 further rotates relative to the end caps 202, 203 and the housing 210, the chambers 250, 251 will rotate out of alignment with the passages 206, 207, thus preventing fluid communication between the chambers 250, 251 and the respective conduits 109, 116.

[0049] The pressurizing process described above with respect to FIGS. 1-4 is achieved within each chamber 150, 250, 251 with each full rotation of the rotor 201 relative to the end caps 202, 203. For example, as the rotor 201 rotates relative to the end caps 202, 203 and the housing 210, the non-pressurized dirty fluid is conducted into the chamber 250 during the portion of the rotation in which the chamber 250 is in fluid communication with inlet passage 204 of the first end cap 202, as indicated in FIG. 6 by arrow 231. The rotation is continuous, such that the flow rate of non-pressurized dirty fluid into the chamber 250 increases as the chamber 250 comes into alignment with the inlet passage 204 and then decreases as the chamber 250 rotates out of alignment with the inlet passage 204. Further rotation of the rotor 201 relative to the end caps 202, 203 permits the pressurizing clean fluid to be conducted into the chamber 250 during the portion of the rotation in which the chamber 250 is in fluid communication with the inlet passage 206 of the second end cap 203, as indicated in FIG. 7 by arrow 232. The influx of the pressurizing clean fluid into the chamber 250 pressurizes the dirty fluid, such as due to the pressure differential between the dirty and clean fluids described above with respect to FIGS. 1-4. Further rotation of the rotor 201 relative to the end caps 202, 203 and the housing 210 permits the pressurized dirty fluid to be conducted out of the chamber 250 during the portion of the rotation in which the chamber 250 is in fluid communication with the exit passage 205 of the first end cap 202, as indicated in FIG. 6 by arrow 233. The discharged fluid may substantially comprise just the (pressurized) dirty fluid or a mixture of the dirty and clean fluids (also pressurized), depending on the timing of the rotor 201 and perhaps whether the chambers include the boundary 103 shown in FIGS. 1-4. Further rotation of the rotor 201 relative to the end caps 202, 203 permits the reduced-pressure clean fluid to be conducted out of the chamber 250 during the portion of the rotation in which the chamber 250 is in fluid communication with the exit passage 207 of the second end cap 203, as indicated in FIG. 7 by arrow 234. The pressurizing
process then repeats as the rotor 201 further rotates and the chamber 250 again comes into alignment with the inlet passage 204 of the first end cap 202.

[0050] Depending on the number and size of the chambers 150, the non-pressurized dirty fluid inlet passage 204 and the pressurizing clean fluid inlet passage 206 may be wholly or partially misaligned with each other about the central axis 211, such that the dirty fluid may be conducted into a chamber 150 to entirely or mostly fill the chamber 150 before the clean fluid is conducted into that chamber 150. The non-pressurized dirty fluid inlet passage 204 is completely closed to fluid flow from the conduit 108 before the pressurizing clean fluid inlet passage 206 begins opening. The pressurized dirty fluid exit passage 205 and the reduced-pressure clean fluid exit passage 207, however, may be partially open when the pressurizing clean fluid inlet passage 206 is permitting the clean fluid into the chamber 150. Similarly, the non-pressurized dirty fluid inlet passage 204 may be partially open when one or both of the pressurized dirty fluid exit passage 205 and/or the reduced-pressure clean fluid exit passage 207 is at least partially open.

[0051] The pressurized dirty fluid exit passage 205 and the reduced-pressure clean fluid exit passage 207 may be wholly or partially misaligned with each other about the central axis 211. For example, the pressurized dirty fluid (and perhaps an pressurized mixture of the dirty and clean fluids) may be substantially discharged from a chamber 150 via the pressurized dirty fluid exit passage 205 before the remaining reduced-pressure clean fluid is permitted to exit through the reduced-pressure clean fluid exit passage 207. As the rotor 201 continues to rotate relative to the end caps 202, 203 and the housing 210, the pressurized dirty fluid exit passage 205 becomes closed to fluid flow, and the reduced-pressure clean fluid exit passage 207 becomes open to discharge the remaining reduced-pressure clean fluid. Thus, the reduced-pressure clean fluid exit passage 207 may be completely closed to fluid flow while the pressurized dirty fluid (or mixture of the dirty and clean fluids) is discharged from the chamber 150 to the wellhead. Complete closure of the reduced-pressure clean fluid exit passage 207 may permit the pressurized fluid to maintain a higher-pressure flow to the wellhead.

[0052] The inlet and exit passages 204-207 may also be configured to permit fluid flow into and out of more than one chamber 150 at a time. For example, the non-pressurized dirty fluid inlet passage 204 may be sized to simultaneously fill more than one chamber 150, the inlet and exit passages 204-207 may be configured to permit non-pressurized dirty fluid to be conducted
into a chamber 150 while the reduced-pressure clean fluid is simultaneously being discharged from that chamber 150. Depending on the size of the rotor 201 and the chambers 150, the fluid properties of the dirty and clean fluids, and the rotational speed of the rotor 201 relative to the end caps 202, 203, the pressurizing process within each chamber 150 may also be achieved in less than one rotation of the rotor 201 relative to the end caps 202, 203 and the housing 210, such as in implementations in which two, three, or more iterations of the pressurizing process is achieved within each chamber 150 during a single rotation of the rotor 201.

[0053] The fluid pressure exchanger 200 shown in FIG. 5-7 and/or otherwise within the scope of the present disclosure may utilize various forms of the dirty and clean fluids described above. For example, the dirty fluid may be a high-density and/or high-viscosity solids-laden fluid comprising insoluble solid particulate material and/or other ingredients that may compromise the life or maintenance of pumps disposed downstream of the fluid pressure exchanger 200, especially when such pumps are operated at higher pressures. Examples of the dirty fluid utilized in oil and gas operations may include treatment fluid, drilling fluid, spacer fluid, workover fluid, a cement composition, fracturing fluid, acidizing fluid, stimulation fluid, and/or combinations thereof, among others within the scope of the present disclosure. The dirty fluid may be a foam, slurry, emulsion, or a compressible gas. The viscosity of the dirty fluid may be sufficient to permit transport of solid additives or other solid particulate material (collectively referred to hereinafter as "solids") without appreciable settling or segregation. Chemicals, such as biopolymers (e.g., polysaccharides), synthetic polymers (e.g., polyacrylamide and its derivatives), crosslinkers, viscoelastic surfactants, oil gelling agents, low molecular weight organogelators, and phosphate esters may be included in the dirty fluid to control viscosity of the dirty fluid.

[0054] The composition of the clean fluid may permit the clean fluid to be pumped at higher pressures with reduced adverse effects on the downstream pumps. For example, the clean fluid may be a solids-free fluid that does not include insoluble solid particulate material or other abrasive ingredients, or a fluid that includes low concentrations of insoluble solid particulate material or other abrasive ingredients. The clean fluid may be a liquid, such as water (including freshwater, brackish water, or brine), a gas (including a cryogenic gas), or combinations thereof. The clean fluid may also include substances, such as tracers, that can be transferred to the dirty fluid upon mixing within the chamber 150 or upon transmission through a semi-permeable
implementation of the boundary 103. The viscosity of the clean fluid may also be increased, such as to minimize or reduce viscosity contrast between the dirty and clean fluids. Viscosity contrast may result in channeling of the lower viscosity fluid through the higher viscosity fluid. The clean fluid may be viscosified utilizing the same chemicals and/or techniques described above with respect to the dirty fluid.

[0055] The following are additional examples of the dirty and clean fluids that may be utilized during oil and gas operations. However, the following are merely examples, and are not considered to be limiting to the dirty and clean fluids and that may also be utilized within the scope of the present disclosure.

[0056] For fracturing operations, the dirty fluid may be a slurry with a continuous phase comprising water and a dispersed phase comprising proppant (including foamed slurries), including implementations in which the dispersed proppant includes two or more different size ranges and/or shapes, such as may optimize the amount of packing volume within the fractures. The dirty fluid may also be a cement composition (including foamed cements), or a compressible gas. For such fracturing implementations, the clean fluid may be a liquid comprising water, a foam comprising water and gas, a gas, a mist, or a cryogenic gas.

[0057] For cementing operations, including squeeze cementing, the dirty fluid may be a cement composition comprising water as a continuous phase and cement as a dispersed phase, or a foamed cement composition. For such cementing implementations, the clean fluid may be a liquid comprising water, a foam comprising water and gas, a gas, a mist, or a cryogenic gas.

[0058] For drilling, workover, acidizing, and other wellbore operations, the dirty fluid may be a homogenous solution comprising water, soluble salts, and other soluble additives, a slurry with a continuous phase comprising water and a dispersed phase comprising additives that are insoluble in the continuous phase, an emulsion or invert emulsion comprising water and a hydrocarbon liquid, or a foam of one or more of these examples. In such implementations, the clean fluid may be a liquid comprising water, a foam comprising water and gas, a gas, a mist, or a cryogenic gas.

[0059] In the above example implementations, and/or others within the scope of the present disclosure, the dirty fluid 110 may include proppant; swellable or non-swellable fibers and/or other particles of higher aspect ratio (e.g., an aspect ratio greater than about 2); a curable resin; a tackifying agent; a lost-circulation material; a suspending agent; a viscosifier; a filtration control
agent; a shale stabilizer; a weighting agent; a pH buffer; an emulsifier; an emulsifier activator; a dispersion aid; a corrosion inhibitor; an emulsion thinner; an emulsion thickener; a gelling agent; a surfactant; a foaming agent; a gas; a breaker; a biocide; a chelating agent; a scale inhibitor; a gas hydrate inhibitor; a mutual solvent; an oxidizer; a reducer; a friction reducer; a clay stabilizing agent; an oxygen scavenger; cement; a strength retrogression inhibitor; a fluid loss additive; a cement set retarder; a cement set accelerator; a light-weight additive; a de-foaming agent; an elastomer; a mechanical property enhancing additive; a gas migration control additive; a thixotropic additive; and/or combinations thereof.

[0060] FIG. 8 is a schematic view of an example wellsite system 370 that may be utilized for pumping a fluid from a wellsite surface 310 to a well 311 during a well treatment operation. Water from a plurality of water tanks 301 may be substantially continuously pumped to a gel maker 302, which mixes the water with a gelling agent to form a carrying fluid or gel, which may be a clean fluid. The gel may be substantially continuously pumped into a blending/mixing device, hereafter referred to as a mixer 304. Solids, such as proppant and/or other solid additives stored in a solids container 303, may be intermittently or substantially continuously pumped into the mixer 304 to be mixed with the gel to form a substantially continuous stream or supply of treatment fluid, which may be a dirty fluid. The treatment fluid may be pumped from the mixer 304 to a plurality of plunger, frac, and/or other pumps 306 through a system of conduits 305 and a manifold 308. Each pump 306 pressurizes the treatment fluid, which is then returned to the manifold 308 through another system of conduits 307. The stream of treatment fluid is then directed to the well 311 via a wellhead 313 through one or more conduits 309. A control unit 312 may be operable to control various portions of such processing via wired and/or wireless communications (not shown).

[0061] FIG. 9 is a schematic view of an example implementation of another wellsite system 371 according to one or more aspects of the present disclosure. The wellsite system 371 comprises one or more similar features of the wellsite system 370 shown in FIG. 8, including where indicated by like reference numbers, except as described below.

[0062] The wellsite system 371 includes a fluid pressure exchanger 320, which may be utilized to eliminate or reduce pumping of dirty fluid through the pumps 306. The dirty fluid may be conducted from the mixer 304 to one or more chambers 100/150/250/251 of the fluid pressure exchanger 320 via the conduit system 305. The fluid pressure exchanger 320 may be,
comprise, and/or otherwise have one or more aspects in common with the apparatus shown in one or more of FIGS. 1-7. Thus, as similarly described above with respect to FIGS. 1-7, the fluid pressure exchanger 320 comprises a non-pressurized dirty fluid inlet 331, a pressurized clean fluid inlet 332, a pressurized fluid discharge 333, and a reduced-pressure fluid discharge 334. Consequently, the pumps 306 may conduct the clean fluid to and from the manifold 308 and then to the pressurized clean fluid inlet 332 of the fluid pressure exchanger 320, where the pressurized clean fluid may be utilized to pressurize the dirty fluid received at the non-pressurized dirty fluid inlet 331 from the mixer 304.

[0063] A centrifugal or other type of pump 314 may supply the clean fluid to the manifold 308 from a holding or frac tank 322 through a conduit system 315. An additional source of fluid to be pressurized by the manifold 308 may be flowback fluid from the well 311. The pressurized clean fluid is conducted from the manifold 308 to one or more chambers of the fluid pressure exchanger 320 via a conduit system 316. The pressurized fluid discharged from the fluid pressure exchanger 320 is then conducted to the wellhead 313 of the well 311 via a conduit system 309. The reduced-pressure clean fluid remaining in the fluid pressure exchanger 320 (or chamber 100/150 thereof) may then be conducted to a settling tank/pit 318 via a conduit system 317, where the fluid may be recycled back into the high-pressure stream via a centrifugal or other type of pump 321 and a conduit system 319, such as to the tank 322.

[0064] Some of the components, such as conduits, valves, and the manifold 308, may be configured to provide dampening to accommodate pressure pulsations. For example, liners that expand and contract may be employed to prevent problems associated with pumping against a closed valve due to intermittent pumping of the high-pressure fluid stream.

[0065] FIG. 10 is a schematic view of an example implementation of another wellsit system 372 according to one or more aspects of the present disclosure. The wellsit system 372 is substantially similar in structure and operation to the wellsit system 371, including where indicated by like reference numbers, except as described below.

[0066] In the wellsit system 372, the clean fluid may be conducted to the manifold 308 via a conduit system 330, the pump 314, and the conduit system 315. That is, the fluid stream leaving the gel maker 302 may be split into a low-pressure side, for utilization by the mixer 304, and a high-pressure side, for pressurization by the manifold 308. Similarly, although not depicted in FIG. 10, the fluid stream entering the gel maker 302 may be split into the low-pressure side, for
utilization by the gel maker 302, and the high-pressure side, for pressurization by the manifold 308. Thus, the clean fluid stream and the dirty fluid stream may have the same source, instead of utilizing the tank 322 or other separate clean fluid source.

[0067] FIG. 10 also depicts the option for the reduced-pressure fluid discharged from the fluid pressure exchanger 320 to be recycled back into the low-pressure clean fluid stream between the gel maker 302 and the mixer 304 via a conduit system 340. In such implementations, the flow rate of the proppant and/or other ingredients from the solids container 303 into the mixer 304 may be regulated based on the concentration of the proppant and/or other ingredients entering the low-pressure stream from the conduit system 340. The flow rate from the solids container 303 may be adjusted to decrease the concentration of proppant and/or other ingredients based on the concentrations in the fluid being recycled into the low-pressure stream. Similarly, although not depicted in FIG. 10, the reduced-pressure fluid discharged from the fluid pressure exchanger 320 may be recycled back into the low-pressure flow stream before the gel maker 302, or perhaps into the low-pressure flow stream between the mixer 304 and the fluid pressure exchanger 320.

[0068] FIG. 11 is a schematic view of an example implementation of another wellsit system 373 according to one or more aspects of the present disclosure. The wellsit system 373 is substantially similar in structure and operation to the wellsit system 372, including where indicated by like reference numbers, except as described below.

[0069] In the wellsit system 373, the source of the clean fluid is the tank 322, and the reduced-pressure fluid discharged from the fluid pressure exchanger 320 is not recycled back into the high-pressure stream, but is instead directed to a tank 340 via a conduit system 341. However, in a similar implementation, the reduced-pressure fluid discharged from the fluid pressure exchanger 320 is not recycled back into the high-pressure stream, as depicted in FIG. 10. In either implementation, utilizing the tank 322 or other source of the clean fluid separate from the discharge of the gel maker 302 and the fluid pressure exchanger 320 permits a single pass clean fluid system with very low probability of proppant entering the pumps 306.

[0070] FIG. 12 is a schematic view of an example implementation of another wellsit system 374 according to one or more aspects of the present disclosure. The wellsit system 374 is substantially similar in structure and operation to the wellsit system 373, including where indicated by like reference numbers, except as described below.
Unlike the wellsite system 373, the wellsite system 374 utilizes multiple instances of the fluid pressure exchanger 320. The low-pressure discharge from the mixer 304 may be split into multiple streams each conducted to a corresponding one of the fluid pressure exchangers 320 via a conduit system 351. Similarly, the high-pressure discharge from the manifold 308 may be split into multiple streams each conducted to a corresponding one of the fluid pressure exchangers 320 via a conduit system 352. The pressurized fluid discharged from the fluid pressure exchangers 320 may be combined and conducted towards the well 311 via a conduit system 353, and the reduced-pressure discharge from the fluid pressure exchangers 320 may be combined or separately conducted to the tank 340 via a conduit system 354.

FIG. 13 is a schematic view of an example implementation of another wellsite system 375 according to one or more aspects of the present disclosure. The wellsite system 375 is substantially similar in structure and operation to the wellsite system 373, including where indicated by like reference numbers, except as described below.

Unlike the wellsite system 373, the wellsite system 375 includes multiple instances of the fluid pressure exchanger 320 between the manifold 308 and a corresponding one of the pumps 306. The low-pressure discharge from the mixer 304 may be split into multiple streams each conducted to a corresponding one of the fluid pressure exchangers 320 via a conduit system 361. The high-pressure discharge from each of the pumps 306 is conducted to a corresponding one of the fluid pressure exchangers 320 via corresponding conduits (not numbered). The pressurized fluid discharged from each fluid pressure exchanger 320 is returned to the manifold 308 for combination, via a conduit system 362, and then conducted towards the well 311 via a conduit system 363. The reduced-pressure discharge from the fluid pressure exchangers 320 may be combined or separately conducted to one or more tanks 340 via a conduit system 364.

Combinations of various aspects of the example implementations depicted in FIGS. 9-13 are also within the scope of the present disclosure. For example, the high-pressure side may comprise a dual-stage pumping scheme that pumps a clean fluid from the pumps 306 at a medium pressure and pumps flowback fluid into the clean fluid stream to increase the pressure of the pressurized fluid entering the fluid pressure exchanger 320.

A wellsite system within the scope of the present disclosure may be further utilized to form a substantially continuous stream or supply of dirty fluid having a predetermined solids concentration prior to being pressurized by one or more pressure exchangers and injected into a
well during a well treatment operation. For example, the solids concentration of the dirty fluid stream being formed and injected into the well may be held substantially constant during the well treatment operation. However, the solids concentration of the dirty fluid may be dynamically varied during the well treatment operation.

[0076] FIG. 14 is a schematic view of an example implementation of a wellsite system 376 according to one or more aspects of the present disclosure. The wellsite system 376 is substantially similar in structure and operation to the wellsite systems 371, 372, 373, 374, including where indicated by like reference numbers, except as described below. FIGS. 15 and 16 are graphs showing example solids concentration profiles 381, 385 of the dirty fluid formed by the wellsite system 376 relating the varying solids concentration to elapsed time. The following description refers to FIGS. 14-16, collectively.

[0077] The wellsite system 376 may be utilized to form one or more periods, intervals, spikes, peaks, or other pulses 383, 387 of dirty fluid having substantially higher solids concentrations and defining the solids concentration profiles 381, 385 for injection into the wellbore 311 during a well treatment operation. The solids concentration profiles 381, 385 may be varied or otherwise modified during a well treatment process. For example, during a wellsite treatment operation, the solids (e.g., proppant) may be introduced as a single pulse 383 or repeatedly pulsed 387 between minimum and maximum solids concentration values. Such process may permit placement of proppant aggregations or "pillars" in a hydraulic fracture during hydraulic fracturing operations.

[0078] The example solids concentration profile 381 shown in FIG. 15 may include a single pulse 383 maintained over a predetermined period of time 384 characterized by a substantially constant solids concentration. During the pulse 383, a predetermined quantity or flow rate of solids may be introduced into the mixer 304 to be mixed with a stream of the carrying fluid or gel for injection into the well 313. Prior to being mixed with the solids, the gel may be a solids-free or clean fluid. Troughs 382 of the solids concentration profile 381 before and/or after the pulse 383 may be defined by periods characterized by substantially lower solids concentration, during which substantially lower amounts or flow rates of solids may be introduced into the mixer 304, resulting in a stream of dirty fluid having a substantially lower solids concentration. The troughs 382 may also be defined by periods of substantially zero solids concentration,
during which substantially no solids may be introduced into the mixer 304, resulting in a stream of fluid substantially comprising just the gel being discharged from the mixer 304.

[0079] The example solids concentration profile 385 shown in FIG. 16 may include several pulses 387 each having an increased or higher solids concentration and maintained over successive time periods 388, and separated by time periods characterized by decreased or lower solids concentrations. During each pulse 387, a predetermined and perhaps different (i.e., increasing and/or decreasing) quantity or flow rate of solids may be introduced into the mixer 304 to be mixed with a stream of gel to form the pulse 387 of dirty fluid having a predetermined solids concentration for injection into the well 313. For example, the solids concentration during each successive pulse 387 may be substantially higher than the solids concentration during one or each previous pulse 387.

[0080] Each trough 386 of the solids concentration profile 385 before and/or after a corresponding pulse 387 may be maintained over a period of time characterized by substantially lower solids concentrations, during which a substantially lower amount or flow rate of solids may be introduced into the mixer 304, resulting in a stream of dirty fluid having a substantially lower solids concentration. The troughs 386 may be maintained over time periods characterized by substantially zero solids concentration, during which substantially no solids may be introduced into the mixer 304, resulting in a stream of fluid substantially comprising just the gel being discharged from the mixer 304. The rates of increase and decrease in solids concentration may be programmed and modified during the well treatment process.

[0081] During an example well treatment operation, the flow rate of the carrying fluid or gel from the gel maker 302 to the mixer 304 may be set to a predetermined level and maintained substantially constant, while the flow rate of the solids from the solids container 303 to the mixer 304 may be varied to achieve the intended profile 381, 385. The flow rate of the gel from the gel maker 302 may be controlled via a flow rate control device 323 fluidly connected between the gel maker 302 and the mixer 304. The flow rate control device 323 may be or comprise a needle valve, a metering valve, a butterfly valve, a globe valve, and/or other valves operable to substantially instantaneously and/or progressively (e.g., gradually) open and close to control the rate of fluid flow from the gel maker 302 to the mixer 304. The flow rate control device 323 may also be or comprise a metering pump, such as a gear pump, a lobe pump, and/or a progressive cavity pump, among other examples. The gel flow rate from the gel maker 302 may also be controlled by controlling a rotational speed and/or operational rate of the mixer 304, whereby the flow rate at which the mixer 304 draws the gel from the gel maker 302 may be
proportional or otherwise related to the rotational speed and/or other operational rate of the mixer 304. Controlling the rotational speed and/or other operational rate of the mixer 304 may also control the flow rate at which the mixer 304 discharges the dirty fluid to the pressure exchanger 320, such that the flow rate of the dirty fluid may be proportional or otherwise related to the rotational speed and/or other operational rate of the mixer 304.

[0082] The flow rate of the solids from the solids container 303 may be controlled via a flow rate control device 324 connected between the solids container 303 and the mixer 304. The flow rate control device 324 may be a volumetric or mass dry metering device operable to control the volumetric or mass flow rate of the solids into the mixer 304. The flow rate control device 324 may include a proportional valve, such as a knife gate valve, a butterfly valve, a globe valve, and/or other valves operable to substantially instantaneously or progressively open and close. The flow rate control device 324 may also be or comprise a feeder device, such as a metering feeder, a screw feeder, an auger, and/or conveyor, among other examples.

[0083] A fluid analyzer 325 may be disposed along the conduit system 305 in a manner permitting monitoring of the dirty fluid flow rate and/or solids concentration or density of the dirty fluid discharged by the mixer 304. For example, the fluid analyzer 325 may comprise a density sensor operable to measure the solids concentration or the amount of particles in the dirty fluid, which may be indicative of the amount of proppant or other solids in the fluid conducted by the conduit system 305. The density sensor may emit radiation that is absorbed by different particles in the fluid. Different absorption coefficients may exist for different particles, which may then be utilized to translate the signals or information generated by the density sensor to determine the density or solids concentration. The fluid analyzer 325 may also comprise a flow rate sensor, such as a flow meter, operable to measure the volumetric and/or mass flow rate of the dirty fluid. The fluid analyzer 325 may be operable to generate signals or information indicative of the flow rate and/or solids concentration of the dirty fluid and utilized by a controller 410 (shown in FIG. 21), for example, to facilitate intended changes to the flow rate and/or solids concentration of the dirty fluid.

[0084] The shape of the solids concentration profile 381, 385 may be substantially retained as each pulse 383, 387 exits the mixer 304 and travels into the pressure exchanger 320 at low pressure via the conduit system 305, and then into the wellbore at a higher pressure via the conduit system 309. The pressure exchange process performed via the pressure exchanger 320 may permit the overall shape of the solids concentration profile 381, 385 to be substantially retained and/or maintained while pressurizing the
dirty fluid stream, whereby the profiles 381, 385 or each pulse 383, 387 are substantially the same upstream and downstream of the pressure exchanger 320. Accordingly, during communication of the dirty fluid from the mixer 304 to the well 311, the shape of profiles 381, 385, and/or the solids concentration pulses 383, 385 thereof, may be retained and/or remain substantially distinct. To help maintain the solids concentration profiles 381, 385, the viscosity of the gel may be maintained at a level sufficient to maintain the solids suspended during communication. Accordingly, to minimize the disruption of the profiles 381, 385, the gel viscosity may be increased as described above.

[0085] In a manner similar to that shown in FIGS. 12 and 13, several pressure exchangers 320 may be combined to perform the well treatment process. The solids concentration in each dirty fluid stream received by each pressure exchanger 320 may be controlled independently (such as via separate mixers 304). The average collective solids concentration at a point in time may be determined, for example, by utilizing Equation (1) set forth below.

\[ c(t) = \frac{\sum \phi_i(t) Q_i(t)}{\sum Q_i(t)} \]  

(1)

where, \( c_i(t) \) is a time-dependent solids concentration and \( Q_i(t) \) is a time-dependent volumetric flow rate through the \( i \)th pressure exchanger 320.

[0086] The flow rates and solids concentrations through each pressure exchanger 320 may be substantially the same. In such implementations, among others within the scope of the present disclosure, variations in solids concentration may be achieved by varying the solids concentration in the cumulative dirty fluid stream that is fed via a conduit system to the array of pressure exchangers 320 and split equally between the pressure exchangers (i.e., \( c_1 = c_2 = \ldots \) and \( Q_1 = Q_2 = \ldots \)).

[0087] As described above, the predetermined solids concentration of the dirty fluid being substantially continuously formed and injected into the wellbore may also be dynamically varied during the well treatment operation. FIG. 17 is a schematic view of an example implementation of another wellsite system 377 according to one or more aspects of the present disclosure. The wellsite system 377 is substantially similar in structure and operation to the井site systems 371, 372, 373, 374, including where indicated by like reference numbers, except as described below. FIGS. 18-20 are graphs showing example solids concentration profiles 391, 392, 393 of the dirty fluid formed by the wellsite system 377. The following description refers to FIGS. 17-20, collectively.
The flow rate of each dirty fluid stream supplied to a corresponding pressure exchanger 320 may be independently varied to achieve a predetermined cumulative solids concentration profile of varying solids concentration, while maintaining the solids concentration of each dirty fluid stream as substantially constant. For example, 50% of the pressure exchangers 320 may be operated to produce a substantially constant fluid stream having a solids concentration of about one pound of solids per gallon of gel (PPA), such as depicted in FIG. 18, and the other 50% of the pressure exchangers 320 may be operated to produce another substantially constant fluid stream having a solids concentration of about five PPA, such as depicted in FIG. 19. A variable, time-dependent solids concentration of the cumulative dirty fluid stream injected into the wellbore 311 via a conduit system 359 may be achieved by varying the flow rates of the individual dirty fluid streams introduced into the corresponding pressure exchangers 320 via conduit systems 355, 356, while maintaining the solids concentration of each individual dirty fluid stream as substantially constant. Accordingly, the solids concentration of the cumulative dirty fluid stream injected into the wellbore 3110 may be varied between the solids concentration of the individual dirty fluid streams, such as between about one PPA and about five PPA (such as depicted in FIG. 20).

As depicted in FIG. 17, the wellsite system 377 may comprise separate mixers 304 each fluidly connected with corresponding pressure exchangers 320. Such implementations may permit formation of individual dirty fluid streams, each having a different solids concentration and/or profile, to be communicated to the corresponding pressure exchanger 320 via the corresponding conduit systems 355, 356. For example, as shown in FIGS. 18 and 19, the first dirty fluid stream may have a substantially constant solids concentration 391, and the second dirty fluid stream may have a substantially constant solids concentration 392 that is substantially lower than the solids concentration 391 of the first dirty fluid stream. However, the first and second dirty fluid streams may have substantially similar solids concentrations in some implementations.

The solids and the gel may be supplied to each mixer 304 from a common gel maker 302 and a common solids container 303. However, it is to be understood that the wellsite system 377 may comprise additional gel makers and solids containers, such that the gel and the solids may be supplied to each mixer 304 from a separate corresponding gel maker and solids container. Prior to being mixed with the solids, the gel may be a solids-free or clean fluid.

Individual pressurized dirty fluid streams discharged by the pressure exchangers 320 may be combined by a fluid combiner 360 or otherwise merged into a conduit system 359 to achieve another solids concentration or profile 393, as shown in FIG. 20, which is different from the solid concentrations 391, 392. The flow combiner 360 may be or comprise an eductor, a
mixing valve, an inline mixer, a manifold, a tank, or simply a tee or wye fluid connection or joint.

[0092] During a well treatment operation, the solids concentration 391, 392 of the dirty fluid stream supplied to each pressure exchanger 320 from the corresponding mixer 304 may be set to a predetermined level and maintained substantially constant while the flow rate of each dirty fluid stream may be varied to achieve a variable or otherwise predetermined solids concentration 393 of the cumulative or combined dirty fluid stream to be injected into the wellbore 311 via the conduit system 359. The varying solids concentration 393 of the cumulative dirty fluid stream may be varied between the solids concentrations 391, 392 of the individual dirty fluid streams. As shown in FIG. 20, the varying solids concentration 393 of the cumulative dirty fluid stream may be progressively increased, then maintained, and then progressively decreased. However, other implementations are also within the scope of the present disclosure.

[0093] The flow rate of the dirty fluid stream discharged by each mixer 304 may be controlled by varying the flow rate of the gel from the gel maker 302 to each mixer 304, such as via a corresponding flow rate control devices 365 fluidly connected between the gel maker 302 and each mixer 304. The flow rate control devices 365 may comprise the same or similar structure and/or operation as the flow rate control device 323 described above. The flow rate of the dirty fluid stream discharged by each mixer 304 may be further controlled by varying the flow rate of the solids from the solids container 303 to each mixer 304, such as via a corresponding flow rate control device 366 fluidly connected between the solids container 303 and each mixer 304. The flow rate control devices 366 may comprise the same or similar structure and/or operation as the flow rate control device 324 described above. The solids concentration 391, 392 of each dirty fluid stream discharged by the mixers 304 may be maintained at a substantially constant concentration. Accordingly, a variation in the flow rate of the gel or solids may be accompanied by a corresponding variation in the flow rate of the other of the gel or solids, such that the solids concentration 391, 392 of the resulting dirty fluid may remain substantially the same.

[0094] The flow rate of the dirty fluid discharged by each mixer 304 and/or communicated to each pressure exchanger 320 may also be controlled by controlling a rotational speed and/or operational rate of each mixer 304 and/or via a corresponding flow rate control device 357, 358 fluidly connected between each mixer 304 and the corresponding pressure exchanger 320. The
flow rate control devices 357, 358 may comprise the same or similar structure and/or operation as the flow rate control device 323 described above.

[0095] The flow rate of the cumulative dirty fluid stream conducted through the conduit system 359 may be maintained constant at a predetermined flow rate. For example, a variation in the flow rate of the individual dirty fluid stream discharged by one of the mixers 304 may be accompanied by a corresponding, but opposite, variation in the flow rate of the individual dirty fluid stream discharged by the other of the mixers 304, such that the flow rate of the cumulative dirty fluid stream remains substantially constant.

[0096] Fluid analyzers 348, 349, 350 may be disposed along one or more of the conduit systems 355, 356, 359 in a manner permitting monitoring of the dirty fluid flow rate and/or solids concentration of the dirty fluid discharged by each of the mixers 304 and/or the cumulative dirty fluid discharged by the pressure exchangers 320. The fluid analyzers 348, 349, 350 may comprise the same or similar structure and/or operation as the fluid analyzer 325 described above. The fluid analyzers 348, 349, 350 may be operable to generate signals or information indicative of the flow rate and/or the solids concentration of the dirty fluid streams along the conduit systems 355, 356, 359 and utilized by a controller (such as the controller 410 shown in FIG. 21) to, for example, facilitate intended changes to the flow rate and/or solids concentration of the individual and cumulative dirty fluid streams.

[0097] Various portions of the wellsite systems 371-377 described above may collectively form and/or be controlled by a control system, such as may be operable to monitor and/or control operations of the wellsite systems 371-377, including the solids concentrations of the individual and cumulative dirty fluid streams. FIG. 21 is a schematic view of at least a portion of an example implementation of such a control system 400 according to one or more aspects of the present disclosure. The following description refers to one or more of FIGS. 1-20.

[0098] The control system 400 may comprise the above-mentioned controller 410, which may be in communication with the gel maker 302, the solids container 303, the mixers 304, the pumps 306, 314, the manifold 308, the pressure exchangers 320, the flow rate control valves 323, the fluid analyzers 325, 348, 349, 350, and/or actuators associated with one or more of these components. For clarity, these and other components in communication with the controller 410 will be collectively referred to hereinafter as "controlled equipment." The controller 410 may be operable to receive coded instructions 432 from wellsite operators and signals generated by the fluid analyzers 325, 348, 349, 350, process the coded instructions 432 and the signals, and
communicate control signals to the controlled components to execute the coded instructions 432 to implement at least a portion of one or more example methods and/or processes described herein, and/or to implement at least a portion of one or more of the example systems described herein. The controller 410 may be or form a portion of the control unit 312.

[0099] The controller 410 may be or comprise, for example, one or more processors, special-purpose computing devices, servers, personal computers (e.g., desktop, laptop, and/or tablet computers) personal digital assistant (PDA) devices, smartphones, internet appliances, and/or other types of computing devices. The controller 410 may comprise a processor 412, such as a general-purpose programmable processor. The processor 412 may comprise a local memory 414, and may execute coded instructions 432 present in the local memory 414 and/or another memory device. The processor 412 may execute, among other things, the machine-readable coded instructions 432 and/or other instructions and/or programs to implement the example methods and/or processes described herein. The programs stored in the local memory 414 may include program instructions or computer program code that, when executed by an associated processor, facilitate the wellsite system 371-377 to perform the example methods and/or processes described herein. The processor 412 may be, comprise, or be implemented by one or more processors of various types suitable to the local application environment, and may include one or more of general-purpose computers, special-purpose computers, microprocessors, digital signal processors (DSPs), field-programmable gate arrays (FPGAs), application-specific integrated circuits (ASICs), and processors based on a multi-core processor architecture, as non-limiting examples. Of course, other processors from other families are also appropriate.

[00100] The processor 412 may be in communication with a main memory 417, such as may include a volatile memory 418 and a non-volatile memory 420, perhaps via a bus 422 and/or other communication means. The volatile memory 418 may be, comprise, or be implemented by random access memory (RAM), static random access memory (SRAM), synchronous dynamic random access memory (SDRAM), dynamic random access memory (DRAM), RAMBUS dynamic random access memory (RDRAM), and/or other types of random access memory devices. The non-volatile memory 420 may be, comprise, or be implemented by read-only memory, flash memory, and/or other types of memory devices. One or more memory controllers (not shown) may control access to the volatile memory 418 and/or non-volatile memory 420.
[00101] The controller 410 may also comprise an interface circuit 424. The interface circuit 424 may be, comprise, or be implemented by various types of standard interfaces, such as an Ethernet interface, a universal serial bus (USB), a third generation input/output (3GIO) interface, a wireless interface, a cellular interface, and/or a satellite interface, among others. The interface circuit 424 may also comprise a communication device, such as a modem or network interface card to facilitate exchange of data with external computing devices via a network (e.g., Ethernet connection, digital subscriber line (DSL), telephone line, coaxial cable, cellular telephone system, satellite, etc.). One or more of the sensors and controlled components may be connected with the controller 410 via the interface circuit 424, such as may facilitate communication between the sensors and controlled components and the controller 410.

[00102] One or more input devices 426 may also be connected to the interface circuit 424. The input devices 426 may permit the wellsites operators to enter the coded instructions 432, including control commands, operational set-points, and/or other data for use by the processor 412. The operational set-points may include, as non-limiting examples, solids concentration set-points, time interval set-points, and/or flow rate set-points, such as may control the solids concentration levels or profiles of the dirty fluid and/or the flow rate of the dirty fluid and/or dirty fluid components, such as the gel and the solids. The input devices 426 may be, comprise, or be implemented by a keyboard, a mouse, a touchscreen, a track-pad, a trackball, an isopoint, and/or a voice recognition system, among other examples.

[00103] One or more output devices 428 may also be connected to the interface circuit 424. The output devices 428 may be, comprise, or be implemented by display devices (e.g., a liquid crystal display (LCD), a light-emitting diode (LED) display, or cathode ray tube (CRT) display), printers, and/or speakers, among other examples. The controller 410 may also communicate with one or more mass storage devices 430 and/or a removable storage medium 434, such as may be or include floppy disk drives, hard drive disks, compact disk (CD) drives, digital versatile disk (DVD) drives, and/or USB and/or other flash drives, among other examples.

[00104] The coded instructions 432 may be stored in the mass storage device 430, the main memory 417, the local memory 414, and/or the removable storage medium 434. Thus, the controller 410 may be implemented in accordance with hardware (perhaps implemented in one or more chips including an integrated circuit, such as an ASIC), or may be implemented as
software or firmware for execution by the processor 412. In the case of firmware or software, the implementation may be provided as a computer program product including a non-transitory, computer-readable medium or storage structure embodying computer program code (i.e., software or firmware) thereon for execution by the processor 412.

[00105] The coded instructions 432 may include program instructions or computer program code that, when executed by the processor 412, may cause the wellsite system 371-377 to perform methods, processes, and/or routines described herein. For example, the controller 410 may receive and process the operational set-points entered by a human operator. Based on the received operational set-points and the signals generated by the fluid analyzers 325, 348, 349, 350, the controller 410 may send signals or information to the various controlled components to cause the gel maker 302, the solids container 303, the mixers 304, the flow rate control devices 323, 324, 357, 358, and/or other portions of the wellsite system 371-377 to automatically perform and/or undergo one or more operations or routines described herein or otherwise within the scope of the present disclosure.

[00106] FIG. 22 is a flow-chart diagram of at least a portion of an example implementation of a method (500) according to one or more aspects of the present disclosure. The method (500) may be performed utilizing or otherwise in conjunction with at least a portion of one or more implementations of one or more instances of the apparatus shown in one or more of FIGS. 1-14, 17, and 21 and/or otherwise within the scope of the present disclosure. For example, the method (500) may be performed and/or caused, at least partially, by the controller 410 executing the coded instructions 432 according to one or more aspects of the present disclosure. Thus, the following description of the method (500) also refers to apparatus shown in one or more of FIGS. 1-14, 17, and 21. However, the method (500) may also be performed in conjunction with implementations of apparatus other than those depicted in FIGS. 1-14, 17, and 21 which are also within the scope of the present disclosure.

[00107] The method (500) comprises forming (505) a substantially continuous stream of fluid having a varying solids concentration, pressurizing (510) the substantially continuous stream of fluid with a pressure exchanger 320, and injecting (515) the pressurized substantially continuous stream of fluid into a wellbore 311 during a subterranean well treatment operation. For example, the fluid may comprise a fracturing fluid, the solids may comprise a proppant material, and the
subterranean well treatment operation may comprise a subterranean formation fracturing operation.

[00108] Forming (505) the substantially continuous stream may comprise communicating (520) a solids-free fluid into a mixer 304 at a substantially constant flow rate, communicating (525) solids into the mixer 304 at a varying flow rate, and combining (530) the solids-free fluid and the solids with the mixer 304 to form (505) the substantially continuous stream of fluid. The solids-free fluid may comprise a gel comprising water and a gelling agent.

[00109] Combining (530) the solids-free fluid and the solids may comprise forming (545) the substantially continuous stream of fluid with alternating periods of higher and lower solids concentrations. For example, the solids concentration during each successive period of higher solids concentration may be substantially different than during at least one or each previous period of higher solids concentration. That is, the solids concentration during each successive period of higher solids concentration may be substantially higher than during one or more previous periods of higher solids concentration, or the solids concentration during each successive period of higher solids concentration may be substantially higher than during each previous period of higher solids concentration. The solids concentrations during each period of lower solids concentration may vary or be substantially similar.

[00110] Pressurizing (510) the formed (505) substantially continuous stream of fluid may comprise communicating (535) the formed (505) fluid having a first pressure through a first port 204 of the pressure exchanger 320 and communicating (540) a second substantially continuous stream of fluid having a second pressure through a second port 206 of the pressure exchanger 320, thereby pressurizing and substantially continuously discharging the pressurized substantially continuous stream of fluid at a third pressure from a third port 205 of the pressure exchanger 320. As described above, the formed (505) fluid communicated (535) to the first pressure exchanger port 204 may be a low-pressure dirty fluid, and the fluid communicated (540) to the second pressure exchanger port 206 may be a high-pressure clean fluid. Thus, the second and third pressures may each be substantially greater than the first pressure.

[00111] Forming (505) the substantially continuous stream of fluid having the varying solids concentration may comprise forming the substantially continuous stream of fluid having a first solids concentration profile (e.g., profile 381, 385, or 393) that relates the varying solids concentration to elapsed time or cumulative pumping volume with respect to forming (505) the
substantially continuous stream of fluid. The pressurized (510) and injected (515) fluid may have a second solids concentration profile (e.g., profile 381, 385, or 393) that relates the varying solids concentration to elapsed time or cumulative pumping volume with respect to the pressurization (510) and injection (515), wherein the first and second solids concentration profiles 381, 385 may be substantially the same. For example, pressurizing (510) the substantially continuous stream of fluid with the pressure exchanger 320 may not substantially alter the varying solids concentration 383, 387 of the formed (505) substantially continuous stream of fluid, such that the substantially continuous stream of fluid is initially formed (505), pressurized (510), and injected (515) into the wellbore 311 with substantially similar solids concentration variance profiles 381, 385. Thus, alternating intervals of higher and lower solids concentrations of the formed (505) substantially continuous fluid stream may remain substantially distinct during the pressurization (510) and injection (515).

[00112] FIG. 23 is a flow-chart diagram of at least a portion of an example implementation of a method (600) according to one or more aspects of the present disclosure. The method (600) may be performed utilizing or otherwise in conjunction with at least a portion of one or more implementations of one or more instances of the apparatus shown in one or more of FIGS. 1-14, 17, and 21 and/or otherwise within the scope of the present disclosure. For example, the method (600) may be performed and/or caused, at least partially, by the controller 410 executing the coded instructions 432 according to one or more aspects of the present disclosure. Thus, the following description of the method (600) also refers to apparatus shown in one or more of FIGS. 1-14, 17, and 21. However, the method (500) may also be performed in conjunction with implementations of apparatus other than those depicted in FIGS. 1-14, 17, and 21 which are also within the scope of the present disclosure.

[00113] The method (600) comprises pressurizing (605), with a first pressure exchanger 320, a first substantially continuous stream of fluid having a first solids concentration. The method (600) also comprises pressurizing (610), with a second pressure exchanger 320, a second substantially continuous stream of fluid having a second solids concentration that is substantially less than the first solids concentration. The method (600) also comprises combining (615) the pressurized first and second substantially continuous streams of fluid to form a third substantially continuous stream of fluid having a third solids concentration, and injecting (620) the third substantially continuous stream of fluid into a wellbore 311 during a subterranean well treatment
operation. For example, the solids may comprise a proppant material, and the well treatment operation may comprise a subterranean formation fracturing operation.

[00114] The method (600) may also comprise forming (625) the first substantially continuous stream of fluid by combining a first substantially continuous stream of solids-free fluid and a first substantially continuous stream of solids with a first mixer 304. The method (600) may also comprise forming (630) the second substantially continuous stream of fluid by combining a second substantially continuous stream of solids-free fluid and a second substantially continuous stream of solids with a second mixer 304. The solids-free fluid may comprise a gel comprising water and a gelling agent.

[00115] Pressurizing (605) the first substantially continuous stream of fluid may comprise communicating (635) the first substantially continuous stream of fluid having a first pressure through a first port 204 of the first pressure exchanger 320, and communicating (640) a third substantially continuous stream of fluid having a second pressure through a second port 206 of the first pressure exchanger 320 to substantially continuously discharge the first substantially continuous stream of fluid at a third pressure from a third port 205 of the first pressure exchanger 320. The second and third pressures may each be substantially greater than the first pressure.

[00116] Similarly, pressurizing (610) the second substantially continuous stream of fluid may comprise communicating (645) the second substantially continuous stream of fluid having a fourth pressure through a first port 204 of the second pressure exchanger 320, and communicating (650) a fourth substantially continuous stream of fluid having a fifth pressure through a second port 206 of the second pressure exchanger 320 to substantially continuously discharge the second substantially continuous stream of fluid at a sixth pressure from a third port 205 of the second pressure exchanger 320. The fifth and sixth pressures may each be substantially greater than the fourth pressure and/or the third and sixth pressures may be substantially equal.

[00117] The method (600) may further comprise varying (655) the third solids concentration of the third substantially continuous stream of fluid by varying a flow rate of at least one of the first and second substantially continuous streams of fluid. Varying the flow rate of the at least one of the first and second substantially continuous streams of fluid may be performed while maintaining (660) the corresponding first and/or solids concentrations substantially constant. Varying the flow rate may also comprise varying (665) a solids flow rate and a solids-free fluid
flow rate into a first and/or second mixer that forms the corresponding first and/or second substantially continuous stream of fluid. Varying (655) the third solids concentration of the third substantially continuous stream of fluid may comprise progressively (670) increasing the third solids concentration of the third substantially continuous stream of fluid, then maintaining the third solids concentration of the third substantially continuous stream of fluid constant, and then progressively decreasing the third solids concentration of the third substantially continuous stream of fluid.

[00118] It is also noted that the present disclosure is not limited to just fluid-based fracturing, but is also applicable and/or readily adaptable for fracturing using natural gas and/or other gases, foam fracturing using nitrogen, and other fracturing implementations.

[00119] In view of the entirety of the present disclosure, including the figures and the claims, a person having ordinary skill in the art will readily recognize that the present disclosure introduces a method comprising: forming a substantially continuous stream of fluid having a varying solids concentration; pressurizing the substantially continuous stream of fluid with a pressure exchanger; and injecting the pressurized substantially continuous stream of fluid into a wellbore during a subterranean well treatment operation.

[00120] The fluid may comprise a fracturing fluid, the solids may comprise a proppant material, and the subterranean well treatment operation may comprise a subterranean formation fracturing operation. In such implementations, among others within the scope of the present disclosure, the solids may comprise fibers and/or particles having an aspect ratio substantially greater than 2.

[00121] Forming the substantially continuous stream may comprise communicating a solids-free fluid into a mixer at a substantially constant flow rate, communicating solids into the mixer at a varying flow rate, and combining the solids-free fluid and the solids with the mixer to form the substantially continuous stream of fluid. The solids-free fluid may comprise a gel comprising water and a gelling agent.

[00122] The substantially continuous stream of fluid may comprise a first substantially continuous stream of fluid having a first pressure, and pressurizing the first substantially continuous stream of fluid may comprise: communicating the first substantially continuous stream of fluid through a first port of the pressure exchanger; and communicating a second substantially continuous stream of fluid having a second pressure through a second port of the
pressure exchanger to substantially continuously discharge the first substantially continuous stream of fluid at a third pressure from a third port of the pressure exchanger, wherein the second and third pressures are each substantially greater than the first pressure.

[00123] The varying solids concentration may comprise alternating periods of higher and lower solids concentrations. The solids concentration during each successive period of higher solids concentration may be substantially different than during a previous period of higher solids concentration. The solids concentration during each successive period of higher solids concentration may be substantially different than during each previous period of higher solids concentration. The solids concentration during each successive period of higher solids concentration may be substantially higher than during a previous period of higher solids concentration. The solids concentration during each successive period of higher solids concentration may be substantially higher than during each previous period of higher solids concentration. The solids concentrations during each period of lower solids concentration may be substantially similar.

[00124] Forming the substantially continuous stream of fluid having the varying solids concentration may comprise forming the substantially continuous stream of fluid having a first solids concentration profile relating the varying solids concentration to elapsed time or cumulative pumping volume with respect to forming the substantially continuous stream of fluid. The pressurized substantially continuous stream of fluid injected into the wellbore may have a second solids concentration profile relating the varying solids concentration to elapsed time or cumulative pumping volume with respect to injecting the pressurized substantially continuous stream of fluid into the wellbore. The first and second solids concentration profiles may be substantially the same. Pressurizing the substantially continuous stream of fluid with the pressure exchanger may not substantially alter the varying solids concentration of the substantially continuous stream of fluid, such that the substantially continuous stream of fluid may be initially formed, pressurized, and injected into the wellbore with substantially similar solids concentration variance profiles.

[00125] Varying solids concentration may comprise alternating intervals of higher and lower solids concentrations, and the alternating intervals of higher and lower solids concentrations may remain substantially distinct during the pressurization and injection.
The present disclosure also introduces a method comprising: pressurizing, with a first pressure exchanger, a first substantially continuous stream of fluid having a first solids concentration; pressurizing, with a second pressure exchanger, a second substantially continuous stream of fluid having a second solids concentration that is substantially less than the first solids concentration; combining the pressurized first and second substantially continuous streams of fluid to form a third substantially continuous stream of fluid having a third solids concentration; and injecting the third substantially continuous stream of fluid into a wellbore during a subterranean well treatment operation.

The solids may comprise a proppant material, and the well treatment operation may comprise a subterranean formation fracturing operation.

The method may further comprising: forming the first substantially continuous stream of fluid by combining a first substantially continuous stream of solids-free fluid and a first substantially continuous stream of solids with a first mixer; and forming the second substantially continuous stream of fluid by combining a second substantially continuous stream of solids-free fluid and a second substantially continuous stream of solids with a second mixer. The solids-free fluid may comprise a gel comprising water and a gelling agent.

Pressurizing the first substantially continuous stream of fluid may comprise: communicating the first substantially continuous stream of fluid having a first pressure through a first port of the first pressure exchanger; and communicating a third substantially continuous stream of fluid having a second pressure through a second port of the first pressure exchanger to substantially continuously discharge the first substantially continuous stream of fluid at a third pressure from a third port of the first pressure exchanger, wherein the second and third pressures are each substantially greater than the first pressure. Pressurizing the second substantially continuous stream of fluid may comprise: communicating the second substantially continuous stream of fluid having a fourth pressure through a first port of the second pressure exchanger; and communicating a fourth substantially continuous stream of fluid having a fifth pressure through a second port of the second pressure exchanger to substantially continuously discharge the second substantially continuous stream of fluid at a sixth pressure from a third port of the second pressure exchanger, wherein the fifth and sixth pressures are each substantially greater than the fourth pressure. The third and sixth pressures may be substantially equal.
The method may further comprise varying the third solids concentration of the third substantially continuous stream of fluid by varying a flow rate of at least one of the first and second substantially continuous streams of fluid. Varying the flow rate may be performed while maintaining the corresponding first and/or second solids concentrations substantially constant. Varying the flow rate may comprise varying a solids flow rate and a solids-free fluid flow rate into a first and/or second mixer that forms the corresponding first and/or second substantially continuous stream of fluid. Varying the third solids concentration of the third substantially continuous stream of fluid may comprise: progressively increasing the third solids concentration of the third substantially continuous stream of fluid; then maintaining the third solids concentration of the third substantially continuous stream of fluid constant; and then progressively decreasing the third solids concentration of the third substantially continuous stream of fluid.

The present disclosure also introduces an apparatus comprising a system comprising: (A) a mixing device operable to receive and mix a solids-free fluid and a solid material to form a substantially continuous supply of a solids-laden fluid having a predetermined solids concentration and a first pressure; and (B) a pressure exchanger operable to: (1) receive the substantially continuous supply of solids-laden fluid at the first pressure; (2) receive a substantially continuous supply of pressurized fluid at a second pressure; and (3) pressurize the substantially continuous supply of solids-laden fluid to a third pressure utilizing the substantially continuous supply of pressurized fluid at the second pressure, wherein the second and third pressures are substantially greater than the first pressure.

The substantially continuous supply of solids-laden fluid at the third pressure may be for use in a subterranean well treatment operation. For example, the solids-free fluid may comprise a gel comprising water and a gelling agent, the solid material may comprise a proppant material, the solids-laden fluid may comprise a fracturing fluid, and the subterranean well treatment operation may comprise a subterranean formation fracturing operation.

The pressure exchanger may be further operable to: receive the substantially continuous supply of solids-laden fluid at the first pressure into one or more chambers of the pressure exchanger via a first port of the pressure exchanger; receive the substantially continuous supply of pressurized fluid at the second pressure into the one or more chambers of the pressure exchanger via a second port of the pressure exchanger; and discharge the substantially
continuous supply of solids-laden fluid at the third pressure via a third port of the pressure exchanger.

[00134] The predetermined solids concentration may comprise a varying solids concentration, and the mixing device may be operable to: receive the solids-free fluid at a substantially constant flow rate; receive the solid material at a varying flow rate; and combine the received solids-free fluid and solid material to form the substantially continuous supply of the solids-laden fluid having the varying solids concentration.

[00135] The predetermined solids concentration may comprise a varying solids concentration having alternating periods of higher and lower solids concentrations. The varying solids concentration during each successive period of higher solids concentration may be substantially different than during a previous period of higher solids concentration. The varying solids concentration during each successive period of higher solids concentration may be substantially different than during each previous period of higher solids concentration. The varying solids concentration during each successive period of higher solids concentration may be substantially higher than during a previous period of higher solids concentration. The varying solids concentration during each successive period of higher solids concentration may be substantially higher than during each previous period of higher solids concentration. The varying solids concentrations during each period of lower solids concentration may be substantially similar.

[00136] The predetermined solids concentration may comprise a varying solids concentration, the substantially continuous supply of solids-laden fluid upstream from the pressure exchanger may have a first solids concentration profile, the pressurized substantially continuous supply of solids-laden fluid downstream from the pressure exchanger may have a second solids concentration profile, and the first and second solids concentration profiles may be substantially the same. The pressure exchanger may not substantially alter the varying solids concentration of the substantially continuous supply of solids-laden fluid, such that the substantially continuous supply of solids-laden fluid may be initially formed and then pressurized and injected into a wellbore with substantially similar solids concentration variance profiles.

[00137] The predetermined solids concentration may comprise a varying solids concentration comprising alternating intervals of higher and lower solids concentrations, and the alternating intervals of higher and lower solids concentrations may remain substantially distinct during the pressurization.
The mixing device may be a first mixing device, the pressure exchanger may be a first pressure exchanger, the substantially continuous supply of solids-laden fluid may be a first substantially continuous supply of solids-laden fluid, the substantially continuous supply of pressurized fluid may be a first substantially continuous supply of pressurized fluid, the predetermined solids concentration may be a first predetermined solids concentration. In such implementations, the system may further comprise: a second mixing device operable to receive and the mix the solids-free fluid and the solid material to form a second substantially continuous supply of solids-laden fluid having a second predetermined solids concentration and a fourth pressure; a second pressure exchanger operable to receive the second substantially continuous supply of solids-laden fluid at the fourth pressure, receive a second substantially continuous supply of pressurized fluid at a fifth pressure, and pressurize the second substantially continuous supply of solids-laden fluid to a sixth pressure utilizing the second substantially continuous supply of pressurized fluid at the fifth pressure, wherein the fifth and sixth pressures are substantially greater than the third pressure. The system may further comprise a fluid combiner operable to receive and combine the first substantially continuous supply of solids-laden fluid from the first pressure exchanger and the second substantially continuous supply of solids-laden fluid from the second pressure exchanger to form a third substantially continuous supply of solids-laden fluid having a third predetermined solids concentration at a seventh pressure. The third, sixth, and seventh pressures may be substantially equal. The system may be further operable to vary the third predetermined solids concentration of the third substantially continuous supply of solids-laden fluid by varying a flow rate of at least one of the first and second substantially continuous supplies of solids-laden fluid. The system may be further operable to vary the flow rate while maintaining the corresponding first and/or second predetermined solids concentrations substantially constant. The system may be further operable to vary the flow rate by varying a solids flow rate and a solids-free fluid flow rate into the first and/or second mixing device that forms the corresponding first and/or second substantially continuous supply of solids-laden fluid. The system may be operable to vary the third predetermined solids concentration of the third substantially continuous supply of solids-laden fluid by: progressively increasing the third predetermined solids concentration of the third substantially continuous supply of solids-laden fluid; then maintaining the third predetermined solids concentration of the third substantially continuous supply of solids-laden fluid constant;
and then progressively decreasing the third predetermined solids concentration of the third substantially continuous supply of solids-laden fluid.

[00139] The foregoing outlines features of several embodiments so that a person having ordinary skill in the art may better understand the aspects of the present disclosure. A person having ordinary skill in the art should appreciate that they may readily use the present disclosure as a basis for designing or modifying other processes and structures for carrying out the same functions and/or achieving the same benefits of the embodiments introduced herein. A person having ordinary skill in the art should also realize that such equivalent constructions do not depart from the spirit and scope of the present disclosure, and that they may make various changes, substitutions and alterations herein without departing from the spirit and scope of the present disclosure.

[00140] The Abstract at the end of this disclosure is provided to permit the reader to quickly ascertain the nature of the technical disclosure. It is submitted with the understanding that it will not be used to interpret or limit the scope or meaning of the claims.
WHAT IS CLAIMED IS:

1. A method comprising:
   forming a substantially continuous stream of fluid having a varying solids concentration;
   pressurizing the substantially continuous stream of fluid with a pressure exchanger; and
   injecting the pressurized substantially continuous stream of fluid into a wellbore during a
   subterranean well treatment operation.

2. The method of claim 1 wherein the fluid comprises a fracturing fluid, wherein the solids
   comprise a proppant material, and wherein the subterranean well treatment operation
   comprises a subterranean formation fracturing operation.

3. The method of claim 1 wherein the solids comprise particles having an aspect ratio
   substantially greater than 2.

4. The method of claim 1 wherein forming the substantially continuous stream comprises:
   communicating a solids-free fluid into a mixer at a substantially constant flow rate;
   communicating solids into the mixer at a varying flow rate; and
   combining the solids-free fluid and the solids with the mixer to form the substantially continuous
   stream of fluid.

5. The method of claim 4 wherein the solids-free fluid comprises a gel comprising water and a
   gelling agent.

6. The method of claim 1 wherein the substantially continuous stream of fluid comprises a first
   substantially continuous stream of fluid having a first pressure, and wherein pressurizing the
   first substantially continuous stream of fluid comprises:
   communicating the first substantially continuous stream of fluid through a first port of the
   pressure exchanger; and
   communicating a second substantially continuous stream of fluid having a second pressure
   through a second port of the pressure exchanger to substantially continuously discharge the
first substantially continuous stream of fluid at a third pressure from a third port of the pressure exchanger, wherein the second and third pressures are each substantially greater than the first pressure.

7. The method of claim 1 wherein the varying solids concentration comprises alternating periods of higher and lower solids concentrations.

8. The method of claim 7 wherein the solids concentration during each successive period of higher solids concentration is substantially different than during a previous period of higher solids concentration.

9. The method of claim 7 wherein the solids concentration during each successive period of higher solids concentration is substantially different than during each previous period of higher solids concentration.

10. The method of claim 7 wherein the solids concentration during each successive period of higher solids concentration is substantially higher than during a previous period of higher solids concentration.

11. The method of claim 7 wherein the solids concentration during each successive period of higher solids concentration is substantially higher than during each previous period of higher solids concentration.

12. The method of claim 7 wherein the solids concentrations during each period of lower solids concentration are substantially similar.
13. The method of claim 1 wherein:
forming the substantially continuous stream of fluid having the varying solids concentration 
comprises forming the substantially continuous stream of fluid having a first solids 
concentration profile relating the varying solids concentration to elapsed time or cumulative 
pumping volume with respect to forming the substantially continuous stream of fluid; 
the pressurized substantially continuous stream of fluid injected into the wellbore has a second 
solids concentration profile relating the varying solids concentration to elapsed time or 
cumulative pumping volume with respect to injecting the pressurized substantially 
continuous stream of fluid into the wellbore; and 
the first and second solids concentration profiles are substantially the same.

14. The method of claim 13 wherein pressurizing the substantially continuous stream of fluid 
with the pressure exchanger does not substantially alter the varying solids concentration of 
the substantially continuous stream of fluid, such that the substantially continuous stream of 
fluid is initially formed, pressurized, and injected into the wellbore with substantially similar 
solids concentration variance profiles.

15. The method of claim 1 wherein the varying solids concentration comprises alternating 
intervals of higher and lower solids concentrations, and wherein the alternating intervals of 
higher and lower solids concentrations remain substantially distinct during the pressurization 
and injection.
16. A method comprising:
pressurizing, with a first pressure exchanger, a first substantially continuous stream of fluid having a first solids concentration;
pressurizing, with a second pressure exchanger, a second substantially continuous stream of fluid having a second solids concentration that is substantially less than the first solids concentration;
combining the pressurized first and second substantially continuous streams of fluid to form a third substantially continuous stream of fluid having a third solids concentration; and
injecting the third substantially continuous stream of fluid into a wellbore during a subterranean well treatment operation.

17. The method of claim 16 wherein the solids comprise a proppant material, and wherein the well treatment operation comprises a subterranean formation fracturing operation.

18. The method of claim 16 further comprising:
forming the first substantially continuous stream of fluid by combining a first substantially continuous stream of solids-free fluid and a first substantially continuous stream of solids with a first mixer; and
forming the second substantially continuous stream of fluid by combining a second substantially continuous stream of solids-free fluid and a second substantially continuous stream of solids with a second mixer.

19. The method of claim 18 wherein the solids-free fluid comprises a gel comprising water and a gelling agent.
20. The method of claim 16 wherein:
pressurizing the first substantially continuous stream of fluid comprises:
   communicating the first substantially continuous stream of fluid having a first pressure
   through a first port of the first pressure exchanger; and
   communicating a third substantially continuous stream of fluid having a second pressure
   through a second port of the first pressure exchanger to substantially continuously
   discharge the first substantially continuous stream of fluid at a third pressure from a
   third port of the first pressure exchanger, wherein the second and third pressures are
   each substantially greater than the first pressure; and
pressurizing the second substantially continuous stream of fluid comprises:
   communicating the second substantially continuous stream of fluid having a fourth
   pressure through a first port of the second pressure exchanger; and
   communicating a fourth substantially continuous stream of fluid having a fifth pressure
   through a second port of the second pressure exchanger to substantially continuously
   discharge the second substantially continuous stream of fluid at a sixth pressure from
   a third port of the second pressure exchanger, wherein the fifth and sixth pressures are
   each substantially greater than the fourth pressure.

21. The method of claim 20 wherein the third and sixth pressures are substantially equal.

22. The method of claim 16 further comprising varying the third solids concentration of the third
   substantially continuous stream of fluid by varying a flow rate of at least one of the first and
   second substantially continuous streams of fluid.

23. The method of claim 22 wherein varying the flow rate is performed while maintaining the
   corresponding first and/or second solids concentrations substantially constant.

24. The method of claim 23 wherein varying the flow rate comprises varying a solids flow rate
   and a solids-free fluid flow rate into a first and/or second mixer that forms the corresponding
   first and/or second substantially continuous stream of fluid.
25. The method of claim 22 wherein varying the third solids concentration of the third substantially continuous stream of fluid comprises: progressively increasing the third solids concentration of the third substantially continuous stream of fluid; then maintaining the third solids concentration of the third substantially continuous stream of fluid constant; and then progressively decreasing the third solids concentration of the third substantially continuous stream of fluid.

26. An apparatus comprising: a system comprising: a mixing device operable to receive and mix a solids-free fluid and a solid material to form a substantially continuous supply of a solids-laden fluid having a predetermined solids concentration and a first pressure; and a pressure exchanger operable to: receive the substantially continuous supply of solids-laden fluid at the first pressure; receive a substantially continuous supply of pressurized fluid at a second pressure; and pressurize the substantially continuous supply of solids-laden fluid to a third pressure utilizing the substantially continuous supply of pressurized fluid at the second pressure, wherein the second and third pressures are substantially greater than the first pressure.

27. The apparatus of claim 26 wherein the substantially continuous supply of solids-laden fluid at the third pressure is for use in a subterranean well treatment operation.

28. The apparatus of claim 27 wherein: the solids-free fluid comprises a gel comprising water and a gelling agent; the solid material comprises a proppant material; the solids-laden fluid comprises a fracturing fluid; and
the subterranean well treatment operation comprises a subterranean formation fracturing operation.

29. The apparatus of claim 26 wherein the pressure exchanger is further operable to:
receive the substantially continuous supply of solids-laden fluid at the first pressure into one or more chambers of the pressure exchanger via a first port of the pressure exchanger;
receive the substantially continuous supply of pressurized fluid at the second pressure into the one or more chambers of the pressure exchanger via a second port of the pressure exchanger;
and discharge the substantially continuous supply of solids-laden fluid at the third pressure via a third port of the pressure exchanger.

30. The apparatus of claim 26 wherein the predetermined solids concentration comprises a varying solids concentration, and wherein the mixing device is operable to:
receive the solids-free fluid at a substantially constant flow rate;
receive the solid material at a varying flow rate; and
combine the received solids-free fluid and solid material to form the substantially continuous supply of the solids-laden fluid having the varying solids concentration.

31. The apparatus of claim 26 wherein the predetermined solids concentration comprises a varying solids concentration having alternating periods of higher and lower solids concentrations.

32. The apparatus of claim 31 wherein the varying solids concentration during each successive period of higher solids concentration is substantially different than during a previous period of higher solids concentration.

33. The apparatus of claim 31 wherein the varying solids concentration during each successive period of higher solids concentration is substantially different than during each previous period of higher solids concentration.
34. The apparatus of claim 31 wherein the varying solids concentration during each successive period of higher solids concentration is substantially higher than during a previous period of higher solids concentration.

35. The apparatus of claim 31 wherein the varying solids concentration during each successive period of higher solids concentration is substantially higher than during each previous period of higher solids concentration.

36. The apparatus of claim 31 wherein the varying solids concentrations during each period of lower solids concentration are substantially similar.

37. The apparatus of claim 26 wherein the predetermined solids concentration comprises a varying solids concentration, and wherein:
   the substantially continuous supply of solids-laden fluid upstream from the pressure exchanger has a first solids concentration profile;
   the pressurized substantially continuous supply of solids-laden fluid downstream from the pressure exchanger has a second solids concentration profile; and
   the first and second solids concentration profiles are substantially the same.

38. The apparatus of claim 37 wherein the pressure exchanger does not substantially alter the varying solids concentration of the substantially continuous supply of solids-laden fluid, such that the substantially continuous supply of solids-laden fluid is initially formed and then pressurized and injected into a wellbore with substantially similar solids concentration variance profiles.

39. The apparatus of claim 26 wherein the predetermined solids concentration comprises a varying solids concentration comprising alternating intervals of higher and lower solids concentrations, and wherein the alternating intervals of higher and lower solids concentrations remain substantially distinct during the pressurization.

40. The apparatus of claim 26 wherein:
the mixing device is a first mixing device;
the pressure exchanger is a first pressure exchanger;
the substantially continuous supply of solids-laden fluid is a first substantially continuous supply of solids-laden fluid;
the substantially continuous supply of pressurized fluid is a first substantially continuous supply of pressurized fluid;
the predetermined solids concentration is a first predetermined solids concentration; and
the system further comprises:

- a second mixing device operable to receive and the mix the solids-free fluid and the solid material to form a second substantially continuous supply of solids-laden fluid having a second predetermined solids concentration and a fourth pressure;
- a second pressure exchanger operable to:
  - receive the second substantially continuous supply of solids-laden fluid at the fourth pressure;
  - receive a second substantially continuous supply of pressurized fluid at a fifth pressure; and
  - pressurize the second substantially continuous supply of solids-laden fluid to a sixth pressure utilizing the second substantially continuous supply of pressurized fluid at the fifth pressure, wherein the fifth and sixth pressures are substantially greater than the third pressure; and
- a fluid combiner operable to receive and combine the first substantially continuous supply of solids-laden fluid from the first pressure exchanger and the second substantially continuous supply of solids-laden fluid from the second pressure exchanger to form a third substantially continuous supply of solids-laden fluid having a third predetermined solids concentration at a seventh pressure.

41. The apparatus of claim 40 wherein the third, sixth, and seventh pressures are substantially equal.

42. The apparatus of claim 40 wherein the system is further operable to vary the third predetermined solids concentration of the third substantially continuous supply of solids-
laden fluid by varying a flow rate of at least one of the first and second substantially continuous supplies of solids-laden fluid.

43. The apparatus of claim 42 wherein the system is further operable to vary the flow rate while maintaining the corresponding first and/or second predetermined solids concentrations substantially constant.

44. The apparatus of claim 43 wherein the system is further operable to vary the flow rate by varying a solids flow rate and a solids-free fluid flow rate into the first and/or second mixing device that forms the corresponding first and/or second substantially continuous supply of solids-laden fluid.

45. The apparatus of claim 44 wherein the system is operable to vary the third predetermined solids concentration of the third substantially continuous supply of solids-laden fluid by: progressively increasing the third predetermined solids concentration of the third substantially continuous supply of solids-laden fluid; then maintaining the third predetermined solids concentration of the third substantially continuous supply of solids-laden fluid constant; and then progressively decreasing the third predetermined solids concentration of the third substantially continuous supply of solids-laden fluid.
**FIG. 20**

**FIG. 21**

- **MAIN MEMORY** 417
- **VOLATILE MEMORY** 418
- **NON-VOLATILE MEMORY** 420
- **PROCESSOR** 412
- **LOCAL MEMORY** 414
- **MASS STORAGE DEVICE** 430
- **INPUT DEVICE** 426
- **INTERFACE CIRCUIT** 424
- **OUTPUT DEVICE** 428
- **EXTERNAL STORAGE MEDIUM** 434
- **GEL MAKER** 302
- **SOLIDS CONTAINER** 303
- **MIXERS** 304
- **PUMPS** 306, 314
- **MANIFOLD** 308
- **PRESSURE EXCHANGERS** 320
- **FLOW RATE CONTROL VALVES** 323, 357, 358
- **FLUID MONITORS** 325, 348, 349, 350
FIG. 22
600

625
FORM FIRST STREAM OF FLUID WITH FIRST MIXER

630
FORM SECOND STREAM OF FLUID WITH SECOND MIXER

605
PRESSURIZE FIRST STREAM OF FLUID WITH FIRST SOLIDS CONCENTRATION

635
COMMUNICATE FIRST STREAM OF FLUID INTO FIRST PRESSURE EXCHANGER

640
COMMUNICATE THIRD STREAM OF FLUID INTO FIRST PRESSURE EXCHANGER TO DISCHARGE FIRST STREAM OF FLUID

610
PRESSURIZE SECOND STREAM OF FLUID WITH SECOND SOLIDS CONCENTRATION

645
COMMUNICATE SECOND STREAM OF FLUID INTO FIRST PRESSURE EXCHANGER

615
COMBINE PRESSURIZED FIRST AND SECOND STREAMS TO FORM THIRD STREAM OF FLUID WITH THIRD SOLIDS CONCENTRATION

650
COMMUNICATE FOURTH STREAM OF FLUID INTO SECOND PRESSURE EXCHANGER TO DISCHARGE SECOND STREAM OF FLUID

655
VARY THIRD SOLIDS CONCENTRATION BY VARYING FLOW RATE OF FIRST AND/OR SECOND STREAM OF FLUID

660
MAINTAIN FIRST / SECOND SOLIDS CONCENTRATIONS CONSTANT

665
VARY SOLIDS FLOW RATE AND SOLIDS-FREE FLUID FLOW RATE INTO FIRST / SECOND MIXER

670
PROGRESSIVELY INCREASE, THEN MAINTAIN, AND THEN DECREASE THIRD SOLIDS CONCENTRATION OF THIRD STREAM OF FLUID

620
INJECT THIRD STREAM OF FLUID INTO WELLBORE

FIG. 23
INTERNATIONAL SEARCH REPORT

PCT/US2016/029979

A. CLASSIFICATION OF SUBJECT MATTER
E21B 41/00(2006.01)i, E21B 43/17(2006.01)i, E21B 43/26(2006.01)i, C09K 8/62(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
E21B 41/00; B01J 12/00; E21B 43/267; E21B 43/26; E21B 43/16; C07C 7/17; E21B 43/17; C09K 8/62

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic database consulted during the international search (name of database and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: wellbore, fracturing fluid, abrasive, pump, solid concentration, proppant, pressure exchanger, and mixer

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
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<td>US 5899272 A (LORKE, DWIGHT N.) 04 May 1999 See column 4, line 9 - column 5, line 50, column 7, lines 51-54 and figures 1-2, 4-5.</td>
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<td>US 2014-0128655 A1 (ENERGY RECOVERY, INC.) 08 May 2014 See paragraphs [0022]-[0033] and figures 1-6.</td>
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Further documents are listed in the continuation of Box C.  See patent family annex.

* Special categories of cited documents:
  "A" document defining the general state of the art which is not considered to be of particular relevance
  "E" earlier application or patent but published on or after the international filing date
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  "O" document referring to an oral disclosure, use, exhibition or other means
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  "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
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  "&" document member of the same patent family

Date of the actual completion of the international search
04 August 2016 (04.08.2016)

Date of mailing of the international search report
04 August 2016 (04.08.2016)

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