

MECHANICAL TUBE WAVE SOURCES AND METHODS OF USE FOR LIQUID FILLED BOREHOLES

BACKGROUND

[0001] The statements in this section merely provide background information related to the present disclosure and may not constitute prior art.

[0002] Tube waves, otherwise known as Stoneley waves, are plane pressure waves that propagate through a tubular medium, or an annulus. In some cases, these waves reflect from changes in the characteristic impedance of the medium. Examples of such changes include: pipe diameter, closed end, free surface, gas bubble, compressibility, density, speed of sound, pipe elastic modulus, pipe supporting material (or lack thereof), holes with flow capacity, etc. With some knowledge of the wellbore geometry and/or the speed of the tube wave, the complex reflection patterns can be interpreted to yield useful information about the wellbore. Some examples of such information include locating the top of cement, identifying the setting of cement, locating which perforations in a well are passing fluid, confirming shifting of control valves, locating coiled tubing relative to downhole features, etc. One particular advantage of using methods based upon tube waves, is information about the bottom of the well can be gleaned using only surface equipment. A particular challenge in applying these techniques is developing a repeatable and reliable means to generate useful tube wave forms. Figures of merit for these sources include rate of pressure change, frequency spectrum, peak power, total energy, repeatability, and reliability.

[0003] U.S. Patent No. 3254524 discloses a method and apparatus for testing tubular equipment such as a pipe. A mechanical shock wave is generated by suddenly obstructing a moving fluid, causing a local expansion of the fluid followed by a reversely directed pressure or shock wave that is propagated through the fluid, a phenomenon commonly referred to as "water hammer". A centrifugal pump is employed to move the fluid in a closed circuit of pipes and to maintain the fluid under a constant pressure. A fast-acting valve is connected to the pipe line downstream from the test specimen. A sudden close of the valve generates a shock wave that propagates reversely through the test specimen and therefore measures the feature of the test specimen.

[0004] U.S. Patent No. 3979724 discloses a method and apparatus for determining the position of the bottom end of a long pipe in a deep water-filled borehole. A shock wave is first generated in the water at the surface end of the pipe. The shock wave travels down the pipe to the bottom end of the pipe and passes into the liquid in the borehole, generating an expanding seismic wave in the earth. A plurality of geophones is set out at the surface of the earth to detect the arrival of the seismic wave, based on which the position of the end of the pipe is calculated. In some embodiments, a chamber filled with a combustible mixture is detonated by a spark plug to make the shock wave. In some other embodiments, a chamber containing one or more explosive materials is detonated to produce the shock wave. In some further embodiments, a high pressure liquid is provided through a pipe and a valve to a disc that is sealed across an opening connected to a chamber. The disc is frangible and at a selected pressure of liquid on its surface, will fracture and explosively permit the pressurized liquid in the pipe to expand into the chamber and initiate a shock wave therein.

[0005] U.S. Patent No. 6401814 discloses a method for determining the location or displacement of a cementing plug during a cementing operation by transmitting one or more pressure pulses through the fluid in the wellbore. The pressure pulses are reflected off of the plug and received by a pressure sensor. Information regarding the timing of the reflected pressure pulses may be used to determine the location or displacement of the plug. A valve can be opened momentarily to vent pressure from a flowline and, thus, transmit a negative pressure pulse through the fluid in the casing string. Alternatively, an air gun can be used to transmit a positive pressure pulse through the fluid in the casing string. Alternatively, a pump can be operated in a manner to transmit a pressure pulse, such as by varying the pump's motor speed or by momentarily disengaging the motor from the pump, etc.

[0006] As disclosed in published U.S. Pat. App. No. 20080239872 A1, achieving accurate, real-time measurements during well completion and stimulation treatments has long been a goal in the oil and gas industry. Accurate measurement of bottom hole pressure during fracture treatments, for example, would allow an operator to observe fracture growth trends in real-time, and change treatment conditions accordingly. Similarly, location of balls seated in perforations would facilitate acid diversion treatments. However, real-time measurements of borehole completion and stimulation

treatments are rarely performed with current technology because the borehole environment is hostile to wiring and tends to rapidly attenuate electromagnetic signals. For example, the abrasiveness of the fracturing slurry is destructive to any exposed cable placed in the wellbore for delivering data to the surface.

[0007] U.S. Pat. App. No. 20090159272 A1 discloses that tube waves may be used for detection and monitoring of feature state to enhance stimulation operations and remediate failure conditions. For example, proper sealing of perforations may be confirmed based on lack of a reflection of a tube wave by the perforations. Alternatively, at least one of amplitude, frequency, attenuation, dispersion and travel time associated with a tube wave and reflection may be used to determine feature state. If a sealant fails during treatment then the failure condition is indicated by appearance of a tube wave reflection. Consequently, the stimulation operation can be stopped in a timely manner, and remediation by means, for example, of pumping diversion fluid or dropping of balls, can be reinitiated until the difference between the expected responses and responses measured by the instrument along the segment to be stimulated confirm that sealing has taken place and that stimulation of the intended zone can resume. Further, specific remediation steps may be selected based on response of the borehole system to tube waves. The efficacy of the selected remediation steps may also be determined by response of the borehole system to tube waves during or after execution of those steps.

[0008] U.S. Pat. App. No. 20080236935 A1 discloses that tube waves may be used to transmit an indication of the depth at which a condition is detected in a well. In particular, the depth is calculated based on the difference in arrival time at the surface of a first tube wave which propagates directly upward in the borehole and a second tube wave which initially travels downward and is then reflected upward. The tube waves may be generated by a canister designed to implode at a certain pressure.

[0009] WO2009086279 discloses methods and systems for measuring acoustic signals in an annular region. The system includes a tool housed in a tool housing for deployment downhole in a borehole, and an acoustic transducer mounted on the tool. The acoustic signals can be measured by sensors mounted on a borehole wall or within the downhole tool.

[0010] However, there remains a need to further improve the system and method for generating tube waves for use in liquid filled boreholes penetrating subterranean formations.

SUMMARY

[0011] According to one aspect, there is provided a system for generating tube waves in a liquid-filled borehole penetrating a subterranean formation. The system comprises an energy storage chamber, a fast operating valve connected to the chamber, a pipe connected to the valve and extending to the liquid-filled borehole, where said energy storage chamber contains a first pressure that is substantially different from a second pressure in the pipe so that a fast operation of the valve generates a tube wave in the pipe. In some embodiments, the system of claim 1, wherein the first pressure is higher than the second pressure and the generated tube wave is a positive tube wave. In some other embodiments, the first pressure is lower than the second pressure and the generated tube wave is a negative tube wave.

[0012] The energy storage chamber may contain a compressible medium, which may be selected from a group consisting of air, nitrogen, alcohol, ethyl ether, water, drilling fluid, cement slurry, oil, and their mixtures. In one example, the compressible medium is compressed nitrogen.

[0013] In one illustrated embodiment, the energy storage chamber comprises a plurality of accumulators connected to a common hub, with each accumulator containing compressed nitrogen. Such Nitrogen may be emplaced at a pressure up to 15,000 psi. In one embodiment, such nitrogen was emplaced at a pressure up to 5,000 psi.

[0014] The system for generating tube waves in a liquid-filled borehole may optionally include a charger that is connected to the energy storage chamber for pre-charging the energy storage chamber. The charger can be a pump, a compressor, a vent line leading to atmospheric pressure, a plunger that can be moved in or out, or a vacuum, depending on the system setup.

[0015] In some embodiments, the generated tube wave is at a pressure that is at least 50 psi above or below the pressure in the pipe. In some other embodiments, the generated tube wave is at a pressure that is at least 200 psi above or below the pressure in the pipe. In some further embodiments, the generated tube wave is at a

pressure that is at least 500 psi above or below the pressure in the pipe. In further embodiments where extreme pressure differences are desired, the generated wave may be near the vapor pressure of the fluid or as high as the rated working pressure of the tubulars conveying the pressure wave.

[0016] Moreover, the fast operating valve is configured to open or close a flow path of the medium through the valve in less than or equal to approximately 500 milliseconds. In some embodiments, the fast operating valve is configured to open or close a flow path of the medium through the valve in approximately 50 milliseconds. In some other embodiments, the fast operating valve is configured to open or close a flow path of the medium through the valve in approximately 100 milliseconds. In some further embodiments, the fast operating valve is configured to open or close a flow path of the medium through the valve in approximately 200 milliseconds. In one specific embodiment, the fast operating valve was configured to open or close a flow path of the medium through the valve in approximately 120 milliseconds.

[0017] In one specific example, the fast operating valve is a rotary valve that operates on a quarter turn by a pneumatic actuator assisted in opening by a spring. In some other examples, the valve is a regenerative valve, including but not limited to poppet valves, diaphragm valves, flow actuated valves, etc. A regenerative valve is one in which once the motion of the valve has been initiated by an external signal, the motion of the valve is driven by either pressure differences or flow forces internal to the valve such that it will complete its motion even in the event that the external signal is removed. In one embodiment, there is provided a regenerative valve comprising a control chamber, a treating chamber disposed below the control chamber but not in fluid communication with the control chamber, and a poppet that extends from the control chamber to the treating chamber and is capable of reciprocating within the control chamber and the treating chamber. The treating chamber can be connected to the energy storage chamber via an upstream port and the fluid-filled borehole via a downstream port.

[0018] In one embodiment, the poppet comprises a control piston disposed inside the control chamber, a treating seat disposed inside the treating chamber, and a stem connecting the control piston and the treating seat. The control piston divides the control chamber into an upper sub-chamber and a lower sub-chamber that are not in fluid communication with each other. The upper sub-chamber is in fluid communication with

an outside of the control chamber via an upper port, and the lower sub-chamber is in fluid communication with the outside of the control chamber via a lower port, so that a control fluid can be injected into or depleted from the upper sub-chamber or the lower sub-chamber in order to move the poppet up or down.

[0019] In one case, the control piston is a monolithic component of the poppet. In another case, the control piston is a separate component from the poppet, and the control piston is slidably connected to a narrowed stem of the poppet and is further restricted by a stopper fastened to a top of the poppet.

[0020] In an improved version of the poppet valve, a buffering chamber is provided above the control chamber but not in fluid communication with the control chamber. The poppet extends from the buffering chamber through the control chamber to the treating chamber and is capable of reciprocating within the buffering chamber, the control chamber, and the treating chamber. The poppet contains a hollow passage so that the downstream port is in fluid communication with the buffering chamber.

[0021] In one embodiment, the treating seat has a cross sectional profile that is larger than that of the stem of the poppet. In another embodiment, the treating seat has a cross sectional profile that is substantially the same as that of the stem of the poppet. In a further embodiment, the treating seat has a cross sectional profile that is smaller than that of the stem of the poppet.

[0022] In several illustrated embodiments, the treating seat is configured to engage a structure at the juncture of the downstream port and the treating chamber and seal off a fluid passage from the treating chamber to the downstream port. In one case, the treating seat seals off the fluid passage by a seal disposed in a retaining space formed on a side surface of the treating seat of the poppet. In another case, the treating seat seals off the fluid passage by a seal disposed in a retaining space formed on a bottom surface of the treating seat of the poppet. In a further case, the treating seat seals off the fluid passage by a seal disposed in a retaining space formed on an inner side surface of the downstream port. In an even further case, the treating seat seals off the fluid passage by engaging a disposable component located at an opening of the downstream port to the treating chamber. In yet another case, the treating seat seals off the fluid passage by a disposable component located at a tip of the poppet.

[0023] The regenerative valve can also be a regenerative diaphragm valve which may comprise a control chamber, a treating chamber disposed below the control chamber, a diaphragm disposed between the control chamber and the treating chamber, and a poppet disposed at a center of the diaphragm. The treating chamber can be connected to the energy storage chamber via an upstream port and the fluid-filled borehole via a downstream port. The control chamber can be connected to an outside of the valve via a control port. The poppet can be substantially in the shape of a reversed "T" and contain an orifice through a center of the poppet, which enables the control chamber to be in fluid communication with the treating chamber under substantial restrictions.

[0024] The regenerative valve can also be a pop-safety relief type valve which comprises an upstream port, a downstream port, a poppet chamber formed between the upstream port and the downstream port, and a poppet disposed in the poppet chamber. Said poppet chamber comprises a section where the poppet is a substantial portion of the cross section of the chamber and the chamber has a larger cross section than the upstream port. A spring can be provided to connect the poppet to the downstream port and push the poppet towards the upstream port. A stopper can be optionally included in the poppet chamber to restrict a movement of the poppet. An orifice can also be provided around a center of the poppet that allows a fluid to pass but with substantial restrictions. Moreover, a trigger can be provided so that when the trigger is engaged, it holds the poppet in a first position, and when the trigger is released, the poppet moves to a second position.

[0025] When the regenerative valve is a flow actuated tube wave valve, it may comprise an upstream port, a downstream port, and a swing check disposed between the upstream port and the downstream port. The swing check can be pivotally connected to an inner surface of the valve and is capable of assuming one of two positions: a first position where the swing check is substantially parallel to a longitudinal axis of the valve thereby allowing fluids to pass between the upstream port and the downstream port, and a second position where the swing check is substantially perpendicular to the longitudinal axis of the valve thereby obstructing fluids from passing between the upstream port and the downstream port.

[0026] According to another aspect of the application, there is provided a system for generating tube waves in a liquid-filled borehole penetrating a subterranean formation,

where the system comprises a weight, an actuator that controls a movement of the weight, a plunger, and a pipe having a top end and a bottom end, where the top end is transverse by the plunger and is not in fluid communication with an outside of the pipe, and the bottom end extends to the liquid-filled borehole for delivering the tube waves generated by the system. The weight is configured to render mechanical impact on the plunger upon an operation of the actuator.

[0027] In one embodiment, the system further comprises a spring disposed between the plunger and a top surface of the top end the pipe so that the spring exerts an upward force upon the plunger. In another embodiment, the system may comprise a spring disposed between the plunger and a bottom surface of the top end of the pipe so that the spring exerts a downward force upon the plunger.

[0028] According to further aspect of the application, there is provided a system for generating tube waves in a liquid-filled borehole penetrating a subterranean formation, where the system comprises a housing that is connected to a cavity on one end and a downstream port on the other end that is further connected to the liquid-filled borehole; a flyer disposed inside the housing, where said flyer further comprises a hollow space around a center of the flyer; and a piston disposed inside the hollow space of the flyer; where the piston is configured to move up and down inside the hollow space to exert mechanical impacts on the flyer, which in turn moves up and down inside the housing to generate tube waves in the downstream port.

[0029] The hollow space of the flyer can be further divided into an upper space and a lower space that are not in fluid communication with each other so that injecting fluids into or depleting fluids out of the upper space or the lower space moves the piston up or down inside the hollow space of the flyer. Optionally, the pressure in the cavity is equalized with the pressure in the downstream port. Optionally, the cavity is made of elastic materials and contains a low bulk modulus fill fluid. Also optionally, a first spring is provided to connect the flyer to the cavity and a second spring is provided to connect the flyer to the downstream port.

[0030] According to yet another aspect of the application, there is provided a system for generating tube waves in a liquid-filled borehole penetrating a subterranean formation, where the system comprises a pipe that connects an upstream port on one side and a downstream port on another side; an orifice formed inside the pipe around the juncture

of the upstream port and the downstream port; and a deformable object that is configured to assume a first position wherein the deformable object lodges at the orifice and blocks a fluid communication between the upstream port and the downstream port and a second position where the deformable object deforms and passes through the orifice and reopens the fluid communication between the upstream port and the downstream port. In one embodiment, the deformable object is made of degradable material, such as collagen or the plastic poly-lactic acid.

[0031] According to an even further aspect of the application, there is provided a system for generating tube waves in a liquid-filled borehole penetrating a subterranean formation, where the system comprises a stinger having a first end and a second end; an actuator connected to the first end of the stinger; a plate formed at the second end of the stinger, said plate having a cross-sectional profile that is larger than that of the stinger; where the actuator is configured to move the stinger up and down in the liquid-filled borehole and the plate generates tube waves in the liquid-filled borehole. This system is particularly useful in the liquid-filled borehole having a free liquid surface under which the second end of the stinger is immersed.

[0032] In some cases, the system further comprises a first pressure transducer that is positioned proximate to the second end of the stinger and is connected to a ground surface via a first cable. The first cable can run within an annulus formed between the borehole and the stinger, and is fastened to an external surface of the tube by a clamp. In some other cases, the system further comprises a second pressure transducer that is positioned at a bottom of the plate and is connected to a ground surface via a second cable. The second cable may run within the stinger. Optionally, a suspension system is provided to afford compliance for the stinger to move up and down.

[0033] According to an additional aspect of the application, there is provided an apparatus for generating tube waves in a liquid-filled borehole penetrating a subterranean formation, where the apparatus comprises a canister covered by a microscope slide. In one embodiment, the canister is a glass tube such as a centrifuge tube. The canister may further contain a weighting material.

BRIEF DESCRIPTION OF THE DRAWINGS

[0034] These and other features and advantages will be better understood by reference to the following detailed description when considered in conjunction with the accompanying drawings.

[0035] FIG. 1 is a schematic representation of a tube wave generating system generator according to one embodiment of the current application.

[0036] FIG. 2A is a diagram showing data recorded by using a tube wave generating system according to one embodiment of the current application.

[0037] FIG. 2B is another diagram showing data recorded by using a tube wave generating system according to one embodiment of the current application.

[0038] FIG. 3 is a cross-sectional view of a regenerative valve according to one embodiment of the current application.

[0039] FIG. 4 is a cross-sectional view of a regenerative valve according to one embodiment of the current application.

[0040] FIG. 5 is a cross-sectional view of a regenerative valve according to one embodiment of the current application.

[0041] FIGs. 6A-6F illustrate various sealing mechanisms that can be employed in the embodiments of the current application.

[0042] FIG. 7 is a cross-sectional view of a regenerative diaphragm valve according to one embodiment of the current application.

[0043] FIGs. 8A-8C are cross-sectional views of various pop-safety relief valves according to embodiments of the current application.

[0044] FIG. 9 is a cross-sectional view of a flow actuated valve according to one embodiment of the current application.

[0045] FIG. 10 is a cross-sectional view of a hammer source according to one embodiment of the current application.

[0046] FIG. 11 is a diagram showing data recorded by using a hammer source according to one embodiment of the current application.

[0047] FIG. 12 is a cross-sectional view of another hammer source according to one embodiment of the current application.

[0048] FIGs. 13A-13D are cross-sectional views of a system involving pumping objects through an orifice to generate tube waves according to one embodiment of the current application.

[0049] FIG. 14 is a diagram showing data recorded by using a system involving pumping objects through an orifice to generate tube waves according to one embodiment of the current application.

[0050] FIG. 15 is a cross-sectional view of a stinger system according to one embodiment of the current application.

[0051] FIG. 16 is a cross-sectional view of a system for coupling a tube wave source to a bore hole according to one embodiment of the current application.

[0052] FIGs. 17A and 17B are diagrams illustrating tube waves generated by systems of the current application.

[0053] FIGs. 18A-18I illustrate various examples of tube wave manipulation apparatuses according to embodiments of the current application.

[0054] FIGs. 19A-19C illustrate various examples of tube wave terminators according to embodiments of the current application.

[0055] FIG. 20 is a cross-sectional view of an imploding apparatus for generating tube waves according to one embodiment of the current application.

DETAILED DESCRIPTION OF SOME ILLUSTRATIVE EMBODIMENTS

[0056] Embodiments of the current application generally relate to systems and methods for generating tube waves for use in wellbores penetrating subterranean formations. The following detailed description illustrates embodiments of the application by way of example and not by way of limitation. All numbers disclosed herein are approximate values unless stated otherwise, regardless whether the word "about" or "approximately" is used in connection therewith. The numbers may vary by up to 1%, 2%, 5%, or sometimes 10% to 20%. Whenever a numerical range with a lower limit and an upper

limit is disclosed, any number falling within the range is specifically and expressly disclosed.

[0057] FIG. 1 shows a system **100** for generating tube waves for use in a borehole **10** that penetrates a subterranean formation **20** containing, for example, hydrocarbons. The system **100** comprises an energy storage chamber **50**, a fast operating valve **40** which is connected to the energy storage chamber **50**, and a pipe **30** which is connected to the valve **40** and extends to the wellbore **10**. The energy storage chamber **50** may contain a compressible medium, such as air, nitrogen, alcohol, ethyl ether, water, drilling fluids, cement slurries, oil, etc. that can be subject to an elevated pressure that is substantially higher than the pressure in the borehole **10**. In such an embodiment, a rapid opening of the valve **40** may generate a tube wave that starts with a positive or increasing pressure in the borehole **10** as fluid rapidly moves from the energy storage chamber **50**, through the valve **40** and into the pipe **30** to relieve the high pressure down to the wellbore pressure. The resulting tube wave is referred to as a positive tube wave. Alternatively, the energy storage chamber **50** can be substantially vacuum or under a pressure that is significantly lower than the pressure in the borehole **10**. In such an event, a fast opening of the valve **40** may generate a tube wave that starts with a negative or falling pressure in the borehole **10** as fluid from the wellbore **10** moves into the pipe **30** and further through valve **40** to finally bring the pressure in the energy storage chamber **50** to substantially the wellbore pressure. The resulting tube wave is referred to as a negative tube wave. In both types of systems the pressure wave generated frequently consists of a complex waveform of which only the beginning part is well described by the “positive” and “negative” language above, but this initial pressure change is what is used to name these waves. Positive is to be interpreted as being positive with respect to or higher than the wellbore pressure with negative being similarly interpreted to be lower than the well bore pressure. A further type of wave consists of an initial peak immediately followed by a peak of opposite sign and similar magnitude. Such a wave is referred to as a doublet.

[0058] Optionally, system **100** may further comprise a charger **60** that is positioned at the surface of the wellsite and connected to the energy storage chamber **50** to pre-charge the energy storage chamber **50** before opening valve **40**. When a positive pressure tube wave is needed, the charger **60** can be a pump, an actuated plunger, or compressor that compresses the medium contained in the energy storage chamber **50**

and increases the pressure in the energy storage chamber **50**. When a negative pressure tube wave is desired, the charger **60** may be a suction device or a vent that depletes the medium contained in the energy storage chamber **50** to create a pressure below that in the borehole **10**.

[0059] The energy storage chamber **50** may comprises one or more sub-chambers (not shown) that are in fluid communication with each other, either in series or in parallel. In one embodiment, the energy storage chamber **50** comprises a plurality of metal containers (called “accumulators”) that enclose a compressed air, such as nitrogen. The accumulators can be substantially cylindrical in shape, with approximately 80 mm in diameter and 388 mm in length. An internal mechanism is provided to allow a charge of gas or fluid to be retained inside the accumulator at some initial or pre-charge pressure. This mechanism allows the external fluid to enter the accumulator and further compress the pre-charged media to a higher pressure. The fluid that has entered may be later allowed to leave, at which point the internal media will resume substantially its pre-charged pressure. In the case of gas as a pre-charge media, the compression and expansion of the gas during this cycle may occur on a time scale short enough that there is little heat exchange with the structures, leading to significant changes in the temperature of the gas and a reduction of the energy delivered while discharging the external fluid. This loss may be mitigated by using internal structures (such as open cell foam, liquids, and open metal forms like mesh and perforated metal) to provide heat during expansion. In the case of a media that is substantially liquid at room temperature this pre-charge pressure is sometimes atmospheric pressure or the vapor pressure of the fluid. Each accumulator may contain an initial pressure up to 15,000 psi in the case where the charging and working pressure of the chamber are 15,000 psi as is common in oilfield treating equipment. The charging pressure may be substantially higher than the working pressure of the pipe **30** or the wellbore **10** due to pressure losses in the fast opening valve **40**. In some cases, the pre-charge for an accumulator used to generate positive tube waves will be pre-charged to approximately 1/3 of the planned charging pressure. In some cases, this pre-charge pressure will be approximately 5,000 psi in the case of a chamber rated for 15,000 charging and working pressure. The accumulators can be charged with external fluid at the wellsite by charger **60** as shown in FIG. 1 of the application. With the appropriate charger **60** they may also be pre-charged with gas at the well site. Alternatively, the accumulators can be charged offsite at a factory and

transported to the wellsite when needed. Due to the small size of the accumulator, it is highly portable and affords great flexibility to oilfield operations.

[0060] Typically, for applications in fluid-filled boreholes penetrating subterranean formations, tube waves need to be delivered under relatively high pressure and carry relatively high energy compared with tube waves generated for other uses. This is because the fluid in the borehole is normally under high pressure from the subterranean formation and/or surface equipment such as pumps. Low-energy tube waves may not be able to propagate far enough before it is absorbed by the fluid in the borehole. Also, a low-energy tube wave may not be able to produce a sufficiently high signal-noise ratio for sensors to detect the reflected wave when accompanied by the noise produced during well servicing. Accordingly, in one embodiment of the current application, there is provided a method or system for generating tube waves with a pressure that is equal to or below about 1% of wellbore pressure or equal to below about 50 psi, which are primarily suitable for wellbores not under services, i.e. quiet wellbores. The pressure difference can be either positive or negative. In another embodiment, there is provided a method or system for generating tube waves with a pressure that is between about 2% to about 20% (inclusive) of wellbore pressure or between about 100 psi to 500 psi (inclusive). Again, the pressure difference can be either positive or negative. Tube waves in this range are particularly useful in wellbores under some services but without an extraordinary amount of noises. For wellbores having a substantial amount of background noises (such as wellbores under hydraulic fracturing treatment) or wellbores having changed dimensions and/or structures, tube waves with higher energy are needed. Accordingly, in a further embodiment, there is provided a method or system for generating tube waves with a pressure that is between -30% to -100% of wellbore pressure or +50% to +200% of wellbore pressure.

[0061] The valve **40** can be a plug valve (sometimes referred to as a hammer valve in the oilfield due to the end connections that are assembled using a hammer), a ball valve, or any other type of valves that are capable of opening/closing in a relatively fast speed. In some cases, the valve **40** is a rotary valve that operates on quarter turns, although other variations can be employed as well. In this patent application, when the terms “fast”, “quick”, and “rapid” are used in connection with the description of the valve **40**, they generally mean that the valve **40** is capable of opening or closing the flow path of the medium in a time that is within an order of magnitude of the firing duration of the tube

wave, illustrated in for example in FIG. **2A** as time “**t**”. In one embodiment, the valve **40** is capable of opening or closing the flow path of the medium in a time that is less than the firing duration of the tube wave. In another embodiment, the valve **40** is capable of opening or closing the flow path of the medium in a time that is between about 1-3 times (inclusive) the firing duration of the tube wave.

[0062] In general, the fast operating valve of the current application is capable of opening or closing the flow path of the medium in less than or equal to approximately 500 milliseconds. In one exemplary embodiment as illustrated in FIG. **2A**, the firing duration of the tube wave was approximately 50 milliseconds and the fast-operating valve **40** was capable of opening or closing the flow path of the medium in approximately 120 milliseconds. In other embodiments, the fast-operating valve **40** is capable of opening or closing the flow path of the medium in approximately 50 milliseconds, 75 milliseconds, 100 milliseconds, 150 milliseconds, 175 milliseconds, 200 milliseconds, 250 milliseconds, 300 milliseconds, 350 milliseconds, 400 milliseconds, 450 milliseconds, or 500 milliseconds.

[0063] The valve **40** can be pneumatically or hydraulically operated. An actuator (not shown) incorporating a spring (not shown) that acts during the opening or closing cycle of the valve **40** can be used to increase the opening or closing speed of the valve **40**. Vane actuators may be selected over piston actuators for this application. In general, the higher the chamber pressure, the more torque is required to open the valve **40** due to the friction in the seals. However, an increased torque typically means slower opening/closing of the valve **40**, hence increasing volumes of air or other medium that is passed through the valve **40**. Therefore, an operator often needs to carefully balance the benefit of operating under higher chamber pressure (hence higher-energized tube waves) and the drawback associated with the increased torque (hence the slower opening/closing of the valve). A proper balance needs to be struck to achieve an overall satisfactory result.

[0064] In one specific embodiment of the application, a standard 2x1 size 1502 hammer valve such as the FMC's ULT 150 plug valve part number P516108 was used as the actuator. The specification of the valve can be found at FMC's online catalogue, (<http://www.fmctechnologies.com/en/FluidControl/Technologies/~media/FluidControl/Flo wline/pdfs/FMC>). A spring was used to assist the opening of the valve. This valve has a

cylindrical plug with a round cross drill for the fluid passage that is 0.75" bore. The two ports tapered from the full bore of the end connections (1.75") down to match the bore of the plug. Two seal sections were disposed, one on each port such that pressure applied to one port pushes the plug into the opposite seal section, effecting a seal. Each seal section had a central hole matching the plug bore. When the plug was rotated such that the plug bore, the two seal section bores, and the two valve port bores are lined up, it was in the open position and provided a path with at least 0.75" inside diameter through the entire valve. When the plug is rotated 90 degrees this path was closed. When three accumulators were connected to a common wellsite manifold (not shown), an initial pressure of 15,000 psi was achieved upstream of the valve **40**. The actuator was then activated to rapidly open the valve **40**, producing a tube wave of approximately 230 psi. The result of one experiment is shown in FIG. **2A** of the current application. The result of another experiment is shown in FIG. **2B** of the current application where the valve was fired into an orifice rather than a well so the outlet pressure signature is simpler comparing to that in FIG. **2A** because there were no reflections from the borehole.

[0065] In some other embodiments, the valve **40** can be one of the regenerative valves as discussed in more detail below. Generally speaking, a regenerative valve means a type of valve that opens with an increasing force once an initial stage of opening is assumed. In some cases, the regenerative valve has a moving element disposed therein, said moving element having a first area that is exposed to a first port and a second area that is exposed to a second port, where said first area is different from the second area so that the moving element is held in a closed position upon the second port until an external force is applied to push the moving element away from the second port. At that moment, an increasing force is exerted by one of the first pressure in the first port and the second pressure in the second port functions on one of the first area and the second area, therefore push the moving element to a fully opened state.

[0066] An example of a regenerative valve **140** is shown in FIG. **3**, which comprises a control chamber **130**, a treating chamber **120**, and a poppet **103** disposed therein. A set of seals **107**, **108** are provided between poppet **103** and the valve body **170**, therefore preventing the control chamber **130** and the treating chamber **120** from being in fluid communication with each other. For clarity, the seal that is positioned close to the control chamber **130** side is called the control fluid seal **108**; the seal that is positioned close to the treating chamber **120** side is called the treating fluid seal **107**. Optionally, a

port **155** can be provided between the control fluid seal **108** and the treating fluid seal **107** and used for purposes such as lubricating the friction between the poppet **103** and the valve body **170** and providing a path for leakage to leave the valve body **170** and be visible externally.

[0067] Within the control chamber **130**, the poppet **103** further comprises a control piston **135** that extends substantially perpendicularly from the longitudinal axis "Y" of the poppet **103**. A control piston seal **109** is provided between the control piston **135** and the side walls of the control chamber **130**, therefore separating the control chamber **130** into two sub-chambers **131**, **132** that are not in fluid communication with each other inside the control chamber **130**. An upper port **151** is provided to open the upper sub-chamber **131** of the control chamber to the control fluid. A lower port **152** is provided to open the lower sub-chamber **132** of the control chamber **130** to the control fluid. A cushion **160** can be provided at the top wall of the control chamber **130** to reduce the mechanical impact of the poppet **103** on the valve **140** by providing an orifice that slows the end of the poppet's motion in a gradual fashion rather than by an abrupt impact.

[0068] Within the treating chamber **120**, the poppet **103** similarly comprises a treating seat **137** that extends substantially perpendicularly from the longitudinal axis "Y" of the poppet **103**. Unlike the control piston **135** in the control chamber **130**, the treating seat **137** in the treating chamber **120** does not extend all the way to the side walls of the treating chamber **120**. Instead, the peripheral wall of treating seat **137** may be fully surrounded by the treating fluid during operation and the treating seat **137** does not divide the treating chamber **120** into multiple sub-chambers.

[0069] As used in this patent application, terms such as "up", "down", "upper", "lower", "top" and "bottom" and other like terms indicate relative positions of the various embodiments of the system and apparatus of the present application which is vertically oriented as shown in the drawings. However, it should be borne in mind that the system and apparatus of the present application can be oriented vertically, highly deviated from the vertical, or horizontally. Depending on the circumstances, such terms may refer to a left to right, right to left, or other relationship as appropriate.

[0070] In one embodiment, the lower portion of the treating seat **137** tapers downwardly and inwardly, generally indicated as **113** in FIG. 3 of the application. Therefore, the horizontally cross-sectional area of the treating seat **137** is reduced from a larger top

surface area to a smaller bottom surface area. A complimentary but steeper profile can be provided at the bottom wall of the treating chamber **120** where a downstream port **110** is connected to the treating chamber **120**. Therefore, when the poppet **103** moves downwardly towards the downstream port **110**, a tight seal can be formed between the treating seat **137** and the bottom wall of the treating chamber **120** where the downstream port **110** joins.

[0071] The treating chamber **120** is further connected to an upstream port **115**. During operation, a treating fluid can be introduced into the treating chamber **120** via the upstream port **115** and, when treating seat **137** is not engaged with the bottom wall of the treating chamber **120**, the treating fluid flows through the treating chamber **120** and discharges through the downstream port **110**.

[0072] For the ease of reference, as used in the current application, the cross-sectional area of the portion of the poppet that engages and seals the downstream port **110** is called the “seat area” of the poppet, and the cross-sectional area of the main body of the poppet is called the “stem area” of the poppet. Therefore, in the embodiment shown in FIG. **3**, the seat area (**A2**) of poppet **103** is larger than the stem area (**A1**) of poppet **103**. This feature leads to a rapid, regenerative opening of poppet **103**.

[0073] Starting with the situation when the poppet **103** is in an opened condition, the upstream port **115** is in fluid communication with the treating chamber **120** which in turn is in fluid communication with the downstream port **110**, i.e. $P_1 = P_2$. To close the valve **140**, the poppet **103** needs to be moved downwardly to engage the downstream port **110**. This can be achieved by introducing the control fluid into the upper sub-chamber **131** of the control chamber **130** via the upper port **151**. The control fluid needs to be supplied at a pressure such that pressure times the area of the control piston **135** is larger than the P_2 pressure times the area of the poppet stem at seal **170**. The increased pressure in the upper sub-chamber **131** pushes down the control piston **135**, which in turn brings down the poppet **103**.

[0074] After the poppet **103** engages with and seals off the downstream port **110**, the pressure in the treating chamber **120** is increased by introducing high-pressured treating fluid via the upstream port **115**. The increased pressure in the treating chamber **120** acts to push the poppet **103** down. Eventually, the pressure in the treating chamber **120** is sufficiently high that it is no longer necessary to maintain a positive pressure in the

upper sub-chamber **131** of the control chamber **130** because the pressure **P2** times the annular area between **A1** and **A2** exceeds the force due to the pressure **P2** times the area **A2**. At this point, the positive pressure in the upper sub-chamber **131** can be completely removed. In some cases, even a negative pressure can be introduced into the upper sub-chamber **131**, which may further facilitate the rapid opening of the valve **140** when it is time for the valve to open. It may also be advantageous to have **A1** and **A2** disposed such that some pressure is always required in the upper sub-chamber **131** to keep the valve closed.

[0075] To open the valve **140**, a positive pressure can be introduced into the lower sub-chamber **132** of the control chamber **130**. Alternatively, a negative pressure can be introduced into the upper sub-chamber **131**. At a certain point, an equilibrium is achieved when the downward force exerted by the pressure **P2** in the treating chamber **120** on the upper surface of the treating seat **137** is exactly the same as the sum of the upward force exerted by the borehole pressure **P1** on the lower surface of the treating seat **137** plus the upward force exerted by the positive pressure in the lower sub-chamber **132** (or the negative pressure in the upper sub-chamber **131**) of the control chamber **130** on the treating seat **135** of the poppet **103**.

[0076] Thereafter, a slight increase in the positive pressure in the lower sub-chamber **132** (or a slight increase in the negative pressure in the upper sub-chamber **131**) of the control chamber **130** will break the equilibrium and the poppet **103** will begin to move upwards to open the valve **140**. With the treating seat **137** departing slightly from the corresponding structure at the bottom wall of the treating chamber **120** where the downstream port **110** is connected, a small annulus is formed between the tapered portion of the treating seat **137** and the bottom wall of the treating chamber **120**. Accordingly, the treating chamber **120** starts to become in fluid communication with the downstream port **110**. The pressure **P1** in the downstream port **110** starts to rise and the pressure **P2** in the treating chamber **120** starts to decrease. Moreover, with the appearance of the small annulus, the entire seat area (shown as **A2** in FIG. 3) becomes subject to the increasing pressure **P1**. As a result, the upward force exerted by the increasing pressure **P1** on the seat area **A2** of the treating seat **137** grows rapidly, exceeding the downward force exerted by the decreasing pressure **P2** on the upper surface of the treating seat **137**. The net result is a regenerative, upwardly oriented, force that rapidly pushes the poppet **103** to a fully opened position.

[0077] The control fluid can be any medium that is capable of being injected into a cavity and exerting forces therein, such as air, nitrogen, alcohol, diethyl ether, water, silicone, hydrocarbon oil, their mixtures, etc. Similarly, the treating fluid can be any medium that is capable of being injected into a cavity and exerting forces therein, such as air, nitrogen, alcohol, diethyl ether, water, silicone, hydrocarbon oil, their mixtures, etc.

[0078] FIG. 4 shows an improved embodiment of FIG. 3, where an improved regenerative valve **240** is provided. The improved regenerative valve **240** does not contain a control piston **135** that extends all the way to the side walls of the control chamber **130**, as in FIG. 3. Instead, a disc **235** is provided between the poppet **203** and the side walls of the control chamber **230**, which divides the control chamber **230** into an upper sub-chamber **231** and a lower sub-chamber **232**. A set of seals **209**, **209'** are provided at the side walls of the disc **235** to ensure that the upper sub-chamber **231** and the lower sub-chamber **232** are not in fluid communication with each other in the control chamber **230**. In one embodiment, the stem of the poppet **203** is narrowed at the region where the disc **235** is provided. Therefore, a shoulder **237** can be formed on the stem of the poppet **203** so that when disk **235** moves downwardly, the disc **235** can make contact with the shoulder **237** and push down the poppet **203**. Similarly, a stopper **236** can be provided at the top of the poppet **203** so that when disk **235** moves upwardly, the disc **235** can make contact with the stopper **236** and push up the poppet **203**. In this embodiment, the weight of the poppet **203** that needs to be moved upwardly or downwardly during an opening or closing motion of the valve is reduced, because the disc **235** does not form a portion of the poppet **203**. Accordingly, a faster opening or closing of the valve can be achieved.

[0079] In one embodiment, the upper port **251** is connected to a space **260**, which in turn is connected to the upper sub-chamber **231** of the control chamber **230**. The control fluid contained in space **260** can function as a shock absorption mechanism for the upwardly moving poppet **203**. This can be advantageous because a separate cushion (such as cushion **160** in FIG. 3) can be eliminated.

[0080] FIG. 5 shows another improved embodiment of FIG. 3. There, a pressure balanced regenerative valve **340** is provided. In this embodiment, poppet **303** contains a passage way **304** for fluids in the downstream port **310** to travel upwardly towards a

buffering chamber **360** that is located on top of the control chamber **330**, as shown by arrows in FIG. 5. The passage way has a first orifice **302** that opens to the downstream port **310** and a second orifice **302'** that opens to the buffering chamber **360**. Therefore, the buffering chamber **360** is in fluid communication with the downstream port **310**, and the pressure in the buffering chamber **360** is the same as the pressure in the downstream port **310**, i.e. **P1**. Hence, the valve **340** in the current embodiment is called a "balanced pressure" valve. Because one of the treating pressures is balanced by being applied to both sides of the poppet **303**, a much smaller actuator can be used to operate the valve. A faster actuation may also be achieved.

[0081] The buffering chamber **360** is separated from the control chamber **330** by a set of seals **311**, **312** and a port **313** disposed therebetween. Therefore, the buffering chamber **360** is not in fluid communication with the control chamber **330**. Likewise, the control chamber **330** is separate from the treating chamber **320** by a set of seals **307**, **308** and a port **305** disposed therebetween. Therefore, the control chamber **330** and the treating chamber **320** are not in fluid communication with each other. Optionally, a bearing **314** can be provided to facilitate the alignment of the poppet **303** in the middle of the valve **340**, and to reduce the impact of the pressure pulse on the seals, such as seal **307** by providing a throttling orifice. Also optionally, the treating chamber **320** can be equipped with more than one port **315**, **315'** to improve the characteristics of the valve and reduce the side loads on the poppet **303**.

[0082] In this embodiment, the stem area may be selected independently depending on the purpose one intends to achieve. If the seat area is larger than the stem area, the poppet **303** will latch closed when the pressure in the treating chamber **320** is higher than the pressure in the downstream port, i.e. (**P2** > **P1**). Conversely, if the seat area is smaller than the stem area, the poppet **303** will latch closed when the pressure in the treating chamber **320** is lower than the pressure in the downstream port, i.e. (**P1** > **P2**). In one embodiment, the seat area is approximately zero.

[0083] To reduce the mechanical impact caused by rapidly opening the poppet **303** on the body of the valve **340**, a space **337** can be created in the upper sub-chamber **331** of the control chamber **330**, which as in FIG. 3, is separated from the lower sub-chamber **332** of the control chamber by a seal **309** disposed on the side wall of a control piston **335**. An upper port **351** is in fluid communication with the space **337**, which in turn is in

fluid communication with the upper sub-chamber **331** of the control chamber **330**. A lower port **352** is in fluid communication with the lower sub-chamber **332** of the control chamber **330**. Space **337** is configured to closely fit a shoulder **336** formed at the corner of the poppet **303** and the control piston **335**. Therefore, when poppet **303** moves upwardly, the shoulder **336** engages with the space **337** creating an annular orifice. The control fluid in the space **337** is compressed to produce a resistant force against the movement of the poppet **303**. Therefore, the impact of the poppet **303** on the valve **340** is reduced. In one embodiment, the shoulder **336** may be made as a separate ring with some clearance on the poppet stem such that it can self align with space **337** and reduce the requirement for precision machining of these parts.

[0084] Fig. **6** illustrates several different types of sealing mechanisms that may be applicable to the embodiments of the current application. They are provided as examples, not limitations, to the current application. Other variations are possible and should be considered within the scope of the current application. In general, sealing mechanisms in the current application are susceptible to wear and tear due to the high pressure in the chambers, fast motion of the poppet, and/or the pulsation of the fluids. In some cases, positive seal retaining mechanisms are employed; in some other cases, bonded seals are used. In some cases, high yield stress plastic (such as PEEK) or other elastic materials are used in the seal; in some other cases, metal to metal seal is employed. In some cases, one or more components of the sealing mechanism are modular so that they can be disassembled and replaced after wear and tear.

[0085] Referring now to FIG. **6**, various different types of sealing mechanisms are depicted in the context of sealing the poppet **403** and the downstream port **410**. , although it should be noted that such sealing mechanisms may be applicable to other locations of the valves as well. In FIG. **6A**, a retaining space **412** is provided on the poppet **403** to accommodate the seal **411**, so as to prevent seal **411** from being extruded or dislocated from its original position due to pulsations of the fluids, frictions from the wall **414** of the downstream port **410**, etc. Alternatively, in FIG. **6C**, the seal **431** and the retaining space **432** can be provided in the inner surface of wall **414** of the downstream port **410**.

[0086] To reduce the frictional force caused by the inner surface of the wall **414** of the downstream port **410**, in FIG. **6B**, the seal **421** and the retaining space **422** can be

provided at the bottom surface of the poppet **403**. Therefore, the seal is created between the bottom surface of the poppet **403** and the top surface of the wall **414** of the downstream port **410**. In all of these sealing systems the flexible sealing member may be advantageously bonded to either the poppet **403** or to a replaceable part attached to the poppet.

[0087] In FIG. **6D**, a replaceable component **443** is provided between the poppet **403** and the wall **414** of the downstream port **410**. In the illustrated embodiment, the replaceable component **443** is in the shape of a circular disc; however, other shapes can be applicable as well. Also, in the illustrated embodiment, the disc **443** is disposed upon a shoulder **416** created around the opening of the downstream port **410**. A seal **441** within a retaining space **442** can be optionally included between the disc and the wall **414**. A retaining ring **444** can be employed to keep the disc **443** in place. In the illustrated embodiment, the retaining ring **444** is lodged inside a retaining space **445** located in the vertical surface of the shoulder **416** at a location that is above the seal **441**. Protrusion **446** helps steer the high speed flow from a radial direction to an axial direction.

[0088] FIG. **6E** shows an improved version of FIG. **6D**. There, two shoulders **416**, **417** are created in the wall **414** of the downstream port **410**. The first shoulder **416** accommodates the replaceable disc **453**. A seal **451** is provided within a retaining space **452**, both located in the vertical surface of the first shoulder **416**. Alternatively, the seal may be located on the replaceable disc **453**. The second shoulder **417** is wider and higher comparing to the first shoulder **416**, and it accommodates the stopper **454**. Unlike the stopper **444** in FIG. **6D** which is lodged inside a retaining space **445**, in FIG. **6E**, the stopper **454** is lodged in position by threads. That is, the outer surface of the stopper **454** comprises a series of threads which can engage with a series of complimentary threads located on the vertical wall of the second shoulder **417**. Optionally, a slanted surface **458** is created between the poppet **403** and the replaceable disc **453** to improve the overall seal of the assembly. Further, the angle of the poppet nose may sometimes be slightly steeper than the angle of the replaceable seat **453** in order to produce a line contact where the two come together. In this case, one or both of the elements may be expected to deform slightly to produce a contact strip such that the contact pressure is equal to the yield stress of the softer of the two materials.

[0089] FIG. 6F shows a further improved version of the seal mechanism that can be used in the current application. Here, a replaceable component **463** is provided as a portion of the poppet **403** instead of the downstream port **410**. Specifically, in the illustrated embodiment, a tip **466** is created at the bottom of the poppet **403**. A replaceable disc **463** can be slid or screwed on the tip **466** and retained by a stopper **464**. In the illustrated embodiment, the stopper engages the tip **466** by threads, although other means of engagement can be utilized as well. Optionally, a seal **461** located within a retaining space **462** can be provided between the tip and the replaceable disc **463**. In one embodiment, a slanted surface **468** is created between the replaceable disc **463** and the wall **414** of the downstream port **410** to improve the overall seal of the assembly. In all of these sealing systems it may be advantageous to minimize the width of the sealing contact between the poppet and the seat to ensure that the sealing area of the poppet is close to the intended area, facilitating the desired regenerative action of the valve.

[0090] FIG. 7 shows a regenerative diaphragm valve **540**. The left portion of FIG. 7 illustrates the cross-sectional view of the valve **540** in the closed state; the right portion of FIG. 7 illustrates the cross-sectional view of the valve **540** in the open state. Specifically, in the depicted embodiment, a diaphragm **550** is provided between a control chamber **530** and a treating chamber **520**. The control chamber **530** is equipped with a control port **507**; the treating chamber **520** is equipped with a port **515**. In the illustrated embodiment the diaphragm **550** is connected by a screw **551** to the body of the chambers on one side, and by a disc **555** and a stopper **558** to a poppet **503** on another side. A seal **552** within a retaining space **553** can be optionally provided between the disc **555** and the diaphragm **550**. While the drawing shows a relatively thick elastomer diaphragm, a metal diaphragm (typically corrugated) is also suitable for this service.

[0091] In the illustrated embodiment, poppet **503** has a cross-sectional profile that is substantially in the shape of a reversed "T". The large base provides a large seat area that can engage and seal the downstream port **510**, which is optionally equipped with a port **509**; the slender stem comprises threads on the outer surface which can engage the stopper **558** and/or the retaining disc **555** of the diaphragm **550**. Optionally, an orifice is provided through the center of the poppet **503**, which enables the control chamber **503**

to be in fluid communication with the treating chamber **520**, albeit with substantial restrictions.

[0092] In operation, the valve **540** can be regeneratively opened to produce fast onset of tube waves. Starting from the condition when the poppet **503** is in the open state, i.e. right half of FIG. **7**, the treating chamber **520** is in fluid communication with the downstream port **510**. The control port **507** is then opened to allow fluids being pumped into the control chamber **530**. When the pressure in the control chamber **530** is sufficiently high, the diaphragm **550** and the poppet **503** are pushed down to engage with and seal off the downstream port **510**. Once a seal is achieved, the pressure in the treating chamber **520** raises, partially or completely due to fluids passed through the orifice **506** in the poppet **503**. To fire the valve **540**, control port **507** can be opened either to the atmosphere or to the port **509** of the downstream port **510**. When the pressure in the control chamber **530** falls enough to pull the poppet **503** off its seat, the valve **540** regeneratively opens.

[0093] A pressure relief valve (not shown) to limit the maximum differential pressure across the diaphragm **550** can be optionally included, especially for use in high pressure services, which would further expedite the opening of the valve. Moreover, a gas chamber (not shown) can be optionally connected to the control chamber **530**, which would further expedite the opening of the valve by providing the ability to compress the contents of the control chamber **530** during opening.

[0094] Pop-safety relief type valves can also be used to produce tube waves. An example is shown in FIG. **8A**. The valve **540** comprises an upstream port **515**, a downstream port **510**, and a poppet chamber **520** formed between the two ports. A poppet **503** is disposed inside the poppet chamber **520**. The poppet is connected to a spring **504** on one side, which in turn rests upon a seat **512** that is formed where the downstream port **510** connects to the chamber **520**. The spring **504** exerts forces on the poppet **503**, pushing the poppet **503** towards the upstream port **510**.

[0095] Starting with the “closed” condition as shown in the left half of FIG. **8A**, the poppet **503** rests upon a seat **512** formed around the opening of the upstream port **515** to the poppet chamber **520** and seals the upstream port **515** from the poppet chamber **520**. Thereafter, the pressure in the upstream port **515** is increased and/or the pressure in the poppet chamber **520** is decreased. When the pressure difference between the

upstream port **510** and the poppet chamber **520** is sufficiently high to overcome the downward force exerted by the spring **504**, the poppet **503** is started to be lifted off the seat **512**. When this happens, more area of the poppet **503** is exposed to the high pressure coming from the upstream port **510** due to its close proximity to the walls of the poppet chamber **520**, which further compresses the spring **504**. The regenerative force rapidly pushes the poppet **503** to an “open” position, as shown in the right half of FIG. **8A**.

[0096] Optionally, a stopper **505** is provided inside the poppet chamber **520** to restrict the motion of the poppet **503** and avoid fully compressing the spring **504**. In the illustrated embodiment, the stopper **505** is in the form of one or more extrusions located on the inner wall of the poppet chamber **520**. However, other forms of stoppers can be used as well. With the stopper **505** in place, the valve **540** can produce positive pulses followed by sudden steps at the downstream port **510** and negative pulses followed by sudden steps at the upstream port **515**. The sudden impact of the poppet on the stops will tend to form a tube wave with a doublet character in the event that the stored energy is exhausted in a time comparable to the transit time of the poppet **503** between the seat **512** and the stopper **505**. If the stored energy is expended in a time significantly longer than this transit time, port **510** will generally experience a positive tube wave.

[0097] FIG. **8B** shows a variation to the embodiment in FIG. **8A** that acts on a flowing fluid stream rather than opening a connection between two areas of differing pressures. There, valve **540'** comprises an upstream port **515'**, a downstream port **510'**, and a poppet chamber **520'** formed between the two ports. A poppet **503'** is disposed inside the poppet chamber **520'**. The poppet is connected to a spring **504'** on one side, which in turn rests upon an opening where the downstream port **510'** connects to the poppet chamber **520'**. The spring **504'** exerts forces on the poppet **503'**, pushing the poppet **503'** away from the downstream port **510'**.

[0098] Starting with the “open” condition as shown in the right half of FIG. **8B**, the poppet **503'** is held in position between one or more stoppers **505'** formed on the inner surface of the poppet chamber **520'** and a trigger **507'** that transverse the wall of the poppet chamber **520'**. The fluid flows from the upstream port **515'**, into the poppet chamber **520'**, through an orifice **506'** formed in the center of the poppet **503'** and around the outside of poppet **503'** towards the downstream port **510'**, shown by arrows

in FIG. 8B. Due to the small size of the orifice 506', the fluid flows with significant restrictions across the orifice 506'. A pressure drop is created between the poppet chamber 520' and the downstream port 510'.

[0099] When it is time to fire the valve, the trigger 507' is pulled to release the poppet 503'. The force of the spring 504' is overcome by the pressure drop between the two sides of the poppet 503' and the poppet 503' is quickly pushed towards the downstream port 510'. The poppet 503' finally comes into contact with a seat 512' formed around the opening of the downstream port 510' to the poppet chamber 520' and seals the downstream port 510' from the poppet chamber 520', producing a negative tube wave in the downstream port 510' and a positive tube wave in the upstream port 515'. The orifice 506' still allows a small quantity of fluids to pass from the poppet chamber 520' to the downstream port 510', however the flow path is significantly restricted due to the small size of the orifice 506'.

[00100] FIG. 8C shows a further variation to the embodiments in FIG. 8A and 8B. There, the trigger 507' is removed. The valve 540'' operates essentially on the fluids flowing from the upstream port 515'' to the downstream port 510''. Starting from left half of FIG. 8C where the valve 540'' is in a closed position, the fluid flows from the upstream port 515', into the poppet chamber 520', through an orifice 506' formed in the center of the poppet 503' towards the downstream port 510', shown by arrows in FIG. 8C. Due to the small size of the orifice 506'', the fluid flows with significant restrictions across the orifice 506'' in addition to the restriction between the outside diameter of the poppet 503'' and the housing 520''. A pressure drop is created between the poppet chamber 520'' and the downstream port 510''. At a certain point, the pressure drop is sufficiently high so that the downward force caused by the pressure difference exceeds the upward force caused by the spring 504''. As the poppet 503'' approaches the seat 512'', the pressure drop across the poppet rapidly increases, causing the poppet to be driven toward the seat faster. The poppet 503'' is pushed down to rest upon the seat 512'' of the downstream port 510'' abruptly. At this time the flow speed at the upstream port 515'' is suddenly reduced or stopped, generating a negative pulse in the downstream port 510'' and a positive pulse in the upstream port 515''. One or more stoppers 505'' can be provided on the inner surface of the poppet chamber 520'' to provide sudden stops to the poppet 503'' and produce a more repeatable switching behavior with flow.

[00101] FIG. 9 shows a flow actuated tube wave valve **640**. A conduit **670** comprises a downstream port **610**, an upstream port **615**, and a swing check **603** disposed between the two ports. The swing check **603** is pivotally connected to the inner wall of the conduit **670** around a point **604** which is located about the juncture of the downstream port **610** and the upstream port **615**. The swing check **603** can pivot between an “open” position where the swing check **603** is substantially parallel to the longitudinal axis of the conduit **670**, as shown in the right half of FIG. 9, and a “closed” position where the swing check **603** rests upon a seat **612** formed on an opposite inner wall of the conduit **670** so that the swing check **603** can be substantially perpendicular to the longitudinal axis of the conduit **670** when it is in the closed position, as shown in the left half of FIG. 9.

[00102] In operation, the swing check **603** is first held at the open position by an actuator (not shown) to allow the downstream port **610** to be in fluid communication with the upstream port **615**. The actuator is then released. The fluid flow will carry the swing check **603** downwardly into the closed position. This produces a negative pulse at the downstream port **610** and a positive step change at the upstream port **615**. The swing check **603** can then be restored to its open position either by mechanical means or by reversing the fluid flow path in the conduit **670**.

[00103] FIG. 10 discloses one type of hammer source that can also be used to produce tube waves. In this system, i.e. hammer source **700**, kinetic energy from weight **760** driven by actuator **770** is transferred to plunger **703** by impact, which in turn produces tube waves in port **710**. Specifically, in the illustrated embodiment, a plunger **703** is provided across a top wall **711** of the port **710**. A seal **707** is provided between the plunger **703** and the top wall **711** to prevent the port **710** from being in fluid communication from the outside. A bearing **714** can be optionally included to improve the stability of the plunger **703** in the top wall **711** and to reduce pressure pulsations seen by seal **707**. A spring **704** is provided to push the plunger in a resting position where the bottom of the plunger is substantially adjacent to the top wall **711** of the port **710**. Optionally, a vented washer **705** is provided between the bottom of the plunger **703** and the top wall **711** to eliminate the suction created by the bottom of the plunger **703** on the top wall **711** when the plunger **703** moves during firing.

[00104] In operation, the actuator **770** causes the weight **760** to move rapidly towards the top of the plunger **703**. Upon impact, the kinetic energy from the weight **760** is

transferred to the plunger **703**, causing the plunger **703** to move downwardly inside the port **710**. The bottom of the plunger **703** pushes the fluids inside the port **710** and generates a positive pulse at the port **710**. This is the firing position of the plunger **703**. Thereafter, the weight **760** is pulled back by the actuator **770** and the spring **704** (as well as the pressure in the port **710**) pushes the plunger back to its resting position. The plunger **703** is now ready for firing again.

[00105] It should be noted that although in the illustrated embodiment in FIG. **10** the spring **704** is provided outside the port **710**, it can also be provided inside the port **710**, for example, at a location currently occupied by the vented washer **705**. In such a case, the spring will exert a downward force on the plunger **703**, which is in turn balanced by the upward force exerted by the pressure in the port **710**. Therefore, with a suitable strong spring, when the plunger **703** is at the resting station, there is zero or a minimal amount of upward forces on the plunger. A relatively smaller amount of impact by the weight **760** can produce an effective dislocation of the plunger **703**.

[00106] FIG. **11** shows a pulse generated by a hammer source comprising an approximately 60 psi tube wave on top of an approximately 540 psi baseline pressure.

[00107] FIG. **12** discloses a hammer source that is pressure balanced. The hammer source **800** comprises a tubular housing **805** that is connected to a cavity **820** on one end and to a port **810** on the other end. In one embodiment, the pressure in cavity **820** is equalized with the pressure in the port **810**. In one embodiment, the cavity **820** is made of elastic materials and/or contains a low bulk modulus fill fluid such as ethyl alcohol, diethyl ether, silicone oil, or similar.

[00108] A flyer **803** is provided within the housing **805**, between the cavity **820** and the port **810**. A set of springs **870**, **871** are provided to keep the flyer **803** generally centered within the housing **805**. In the illustrated embodiment, the flyer **803** is substantially hollow in the center of its body, where a piston **804** is located. In the illustrated embodiment, the piston **804** is substantially in the shape of a cylindrical rod, although other shapes can be used as well. Approximately around the middle of the longitudinal axis of the piston **804**, a circular extension is formed that divides the hollow space inside the flyer **803** into an upper chamber **830** and a lower chamber **840**. A seal **860** is provided between the circular extension and the inner surface of the hollow space inside

the flyer **803** to ensure that the upper chamber **830** is not in fluid communication with the lower chamber **840**.

[00109] An upper flyer port **832** is formed on the side wall of the flyer **803** to connect the upper chamber **830** to the small space located between the housing **805** and the flyer **803**. An upper housing port **831** is formed on the side wall of the housing **805** to connect the small space located between the housing **805** and the flyer **803** to the outside of the housing **805**. Accordingly, the upper chamber **830** of the flyer **803** is in fluid communication with the outside of the housing **805** via the upper flyer port **832**, the small space located between the housing **805** and the flyer **803**, and then the upper housing port **831**.

[00110] Similarly, a lower flyer port **842** is formed on the side wall of the flyer **803** to connect the lower chamber **840** to the small space located between the housing **805** and the flyer **803**. A lower housing port **841** is formed on the side wall of the housing **805** to connect the small space located between the housing **805** and the flyer **803** to the outside of the housing **805**. Accordingly, the lower chamber **840** of the flyer **803** is in fluid communication with the outside of the housing **805** via the lower flyer port **842**, the small space located between the housing **805** and the flyer **803**, and then the lower housing port **841**.

[00111] A seal **890** is provided between the inner surface of the housing **805** and the outer surface of the flyer **803**, at a longitudinal location that is between (1) the upper flyer port **832**/the upper housing port **831**, and (2) the lower flyer port **842**/the lower housing port **841**. Therefore, the flow path to the upper chamber **830** of the flyer **803** is completely separated from the flow path to the lower chamber **840** of the flyer **803**.

[00112] A set of upper seals **837**, **838** is provided between the inner surface of the housing **805** and the outer surface of the flyer **803**, at a longitudinal location that is above the upper housing port **831** to ensure that the fluid injected from the upper housing port **831** flows towards the upper flyer port **832** and enters the upper chamber **830**, instead of leaking off to towards the cavity **820**. An orifice **833** can be optionally included between the upper seals **837**, **838** for lubricating purposes and the like.

[00113] Similarly, a set of lower seals **847**, **848** is provided between the inner surface of the housing **805** and the outer surface of the flyer **803**, at a longitudinal location that is

below the lower housing port **831** to ensure that the fluid injected from the lower housing port **831** flows towards the lower flyer port **832** and enters the lower chamber **830**, instead of leaking off to towards the port **810**. An orifice **843** can be optionally included between the lower seals **847**, **848** for lubricating purposes and the like.

[00114] In operation, the piston **804** can be moved up and down within the hollow space of the flyer **803** by injecting or depleting fluids in the upper chamber **830** or the lower chamber **840** of the flyer **803**. The moving piston then impacts the upper inner surface **835** or the lower inner surface **845** of the flyer **803**, causing the flyer **803** to move up and down to generate tube waves at the port **810**. Motions of the flyer **803** that do not result in impacts can also generate tube waves if they are rapid enough.

[00115] FIG. **13** discloses a method of generating tube waves by pumping objects through an orifice. In the embodiment illustrated, an orifice **940** is provided on an inner surface of a tube **905**. A ball **903** is introduced into the upstream port **920** of the tube **905** towards the orifice **940**, as shown in FIG. **13A**. At this moment, the upstream port **920** is in fluid communication with the downstream port **910**, although with some restrictions caused by the orifice **940**. Thereafter, the ball **903** reaches the orifice **940** and obstructs the flow path of the fluid from the upstream port **920** to the downstream port **910**, as depicted in FIG. **13B**.

[00116] The pressure in the upstream port **920** then increases, forcing the ball **903** to deform and partially pass through the orifice **940**, as shown in FIG. **13C**. Then, with a slightly further increase of the pressure in the upstream port **920**, the ball **903** is popped free into the downstream port **910**, creating a positive tube wave at the downstream port **910**, as illustrated in FIG. **13D**. An exemplary pulse was recorded and shown in FIG. **14**, where a tube wave of approximately 1000 psi was generated on top of a 3000 psi baseline at the end of 12,000 feet of tubing. The bottom two traces show the tube wave generated while the top trace shows pumping pressure. The first spike on the bottom two traces indicated the ball landing in the orifice. The second spike in the bottom two traces indicated the ball popping through the orifice. In FIG. **14**, HS1 indicated a piezoelectric high speed pressure transducer that only responds to changing pressures; it does not measure continuous pressure. HS1 was illustrated as the bottom trace that was always close to zero. HS1 was located at the outlet of the well, as was the conventional pressure transducer V1 (middle trace). Conventional pressure transducer

V3 (top trace) was located at the inlet to the coiled tubing reel; it observed pump strokes and was around 11,774 feet from the orifice. The first small peak in HS1 and V1 indicated the ball landing in the orifice. When the wave front from the flow stopping reaches the inlet to the coiled tubing, the pressure started to rise (the big hump). The next sharp negative spikes on the bottom two traces were the ball popping through. It took a while for the other end of the coiled tubing to observe the release of pressure.

[00117] It should be noted that the orifice may be located at the surface, downhole, or both. Multiple orifices may be used in parallel to allow higher flows before landing balls. Although ball shaped objects are illustrated in FIG. 13, objects of other shapes may be used as well. Moreover, crushable and/or hollow objects may be used to increase the pulse generated and/or avoid leaving objects in the well. In one embodiment, degradable balls such as the collagen “bioballs” used as sealers in fracturing operations are used, and the balls are fed into the tube by a traditional fracturing ball dropper. The tube wave creation can be conducted at the surface, at the end of a coiled tubing, or at the end of a drill pipe. Other variations are also possible and should be considered within the scope of the current application.

[00118] FIG. 15 discloses a stinger **1003** that is specially suited for providing tube waves when a free surface **1015** is available. In the illustrated embodiment, the stinger **1003** comprises a string of tubes (such as PVC pipes) that is connected to a piece of surface equipment (such as an actuator) on one end and hangs freely inside a wellbore on the other end. In the illustrated embodiment, an actuator **1080** is configured to move the stinger **1003** up and down, and the stinger end **1004** has an enlarged cross-sectional area compared to the remaining portion of the stinger **1003**. Therefore, when the stinger **1003** moves up and down in a wellbore **1001** containing fluids **1002**, tube waves can be produced in the wellbore **1001**. Producing tube waves near free surfaces is particularly difficult because of the limit on negative pressure set by the hydrostatic pressure between the free surface and the tube wave generator. In general, the deeper the tube wave generator can be placed, the larger the amplitude of wave that can be produced.

[00119] Optionally, a first pressure transducer **1009** is provided at the stinger end **1004**, is connected to the surface by a first cable **1011** located inside the hollow center of the stinger **1003**. Also, a second pressure transducer **1012** can be optionally provided at the external surface of the stinger, towards the distal end of the stinger **1003** but upstream

from the stinger end **1004**. The second pressure transducer **1012** is connected to the surface by a second cable **1014**, which may be fastened to the stinger **1003** by clamps **1013**.

[00120] Suspension systems **1086**, **1087** can be optionally included to provide compliance for the stinger **1003** to move up and down. In one embodiment, the suspension systems **1086**, **1087** are springs. In another embodiment, the suspension systems **1086**, **1087** are air bags. In a further embodiment, the suspension systems **1086**, **1087** are inner tubes.

[00121] FIG. **16** discloses a method of coupling a tube wave source **1103** through a free surface **1115** into a fluid filled wellbore **1114**. In general, the coupling device comprises a string of tubes **1102** that has two ends: the first end is connected to the wave source **1103** located on the surface of a wellsite; the second end is hanging freely in the fluid of the wellbore **1114**. In one embodiment, the second end of the tube **1102** comprises an expandable bag **1105**, which can expand or contract depending on the pressure inside the bag **1105**. In one embodiment, the tube **1102** is filled with fluid that is introduced by a pump **1108** through a valve **1107** from a reservoir **1106**, all located on the surface of a wellsite. A valve **1009** can be optionally included to release air or excessive pressure in the tube **1102**. A vacuum pump (not shown) can also be optionally included to facilitate the process of filling the tube **1102**. The compliance of the bag **1105** allows the pressure at the surface of the tube wave source **1103** to be higher than it would be if the tube were open ended. In the event of a free surface **1115** that is much lower than the height of the tube wave source **1103**, the negative pressure that could be generated at the surface of the tube wave source **1103** would be severely limited by cavitation of the working fluid. In the case of water as a fill fluid in the tube, the free surface **1115** must be much less than 32 feet below the tube wave source **1103** for it to produce useful tube waves without the presence of the bag **1105**.

[00122] In one embodiment, the fluid in the tube **1102** is the same as the fluid in the downhole **1110**. In another embodiment, the fluid in the tube **1102** is slightly lower in density compared with the fluid in the downhole **1110**. When the tube wave source **1003** is fired, a tube wave propagates down tube **1102** and causes bag **1105** to expand and contract, therefore coupling the tube wave source to the wellbore **1114**. Optionally, a partial or complete seal (not shown) between the wellbore and the tubes **1102** may be

provided above bag **1105**. Optionally, a pressure transducer **1111** may be attached to tube **1102** with cable **1113** optionally attached to tube **1102** by device **1112**.

[00123] FIG. **17** shows the effect of using a long, tubular chamber whose tube wave transit time is comparable to the physical length of the pressure pulse. This is directly analogous to electrical transmission lines. In general, it is not desirable to have the pulse length and the chamber length to be comparable, as optimized storage chambers are generally larger in diameter than the conduit connected to them and tend to have a chamber length less than 20 to 30 times their bore. Such a structure would be used to produce tube waves of a particular shape. If this is desired, an optimized storage chamber may be placed at one or more locations along a length of normal pipe suited to this service. Appropriately placed changes in impedance of the outlet pipe may also be used to perform this sort of wave shaping. FIG. **17A** shows the physical location of the pressure transducers **1**, **2**, **3**, and **4**. A fast valve is disposed between transducers **1** and **2**. The length of pipe leading to transducer **3** is shorter than that leading to transducer **4**. The closed pipework containing pressure transducers **2**, **3**, and **4** is pressurized to **P0**. The outlet pipe is pressurized to pressure **P1**. The graph shows the four pressure traces vs. time. The fast valve is opened at time **T1** and is assumed to open in a period much less than the time between **T1** and **T2**. When it opens, there is an immediate rise in pressure at transducer **1**, to level **P2** and a corresponding drop in transducer **2** down to level **P2**. The pressure wave travels toward transducers **3** and **4** as the fluid expands, indicated schematically by the arrows. At time **T2**, the pressure wave reaches transducer **3** and its pressure drops to level **P2**. A reflected wave returns from transducer **3** toward transducer **2**. Similarly, the initial wave reaches transducer **4** at time **T3**. When this happens, the pressure falls to **P2** and a reflected wave returns. When the reflected wave from transducer **3** reaches transducer **2** the pressure falls to **P3**, which is still above **P1** due to continued fluid flow. This produces another reflected wave into the pipe to transducer **4**. When the first reflected wave from transducer **4** reaches transducer **2** at time **T5**, the pressure drops to **P4** (which will be equal to **P1** if the outlet pipe system is much larger than the storage volume), as the flow out of the system has stopped temporarily. The first reflection from transducer **3** into the line to transducer **4** produces the short pulse seen between **T7** and **T9** on transducer **2**. Other, smaller reflections may be present but are not shown. Diagrams similar to these are familiar to those skilled in the art of modeling electrical transmission lines. The methods

of modeling transmission lines may be directly applied to tube wave lines once this analogy is understood.

[00124] FIG. **18** discloses a number of arrangements that can be used to fine tune the generation, delivery, and/or propagation of tube waves, based on the underlying similarity between tube waves and electromagnetic waves in transmission lines. These relationships are not generally known and more importantly, the physical configurations of the tube wave analogues to electrical transmission lines are not previously known as such. Figure 18A discloses the tube wave equivalent of a transmission line terminated with a capacitor at its upper end. The tube wave system that has this behavior is a compliant chamber at the end of a pipe. Compliance may be provided by a cavity filled with the tubing fluid (as shown on the left) or an accumulator (as shown on the right). FIG. **18B** shows the tube wave equivalent of a transmission line terminated with a shorted end; a closed end pipe. FIG. **18C** shows a slug of material **1330** with a density that is higher than the fluid hardware and transmission lines. The slug **1330** is configured to be able to move up and down inside the tube **1301** with the pulsation of the tube waves. In one embodiment, the slug **1330** is used to produce a lumped equivalent of an inductance placed between two transmission line segments, in a tube wave system.

[00125] FIG. **18D** shows a tube **1301** having a free surface **1340** near the top of the tube **1301**. The free surface **1340** functions equivalently to an open circuited end on a transmission line. By way of example, a positive tube wave impinging on this boundary will rebound as a negative tube wave. In the case of a transmission line, a positive pulse impinging on an open-circuited transmission line end will reflect as a negative pulse.. FIG. **18E** shows a tube **1301** having a reduced diameter towards a section **1350** further downstream from the surface, therefore creating a shoulder **1351** which may function as a reflector and as an attenuator. Tube waves coming from side **1301** will be strongly reflected off of the step in diameter **1351** and only part of the wave amplitude will pass into the smaller section **1350**. The transmission line analogy is a junction between two transmission lines of different characteristic impedance, such as a 75 Ohm line connected directly to a 50 ohm line. Just as in the transmission line world, the larger the step or change in characteristic impedance, the better the reflection and the less signal passes through. FIG. **18F** shows a different version of FIG. **18E** where the transition from the tube **1301** to the downstream section **1360** is by way of a slanted surface **1361**

instead of a shoulder **1360**. This structure is equivalent to two transmission lines of different impedance (as above), but coupled together by a matching transformer. With an appropriate transformer, the wave may be made to transition across the change in impedance without reflection and without energy loss. There will be a concurrent shift between pressure and velocity due to the different impedances, in the same manner that the transmission line matching transformer trades between voltage and current to keep the same power level on both ends. The efficiency of this section increases as the length of the transition increases, with little transformer action seen for transitions less than $\frac{1}{4}$ wave length.

[00126] FIG. **18G** shows a porous material **1370** inside the tube **1301**. The porous material **1370** provides a lousy reflector, in a manner similar to two transmission lines connected together with a resistor. FIG. **18H** shows a tube **1301** having a perforation **1381** formed on the side wall of the tubing **1301**. In the illustrated embodiment, the perforation **1381** is connected to an enlarged area of enclosure **1380**, which resembles a subterranean formation under hydraulic fracturing, for example. This provides a lousy reflector in a slightly different configuration and is equivalent to two transmission lines joined together with a load resistor placed across the transmission line terminals. FIG. **18I** shows a side branch **1391** connected to a pipe **1301** through a full-bore port **1391**. This is electrically equivalent to two transmission lines joining with a third stub line. In this case the stub line would be open circuited. Such structures can be used to provide impedance matching at specific frequencies and or to provide a frequency selective reflector. They are also referred to as stub filters.

[00127] FIG. **19** discloses a number of exemplary terminators that can be used to attenuate tube waves after use or reduce their reflections. Embodiments disclosed herein may be applicable in attenuating pulsations in hydraulic fracturing operations where excessive pulsations in the fracturing fluids may be damaging to the pump system. Such terminators are equivalent to the terminating resistors or terminating systems commonly employed in transmission line systems to avoid end reflections.

[00128] Specifically, FIG. **19A** shows a tube **1401** having a closed end **1414**. Two types of particles are mixed together and packed into the space created by the closed end **1414** and the side walls of the tube **1401**. The first type of the particles is dense particles **1412**. The second type of the particle is compressible particles **1411**. The

dense particles **1412** can rub against each other and the inner wall of the tube **1401**. The compressible particles **1411** allow the pack to move back and forth within the tube **1401** and absorb the pulse energy. In one embodiment, the compressible particles **1411** are spheres of low bulk modulus. In another embodiment, the compressible particles **1411** are encapsulated alcohol or rubber balls. In a third embodiment, the packing density of one or more particles is caused to vary from very densely packed at the closed end **1414** to low density at the opposite end. Such a structure would minimize reflections even in the instance that the characteristic resistance of the pack is not equal to the characteristic impedance of the tube wave conduit. Other variations can also be used, and should be considered within the scope of the current disclosure. The key characteristics being the ability to absorb energy and having porosity.

[00129]In FIG. **19B**, a tube **1401** terminates upon a cavity **1424**. The cavity **1424** as illustrated in FIG. **19B** is in a spherical shape, although other shaped cavity can be used in the current application as well. A compliant fluid can be used to fill up the cavity **1424**, such as air, alcohol, etc. A porous plug **1421** is provided inside the tube **1401**, at a location proximate to the cavity **1424**. The porous plug **1421** can be made of a porous material commonly known in the art. The porous plug **1421** together with the compliance material in the cavity **1424** can function as an effective terminator of tube waves. In a further embodiment, the compliant cavity can comprise an accumulator to reduce the required volume of the system. Such a system is equivalent to a transmission line terminated with a series combination of a resistor and a capacitor. Such a terminator has a frequency response characteristic that is attenuates high frequencies and does not attenuate low frequencies. With a large capacitor (or equivalently a large compliant volume), this system will not attenuate constant pressures but will strongly attenuate varying pressures.

[00130]FIG. **19C** shows another tube wave structure. There, an orifice **1431** is created inside the tube **1401**, which only allows a portion of the fluid to pass from an upstream chamber **1432** to the downstream chamber **1433**. When the fluid flows sufficiently fast, and/or when the orifice **1431** is of a give size, cavitation **1435** is created behind the orifice **1431**. This cavitation **1435** is effective in blocking tube waves traveling from the downstream chamber **1433** towards the upstream chamber **1432**, but not tube waves traveling in the reverse direction. By varying the flow rate and/or the orifice size, this structure may be made to either allow passage or block passage of tube waves in one

direction while always passing tube waves in the other direction. Electrically, this structure is similar to either two transmission lines coupled by a diode in series, or a directional coupler

[00131] FIG. 20 illustrates another source of tube waves that involves an imploding device such as a canister 1500. In the depicted embodiment, a simple canister 1500 in the cross-sectional view includes a hollow body 1502 which defines an inner chamber 1504. The chamber 1504 may be a vacuum, or be filled with gas at zero to low pressure. The canister body 1502 can be made from any crushable and/or drillable material, such as frangible glass, tempered glass, or ordinary glass. In one embodiment, the canister body 1502 is a glass centrifugal tube. Although in FIG. 20 a tubular body is depicted, spherical and other shapes may be utilized. In particular, canister shape may be selected for ease of movement within the well, and also for producing particular acoustic characteristics.

[00132] The illustrated canister body has an opening 1507 adapted to receive a pressure rupture disk 1508. The opening may be threaded such that a pressure rupture disk with a threaded holder can be mated in the field to yield a canister of selected implosion value. Alternatively, the disk 1508 is securely fastened to the opening 1507 of the canister 1500 by a layer of glue 1506, cement, solder, or other attachment methods familiar to those skilled in the art. Weighing materials 1505 such as bauxite or lead beads can be packed in the canister chamber 1504 to increase the weight of the canister 1500 so it may descend in the wellbore fluid without making the assembly difficult to drill with ordinary well drilling tools.

[00133] Several different types of rupture disks 1508 were tested. In some cases, the rupture disks 1508 were microscope cover slips. In some other cases, the rupture disks 1508 were plastic lids. In some additional cases, the rupture disks 1508 were ceramic disks. In some further cases, the rupture disks 1508 were glass disks or heavy glass disks. Among all the disks tested, microscope cover slips performed exceptionally well because of their precise thickness and consistently high quality.

[00134] FIG. 21 shows an example of data gathered by using a centrifuge tube covered by a microscope slide. The yellow trace was recorded by a surface hydrophone; the black trace is recorded by a DVS sensor.

[00135] The preceding description has been presented with reference to some illustrative embodiments of the Inventors' concept. Persons skilled in the art and technology to which this application pertains will appreciate that alterations and changes in the described structures and methods of operation can be practiced without meaningfully departing from the principle, and scope of this application. Accordingly, the foregoing description should not be read as pertaining only to the precise structures described and shown in the accompanying drawings, but rather should be read as consistent with and as support for the following claims, which are to have their fullest and fairest scope.

We claim:

1. A system comprising:
an energy storage chamber;
a fast operating valve connected to the energy storage chamber;
a pipe connected to the valve and extending to a liquid-filled borehole penetrating a subterranean formation;
wherein said energy storage chamber contains a first pressure that is substantially different from a second pressure in the borehole so that a fast operation of the valve generates a tube wave in the liquid-filled borehole.
2. The system of claim 1, wherein the energy storage chamber contains a compressible medium selected from the group consisting of air, nitrogen, alcohol, diethyl ether, water, silicone, hydrocarbon oil, and mixtures thereof.
3. The system of claim 2, wherein the energy storage chamber comprises a plurality of accumulators connected to a common hub, with each accumulator containing a fraction of a desired pressure.
4. The system of claim 1, wherein the fast operating valve is configured to open or close a flow path of the medium through the valve in a time that is between about 1-3 times of a firing duration of the tube wave.
5. The system of claim 4, wherein the fast operating valve is configured to open or close a flow path of the medium through the valve in less than or equal to approximately 500 milliseconds.
6. The system of claim 5, wherein the fast operating valve is configured to open or close a flow path of the medium through the valve in approximately 120 milliseconds.
7. The system of claim 1, wherein the fast operating valve is a rotary valve that operates on a quarter turn.
8. The system of claim 1, wherein the valve is a regenerative valve, said regenerative valve having a moving element disposed therein, said moving element having a first area that is exposed to a first port and a second area that is exposed to a

second port, wherein said first area is different from the second area so that the moving element is held in a closed position upon the second port until an external force is applied to push the moving element away from the second port, wherein one of the first pressure in the first port and the second pressure in the second port functions on one of the first area and the second area to push the moving element to a fully opened state.

9. The system of claim 6, wherein the valve is a regenerative valve comprising a control chamber, a treating chamber disposed below the control chamber but not in fluid communication with the control chamber, and a poppet that extends from the control chamber to the treating chamber and is capable of reciprocating within the control chamber and the treating chamber.

10. The system of claim 9, wherein the treating chamber is connected to the energy storage chamber via an upstream port and the fluid-filled borehole via a downstream port.

11. The system of claim 10, wherein the poppet comprises a control piston disposed inside the control chamber, a treating seat disposed inside the treating chamber, and a stem connecting the control piston and the treating seat.

12. The system of claim 11, wherein the control piston is a monolithic component of the poppet.

13. The system of claim 11, wherein the control piston is a separate component from the poppet, and the control piston is slidably connected to a narrowed stem of the poppet and is further restricted by a stopper fastened to a top of the poppet.

14. The system of 10, wherein the treating seat is configured to engage a structure at the juncture of the downstream port and the treating chamber and seal off a fluid passage from the treating chamber to the downstream port.

15. The system of 10, wherein a buffering chamber is provided above the control chamber but not in fluid communication with the control chamber; the poppet extends from the buffering chamber through the control chamber to the treating chamber and is capable of reciprocating within the buffering chamber, the control chamber, and the

treating chamber; and the poppet contains a hollow passage so that the downstream port is in fluid communication with the buffering chamber.

16. A fast regenerative valve for generating tube waves, comprising a moving element disposed in the valve, said moving element comprises a first area facing a first port, a second area facing a second port, a first seal disposed above the first port and a second seal formed with the second port, wherein the first seal and the second seal have a substantially similar profile.

17. A fast regenerative valve of claim 16, wherein one of the first area and the second area is zero.

18. A method for generating tube waves in a liquid-filled borehole penetrating a subterranean formation, the system comprising:

- connecting an energy storage chamber with a fast operating valve;
- connecting the fast operating valve to the liquid-filled borehole;
- charging the energy storage chamber to a first pressure that is substantially different from a second pressure in the borehole;
- conducting a fast operation of the valve to generate a tube wave in the borehole.

19. The method of claim 18, wherein the fast operating valve is configured to open or close a flow path of the medium through the valve in a time that is between about 1-3 times of a firing duration of the tube wave.

20. The method of claim 19, wherein the fast operating valve is configured to open or close a flow path of the medium through the valve in less than or equal to approximately 500 milliseconds.