This invention relates generally to the control of well fluid flow, and more particularly concerns apparatus and method for providing remote automatic operation and control of a retrievable valve assembly within production tubing to control production fluid flow.

Past efforts to provide control of production flow at sub-surface locations in well tubing have resulted in the provision of valves connected in the tubing string and operated from the surface by transmitting pressure changes through auxiliary control lines. The latter are connected to the sub-surface valves, generally in the form of predetermined actuating devices subject to damaging contact with the well bore during running of the tubing into the well. Another disadvantage with such a system lies in the fact that the valve is commonly connected in the tubing and hence cannot be inspected, repaired or otherwise made accessible without pulling the tubing from the well.

The present invention is founded upon the fundamental insights and objectives that a sub-surface valve may be operated without use of exterior control lines, and may be made subject to remote automatic operation in response to a decrease in string interior pressure, and independently of pressure in the string or annulus, the valve being retrievable, and further that the plug in such a valve may be displaced out of the straight path of fluid flow therethrough, allowing other tools to be run in the string through the valve.

In its method aspects, the invention basically contemplates the performance of steps that include running a fluid pressure operable valve and actuator assembly downwardly within a tubing string to an operating location, the assembly being operable to control the upward flow of fluid within the string, and communicating to the assembly at said operating location the pressure of control fluid locally contained outside the string bore for conditioning the assembly to operate in response to predetermined decline of internal or production fluid pressure relative to control pressure. Typically, the pressure of fluid within the string constitutes the pressure of upwardly flowing production fluid exerted on the actuator in one direction, while control fluid pressure is locally contained in an accumulator situated outside the string bore to receive pressure from the production fluid, the control pressure to be transmitted into the string and to the actuator in a direction opposite to said one direction.

In one method of operation, the valve is run down the tubing and then operated to reduce the upward flow in response to fluid displacement following a predetermined reduction of production fluid pressure relative to control fluid pressure. This method has the primary advantage that the valve will close to shut in the well in the event of sudden reduction of production fluid pressure, as for example might occur in an off-shore installation where the production tubing was severed in the ocean, the control fluid pressure then automatically acting on the actuator to close the valve independently of fluid pressure in the well annulus. Also, provision is made for automatically recharging the accumulator with the pressure of production fluid, avoiding problems of slow leakage from the accumulator and also avoiding the need for pulling the tubing in order to recharge the accumulator. Further, the valve is retrievable at any time, without pulling the tubing.

Additional features and advantages of the method include the preliminary step of establishing a barrier outside the string and below the valve operating location, the provision for running or establishing the tubing string in a well without need of connecting auxiliary pressure fluid control lines thereto, the provision for retrieving the valve assembly at any time, allowing the accumulator control pressure to equalize with production fluid pressure, and the provision for straight vertical communication entirely through the installed valve assembly in open condition thereof, as will be seen.

As to equipment, the basic apparatus is connectible in a well tubing string and includes a tubular body having flow porting and a flow control member movable to control the upward flow of production fluid in the porting, the apparatus including fluid pressure differential responsive actuator structure with piston surfaces located for exposure to production fluid pressure and control fluid pressure so as to respond to a relative change in the differential between said pressures to effect said member movement, and the apparatus forming a control chamber outside said flow porting to contain said control fluid pressure.

In one form of the apparatus, the member comprises a ball, a ball seat is formed about the porting, and a tubular body has a side opening sized to pass the ball during its movement between seated and unseated positions, whereby the ball may have an unseated position outside a cylinder defined by the bore of the actuator structure, providing an uninterrupted straight line path of communication vertically through the valve assembly. Other forms of flow control members include gates, sleeves and rotary balls having through ports.

The invention has as another object the provision of a novel and unusual combination that includes the retrievable valve assembly together with a tubular sub connectible in a well tubing string to receive the valve assembly, the sub having an inlet port located to communicate control pressure from the exterior accumulator to a piston surface of the valve actuator structure when the valve assembly is landed in the sub. Where the landed assembly has a ball plug, the sub is typically provided with a bore enlargement to receive the ball in unseated position and outside the bore of the tubular actuator. Also, the latter may have a ramp to guide ball travel through the side opening in the actuator and into the sub enlargement; and the sub may also contains, as for example a novel pusher and guide, to trap the ball and also to recapture the ball back through the side opening into the tubular actuator in response to upward displacement of the latter relative to the sub.

These and other objects and advantages of the invention, as well as the details of an illustrative embodiment, will be more fully understood from the following detailed description of the drawings, in which:

FIG. 1 is a view showing a well tubing string into which the apparatus may be run, together with surface controls for operating the valve;

FIGS. 2a and 2b are vertical sections showing the apparatus after landing of the valve assembly in a sub in the string, the valve ball being unseated and the valve fully open;

FIGS. 3a and 3b are vertical sections showing the apparatus with the valve assembly landed in a sub in the string, the valve ball being seated and the valve fully closed;

FIG. 4 is a horizontal section taken on line 4—4 of FIG. 2a;

FIG. 5 is a horizontal section taken on line 5—5 of FIG. 2b; and

FIG. 6 is a vertical fragmentary section of a modified form.
Referring first to FIG. 1, apparatus is shown at 100 as connected in a production tubing string 11 which extends within the well to the valve block 12. The latter extends upwardly to the well head where it mounts the control equipment generally designated at 13. Such equipment includes a main valve 14 for controlling the upward flow through the tubing, and a production flow control valve 15 in line 16. The well annulus is seen at 19.

Control equipment 13 also includes a flexible line 20 through which fluid pressure may be pumped at 21 downwardly into the string 11 via the intermediate structure generally designated at 22; the latter includes shut-off valves 23 and 24 at opposite sides of a releasable coupling 25 through which access may be had to the interior of the control 26 in order to insert and remove equipment as will be described, such apparatus including the retrievable valve assembly and running tool thereafter.

Referring now to FIGS. 3a and 3b, the apparatus 100 includes a sub 10 and retrievable valve assembly there illustrated to include what may be generally characterized as flow passing first means 35 sized to be run in the tubing 11 and to be landed at a predetermined location such as within sub 10. The means 35 may include upper and lower tubular body sections 37 and 38 having threaded interconnection at 39, and below the connection a flow port forming the annulus 40 is tapered to seat and annularly fit a ball plug 41.

Plug 41 is carried by the tubular body for movement between a seated position, such as seen in FIG. 3b, in which the plug blocks upward flow through the body section 37, and an unseated position such as is viewed in FIG. 2a. In the latter condition, the plug is offset from the seat 40 to unblock the upward flow. The seat structure may also be considered to include a non-metallic annulus 36, as for example rubber or molded tetrafluoroethylene, located to seal the reduced space formed between the seated ball and metal annulus 40 in response to fluid pressure exertion there against the seat 40. Also, the assembly is shown to include a rigid anchor member 52 of metal and connected as by bonding to the non-metallic seal 36, for retaining the seal in position against extreme fluid pressure tending to displace it.

The first means 35 also carries fluid pressure differential responsive actuator structure 33 carried for movement lengthwise of the string to effect displacement of the plug between its seated and unseated positions. Such actuator structure typically has piston surfaces, above the valve member, and respectively located for exposure to production fluid pressure and control fluid pressure so as to respond to a relative change in the said pressures to effect movement of the actuator structure in opposite directions lengthwise of the string. Thus, for example, a piston surface 141 on actuator ring 42 is exposed to control fluid pressure communicated from the interior 119 of an accumulator 101 through a side inlet 31 in the sub 10 to the stepped bores 43 and 44 of the sub between annular seal 45 and ring 48. Seal 45 is sandwiched between and bonded to rings 42 and 47 to seal on larger bore 43, whereas seal ring 48 is fitted on body section 37 and against smaller sub bore 44 to slowly and controllably leak control fluid pressure thereby. Accumulator 101 is formed by a shell 102 and sub 10 spaced inwardly therefrom at 119, the shell and sub being connected at 103 and 104.

A tubular spacer 50 extends between rings 45 and 42 and is subjected to fluid pressure communicated through said sub including, accordingly, the sub control fluid pressure exerts a net upward force on actuator piston surface 141 tending to drive the tubular sections 37 and 38 upwardly towards valve seated position. Such upward displacement is opposed by the net pressure of fluid within the string acting downwardly on the actuator and, additionally, the surfaces of the stepped bores 44 and 43; and tending to drive the sections 37 and 38 bodily downwardly toward valve open or unseated position as seen in FIG. 3b. Accordingly, since the areas of surfaces 51 and 141 are substantially equal, the actuator will be in equilibrium when the interior and control fluid pressures exerted thereon are equal, and the ball plug will remain in open condition as seen in FIG. 2b due to the friction of seal 45 on bore 43, and weight of the ball and body sections 37 and 38. On the other hand, should the interior or production fluid pressure decline below the slowly leaking control fluid pressure, the sub surface actuator will respond and move up to shut the valve.

When the ball plug moves between the seated position of FIG. 3b to the unseated position of FIG. 2b, it passes through a side opening 53 in the body section 38. Typically, the section 38 carries a downwardly and laterally inclined ramp 54 to guide the ball as it gravitates away from the downwardly facing seat structure and through the side opening 53. When the ball is in the fully unseated position seen in FIG. 2b, it is received in an annular bore enlargement or side pocket 55 formed within the bore 56 of the sub 10, the ball position then being characterized in that it is substantially completely outside a flow stream cylinder defined by the reduced bore 57 of the body section 38. Accordingly, a fully open vertical passage is provided through the valve assembly, including bore 63, to pass wire line equipment as well as the well fluid.

As will appear, second means 35 sized to be run in the sub to trap the ball plug partly in the enlargement and partly in opening 53, and to urge the ball back through that side opening in response to upward displacement of the tubular body sections 37 and 38 relative to the sub. Thus, for example, such means may take the unusually advantageous form of a ramp surface 58 at the upper portion of the enlargement, and a pusher lip 59 at the outer terminal of ramp 54 for urging the ball toward guide surface 58 in response to upward displacement of body section 38. Guide surface 58 is upwardly tapered with lesser angularity with respect to the ball side of the ramp surface 58 than the ramp, in order that the ramp and guide may cause to urge or pinch the rising ball back through the side opening 53. Guide surfaces 58 may typically have about 30 degree angularity with respect to axis 60, whereas ramp 54 may have about 60 degree angularity with respect to that axis. In FIG. 2b, the ball 41 is thus moved laterally into enlargement 55 and is then trapped in position between ledge 61 and lip 62 of body 38. When the body section 38 thereafter rises for closing the valve, the lip 59 pushes the ball to engage the guide surface 58. The bore diameter of body 38 at 63 is less than the diameter of ball 41 to prevent the ball from differential between the ball and the ramp, in order that the guide and ramp may cause to urge or pinch the rising ball back through the side opening 53.

Referring now to FIGS. 3a and 3b, the retrievable valve assembly includes a collet 65 having a series of circularly spaced flexible fingers 66 carried by a collet ring 67. The latter is carried about body section 37, which is shiftable vertically relative thereto as is clear from a comparison of FIGS. 2a and 3a. Collet fingers 66 project upwardly through slots 266 in the flanged head 267 of body section 37. In this regard, a spacer ring 68 is also provided on section 37 directly below collet ring 67 for engagement with the sub at landing location 69. Fingers 66 have outwardly projecting jaws 70 urged outwardly by the spring fingers for reception in an annular groove sunken in the sub bore 56, whereby the collet anchors the valve assembly to the sub following its landing therein.

The apparatus also includes means to communicate production fluid pressure to the accumulator chamber interior 119, but to controllably block escape therefrom of fluid pressure. Such a means is side passage 105 in body 10 to communicate between flow porting or bore 56 of the sub 10 and the chamber interior 119, and a check valve 106 controlling that passage. This allows the chamber interior 119 to be charged with control pressure on the order of at least as great as production fluid pressure, and overcomes the problem of recharging the accumulator, after pulling the string. At the same
time, ring 48 allows flow and controllable leakage of pressure from the chamber interior 119. Also, the apparatus includes additional means to communicate fluid pressure therethrough from the exterior to the camber interior, but to block escape therethrough of fluid pressure within the accumulator. Such additional means may include a second side passage 107 in the sub body 10 and running to the exterior, plus a second check valve 108, such as a Zerk type fitting, controlling passage 107. As a result, chamber interior 119 may be pre-charged with control pressure, as for example nitrogen, at the surface before the valve is closed.

Basically, the method of operation to control vertical flow of fluid in an installed well tubing string includes running the apparatus downwardly within the installed string to an operating location, and communicating to the actuator at that location the pressures of fluid within the string and within the accumulator for conditioning the actuator to operate in response to a predetermined decline of string internal pressure relative to the control pressures. In this regard, the string may be run into the well with the valve assembly, less the ball, in FIG. 2 position, thereby blocking complete release of pre-charged control pressure from accumulator interior 119 via port 31 and past ring 45. If desired, production fluid may be circulated downwardly through the packer and up through the tubing to remove mud upwardly from the interior of the string. Arrow 17 in FIG. 1 shows the supply of production fluid to the annulus 19 to establish such circulation. The valve assembly is then retrieved by a wire line tool indicated at 110 in FIG. 2a, the ball 41 is inserted and held off the seat 40 by the tool, and the valve assembly is run back in. While the valve assembly is removed, well production fluid pressure equalsizes with control fluid pressure in chamber 119 so that when the valve assembly is run back in, a pressure equal to well shut-in pressure is trapped in chamber 119 for control. Production flowing of the well is then started and increased slowly, as by slowly opening surface valve 15; the reason for this is to allow the shut-in pressure in chamber 119 to slowly drop and remain equal to the production flow pressure, which is lower than shut-in pressure, leakage past ring 48 effecting this adjustment, preventing inadvertent closing of the valve. Production fluid in a flowing well normally consists of gas or gas and liquid.

In the described example, the actuator moves upwardly to release the ball and displace it upwardly to close the valve. The flow pressure holding the ball seated. Thereafter, the valve may be re-operated by bringing the entire tubing to overcome the upward forces applied to the ball and actuator, the latter then moving downwardly with the ball, which moves out of the flow stream to become trapped in the side pocket. The friction of seal 45 on bore 43 may be controllable so as to tend to hold the assembly in the position to which it has been displaced. The assembly may be retrieved when desired, without requiring pulling of the tubing. Preliminary to installing the valve assembly, the packer 28 may be set below side inlet 31 in the landing nipple or sub. One such valve packer is shown in John S. Page, Jr., application Ser. No. 333951 filed Jan. 17, 1964 and entitled "Well Tool Apparatus."

In the FIG. 6 modification, the unchanged parts retain the same numbers as used in FIGS. 2 and 3. On the other hand, the upper seal between the insert means 35 and the sub 10 is such as to have controlled leakage, and to include a metal ring 120. The lower seal is non-leaking, and may take the form of two metal rings 121 and 122 with a rubber seal ring 123 therebetween and bonded thereto.

In operation, with the valve closed, i.e. the ball 41 seated at 49, the gas and liquid pressure in the accumulator chamber interior 119 will tend to flow in the hydrostatic pressure in the tubing above the ball. To open the valve, sufficient pressure is suddenly introduced at 21 in FIG. 1 so as to first equalize the pressure at opposite sides of the ball 41, whereupon the means 35 will then move down in the sub 10 and the ball will move to open position. This movement occurs because the increased pressure in the tubing has not had time to leak past ring 120 and into the accumulator chamber interior 119 for upward application to shoulder 141a. Therefore, the accumulator pressure will slowly increase to the pressure in the tubing interior, due to leakage past ring 120. In the event of a sudden fall off of tubing pressure, the valve will shut because the accumulator interior pressure will be higher than tubing pressure for the small time interval necessary to effect valve closure. In this regard, if the accumulator pressure may be within the string, so long as there is controllable leakage of well pressure into and/or from the accumulator.

The above principles and features may also be incorporated in valves including flapper type, sleeve type and rotating ball type valves as for example are disclosed in my concurrently filed co-pending application "Tubing and Annulus Pressure Responsive and Retrieveable Valve."

I claim:

1. In combination, apparatus connectible in a well tubing string and including a tubular body having flow porting and an annular movable member movable to control the forward flow of production fluid in said porting, said apparatus including actuator structure with piston surfaces located for exposure to production fluid pressure and control fluid pressure so as to respond to a relative change in the differential between said pressures to effect said member movement, the apparatus forming a control chamber to contain said control fluid pressure, and said apparatus including means to communicate production fluid pressure to the control chamber interior and to controllably block escape of fluid pressure within the chamber interior.

2. The combination of claim 1 in which said chamber is outside said body and said means to controllably block escape of fluid pressure within the chamber interior comprises a leaking seal.

3. The combination of claim 1 in which said last named means includes a first side passage in said tubular body to communicate between said flow porting and the control chamber interior and a check valve controlling said first side passage.

4. The combination of claim 1 in which said apparatus includes additional means to communicate fluid pressure therethrough from the exterior of said apparatus to the chamber interior, but to block escape therethrough of fluid pressure within the chamber.

5. The combination of claim 4 in which said additional means includes a second side passage in said tubular body to communicate between the assembly exterior and the interior of the chamber, and a check valve controlling said tubular body to communicate between the assembly exterior and the interior of the chamber, and a check valve controlling said second side passage.

6. In combination, a tubular sub connectible in a well tubing string, the sub having a bore, and an assembly operable to control the upward flow of production fluid in said string, said assembly comprising first means sized to be run in the tubing and to be landed in the sub bore, a flow control member carried by said means for movement between increased and reduced flow controlling positions, fluid pressure differential responsive actuator structure carried by said means for movement lengthwise of the string to effect displacement of said member between said positions, said fluid actuator structure comprising fluid surfaces located for exposure to production fluid pressure and control fluid pressure so as to respond to a relative change in the differential between said pressures to effect said member movement, accumulation means carried to be movable with the sub in a well containing control fluid pressure, and means to communicate production fluid pressure to the accumulator interior and to controllably block escape therethrough of fluid pressure within the accumulator, the sub having a side
inlet through which control fluid pressure is communicable from the interior of said accumulator means to one of said surfaces.

7. The combination of claim 6 in which the member comprises a ball plug, said first means forming flow porting and including a ball seat about the porting and a tubular body having a side opening sized to pass the ball during movement thereof between said seated and unseated positions, and said sub forming a bore enlargement to receive the ball in an unseated position thereof characterized in that the ball is then substantially completely outside a cylinder defined by the tubular body bore.

8. The combination of claim 7 in which said first means and sub extend vertically, the seat faces downwardly, and said first means has a downwardly and laterally inclined ramp proximate said enlargement to guide the ball downwardly and laterally away from the seat and through said side opening toward the interior of said enlargement.

9. The combination of claim 8 including second means contained in the sub to trap the ball partly in said enlargement and partly in said side opening, and to urge the ball back through said side opening into said tubular body in response to upward displacement of said tubular body relative to the sub.

10. The combination of claim 9 in which said second means includes a guide at the upper side of said enlargement, and a pusher carried by said tubular body for urging the ball toward said guide in response to said tubular body upward displacement.

11. The combination of claim 6 including flexible collet fingers carried by said first means and having jaws urged outwardly for attaching to the string, said sub having a bore recess to receive said jaws.

12. In sub-combination in an assembly operable to control the upward flow of production fluid in a well tubing string, and wherein a control fluid pressure is to be utilized, the assembly comprising flow passing first means in a tubing string, the improvement which comprises a generally annular seat on said means, a plug carried by said means for movement between a seated position in which the plug blocks upward flow through said means and an unseated position in which the plug is offset from the seat to unblock said upward flow, and fluid pressure differential responsive actuator structure carried by said means for movement lengthwise of the string to effect displacement of the plug between said positions, the actuator structure having piston surfaces respectively exposable to production fluid pressure and control fluid pressure for urging the actuator in opposite directions lengthwise of the tubing, said first means including a tubular body having a bore and side opening to pass the plug between the interior and exterior of the tubular body bore during said movement of the actuator.

13. The sub-combination of claim 12 including a tubular sub having a bore in which said assembly is received, the sub forming a bore enlargement to receive the plug when passed to the exterior of the tubular body bore, the tubular body having an axis and containing a downwardly and laterally inclined ramp to guide the plug laterally away from the seat and through said side opening toward the interior of said enlargement, the sub carrying a guide surface at the upper side of said enlargement and inclined with lesser angularity with respect to said axis than said ramp so that the plug is urged back through said side opening by said guide surface in response to upward displacement of the tubular body relative to the sub.

14. The sub-combination of claim 13 in which the ramp has a lip engageable with the plug when the plug is confined in said sub bore enlargement for urging the plug toward said guide surface in response to said tubular body upward displacement.

15. The method of controlling vertical flow of production fluid in a well tubing string, that includes lowering a production flow control valve and actuator assembly within and relative to the tubing string to a sub-surface location in the string thereby locally confining control fluid pressure in a sub-surface zone for communication to the actuator, maintaining a path for communication of the pressure of production fluid to said zone, while controllably blocking escape of control fluid pressure from said zone to the production fluid outside said zone, and communicating said production fluid pressure and control fluid pressure to said assembly conditioning the assembly to operate in response to a predetermined decline of production fluid pressure relative to said confined control pressure.

16. The method of claim 15 in which said path establishing step is carried out in response to upward displacement of said assembly in the string prior to said lowering step.

17. The method of claim 15 including the step of circulating production fluid upwardly through the string to remove mud therefrom, and then retrieving said assembly upwardly relative to said zone thereby to establish said path.

References Cited
UNITED STATES PATENTS
3,071,151 1/1963 Sizer 166—224
3,090,443 4/1963 Bostock 166—224
3,092,135 6/1963 Brown et al. 166—224

CHARLES E. O'CONNELL, Primary Examiner.
JAMES A. LEPPINK, Examiner.