

[54] **METHODS FOR DETERMINING
VELOCITIES AND FLOW RATES OF
FLUIDS FLOWING IN A WELL BORE**

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[51] Int. Cl.² E21B 47/10[58] Field of Search 73/151, 152, 155, 198,
73/229; 166/66, 250[56] **References Cited****UNITED STATES PATENTS**

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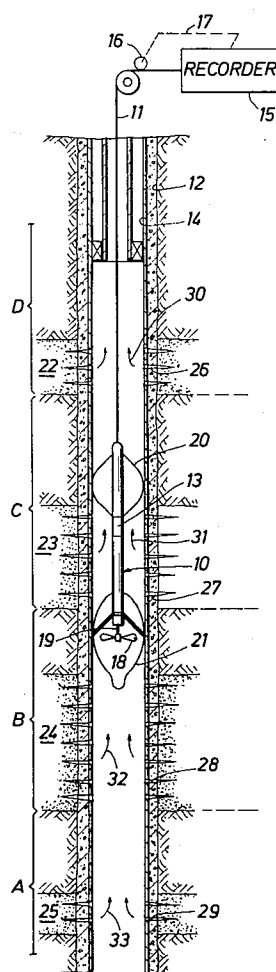
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[57]

ABSTRACT

In the representative embodiments of the new and improved methods disclosed herein, a cable-suspended spinner-type flowmeter is successively raised and lowered at different selected speeds in a well bore containing one or more flowing fluids whose velocity or flow rate are to be determined. In one manner of practicing the invention, output measurements obtained from each of these runs are plotted versus the respective travel speeds at which the tool was moved to uniquely derive one or more correction factors from which the velocity and flow rate of each increment of the well bore fluids can be accurately determined.

21 Claims, 6 Drawing Figures

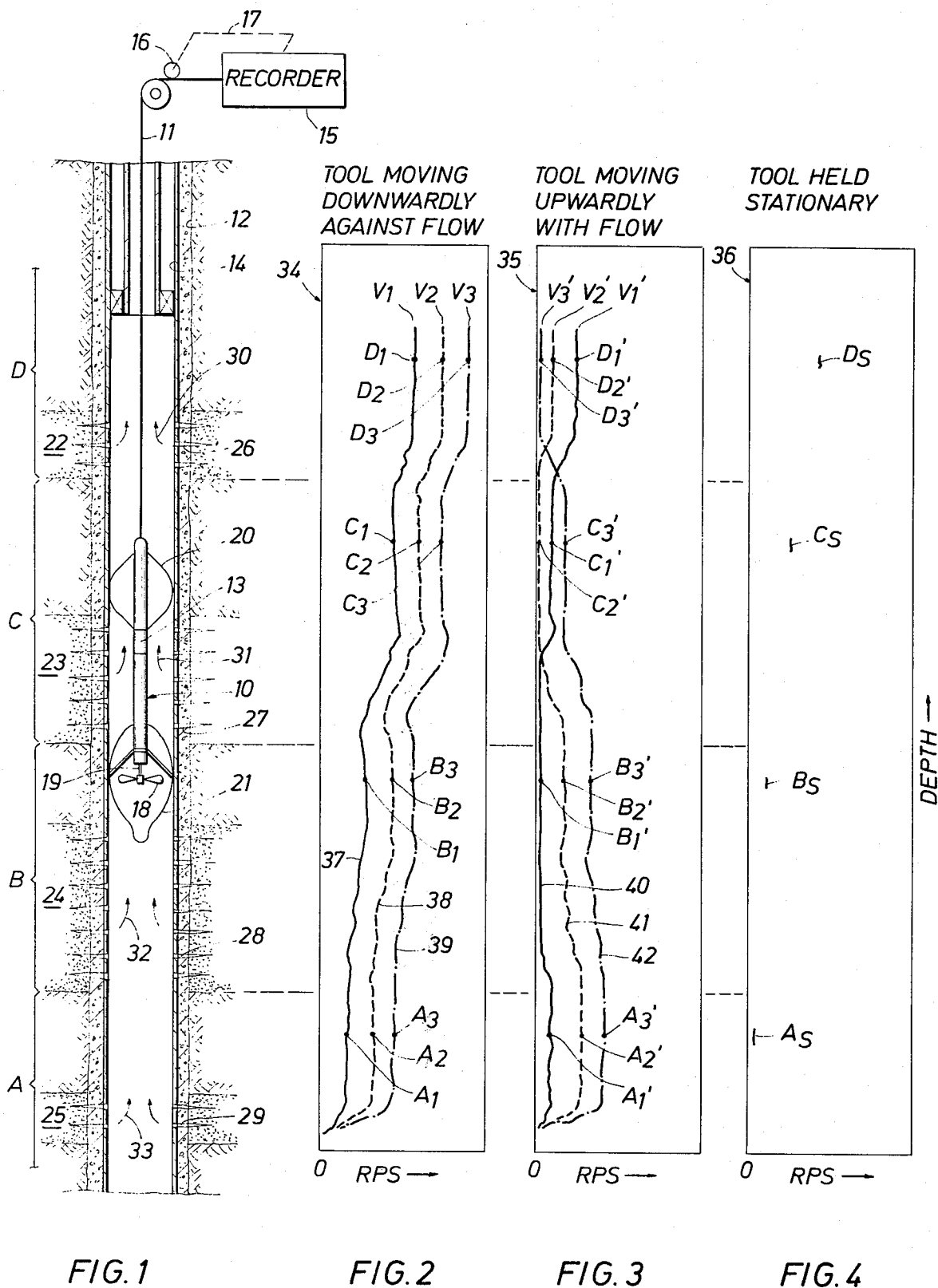


FIG. 5

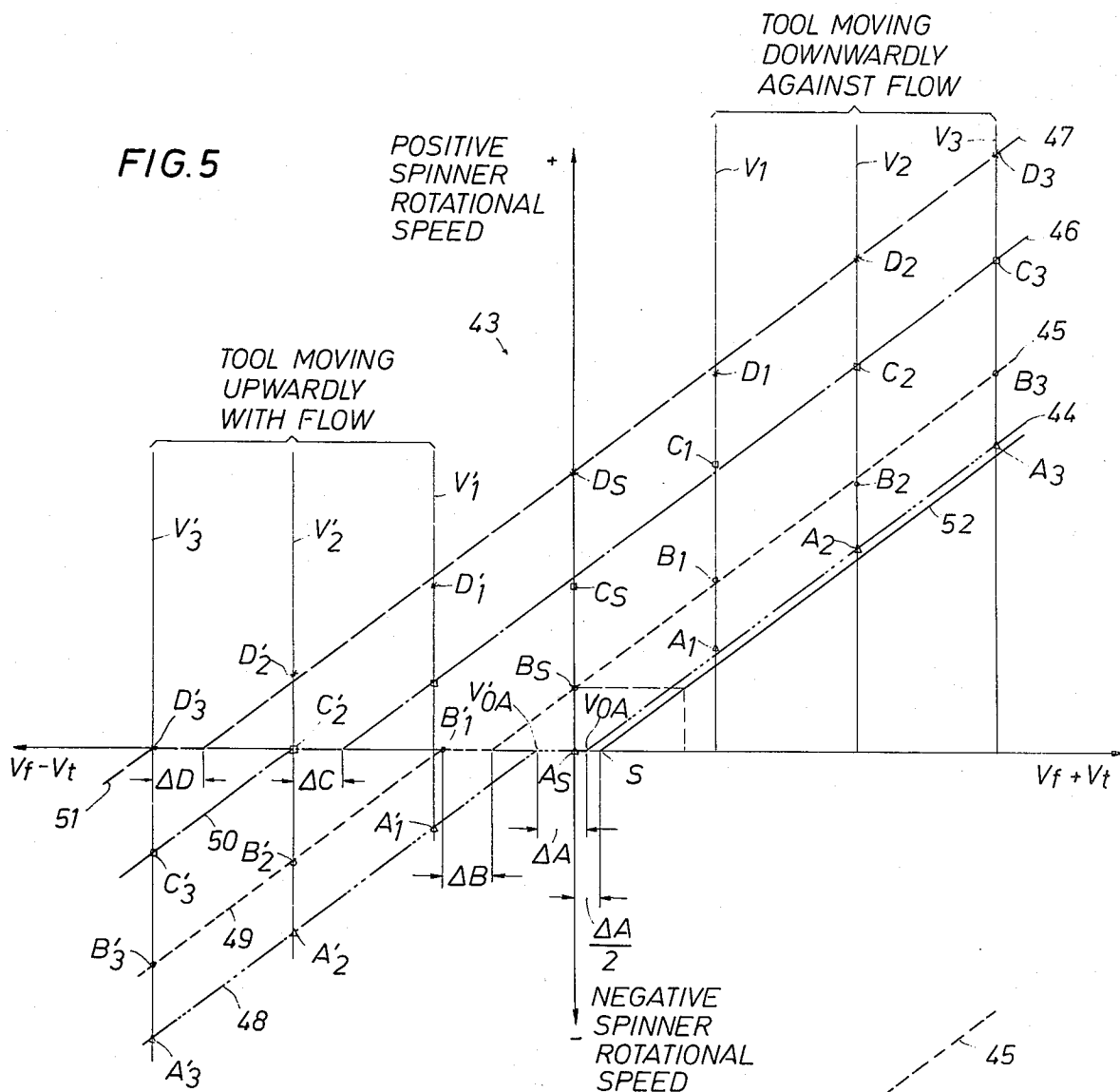
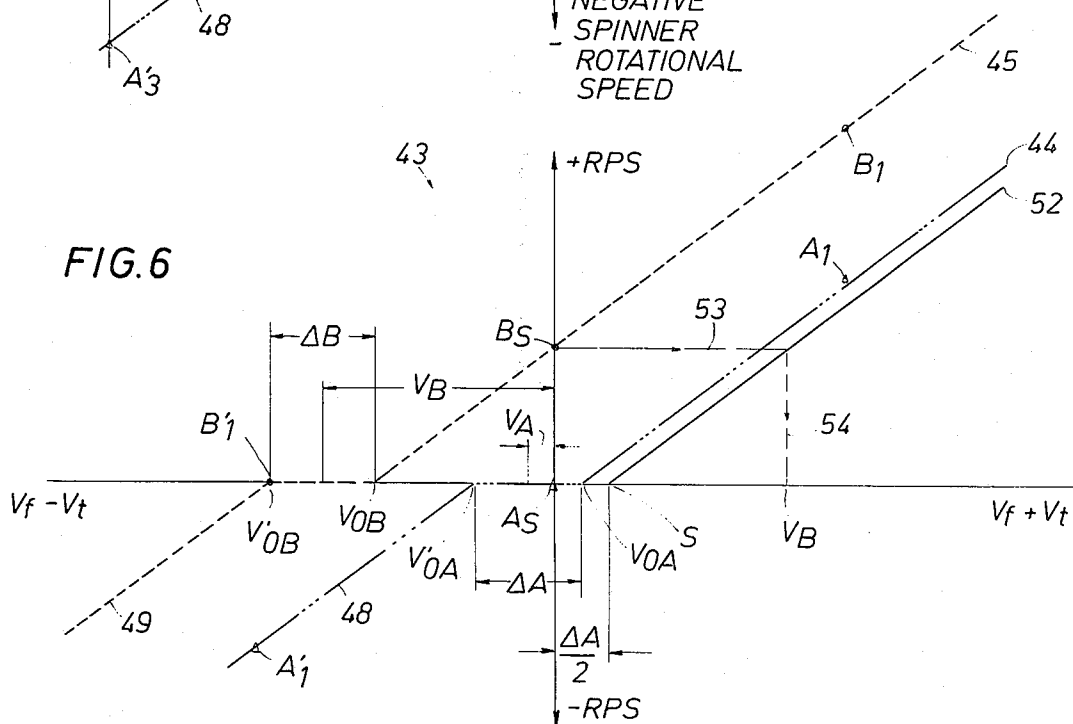


FIG. 6



METHODS FOR DETERMINING VELOCITIES AND FLOW RATES OF FLUIDS FLOWING IN A WELL BORE

As described in U.S. Pat. No. 3,630,078, one of the most successful techniques presently employed for determining the flow rate of fluids flowing in a well bore is to pass a so-called "spinner-type" flowmeter tool at a constant speed through the fluid-filled well bore. By successively recording the resulting rotational speeds of the flowmeter spinner at the corresponding depth locations of the tool, a continuous flow-survey or fluid-velocity log will be obtained from which the flow rates of the well bore fluids at different depth intervals of the well bore can be readily determined. Thus, where the well being surveyed is a production well having two or more producing intervals, the resulting log will clearly indicate the respective velocities or flow rates of the connate fluids which are being produced from each of the several producing intervals. On the other hand, where the well is an injection well in which fluids are being injected simultaneously into two or more formation intervals, the resulting flow survey will show what portion of the injection fluid is entering each formation interval.

Those skilled in the art will, of course, appreciate that the rotational speed of the spinner in a flowmeter of this nature is simply a linear function of the apparent or relative velocity of the well bore fluids in relation to the tool. Thus, the spinner will rotate at the same speed whether the tool is stationary and the well bore fluids are flowing past the tool at a given velocity or the tool is moving at the same velocity through a static column of the fluids. Accordingly, as is typical, by moving the flowmeter tool counter to the flowing fluids, there will be an increased relative velocity which will cause the spinner to turn at a higher speed to provide more-accurate measurements. This typical practice will, of course, at least minimize the errors which would otherwise occur if the relative fluid velocity is so low that viscous drag or frictional losses will cause the spinner to slow significantly, if not stop altogether, at minimum flow rates. Since the output signals from these flowmeters are only representative of the rotational speeds of the spinner, it is, of course, recognized that appropriate corrections must be made to properly take into account the viscosity of the fluids and the diameter of the well bore for determining the actual flow rates.

To make these corrections, one calibration technique which has been commonly used heretofore is to shut the well in and then move the flowmeter through the static column of well bore fluids at two or more selected constant travel speeds. The resulting data will, of course, provide a corresponding number of points defining a straight-line plot of relative fluid velocity versus the rotational speed of the spinner. Thus, data from subsequent logging runs in that well can presumably be used to determine the actual fluid velocities and flow rates at different depth intervals while the well bore fluids are flowing. However, it is recognized that calibration of a flowmeter under static or shut-in conditions is not always fully reliable since the well bore conditions may change significantly when the fluids are flowing. There are, of course, also many situations where a given well cannot be shut in for one reason or another.

Accordingly, it has generally been preferred heretofore to calibrate a flowmeter tool of this nature by mak-

ing a series of measuring runs while normal flow conditions are maintained in the well bore. Typically, these runs are made at three to five widely-different but respectively constant tool speeds, with all of these measurement runs being made counter to the flow direction of the well bore fluids so as to achieve maximum relative fluid velocities across the spinner. The average measured rotational speeds of the spinner and the tool velocity for each run are then typically plotted on linear graph paper, with the spinner speed customarily being scaled along the Y-axis and the tool velocity being in convenient units along the X-axis. If the various measurements are sufficiently accurate, the resulting data for each well bore interval will substantially fall along a straight "relative response" line intercepting the Y-axis at some distance above the zero origin of the X and Y axes and extending upwardly to the right of the Y-axis.

It will, of course, be recognized by those skilled in the art that the resulting "relative response" line obtained by the aforementioned plot is simply based on the linear relationship of the spinner speeds to the relative velocities of the fluids passing over the spinner. Thus, the measured spinner speed during each run through a given well bore interval will actually have two directly-additive components — one component being due solely to the velocity of the tool itself and the other component being caused by the sought-after flow velocity of the well bore fluids in that interval. Accordingly, to eliminate the effects of tool velocity, a so-called "corrected response" line is drawn below and generally parallel to the "relative response" line and which, theoretically, originates at the zero origin or intersection of the X and Y axes. The fluid velocity in each interval is then determined by projecting a horizontal line from the intercept of its associated "relative response" line with the Y-axis (i.e., the average spinner speed at zero tool velocity in that interval) to an intersection with the "corrected response" line and then projecting a vertical line downwardly from this latter intersection to an intercept on the X-axis (i.e., the "velocity" axis) to determine the corresponding fluid velocity. This computed fluid velocity will, of course, theoretically be the velocity of the fluids flowing along the axis of the well bore interval which was being surveyed.

Extensive laboratory experimentation and field operations have shown, however, that the viscosity of the well bore fluids has a marked effect on the rotational speed of the spinner. Thus, the above-described "corrected response" line which originates at the origin or intersection of the X and Y axes does not take into account the possibly-significant effects of viscous drag on the spinner. Accordingly, to better locate this "corrected response" line, the practice heretofore has simply been to arbitrarily shift its origin below the origin of the X and Y axes by a vertical distance which is assumed to be proportionally related to the actual viscosity of the well bore fluids. This distance is, of course, an empirical correction which merely corresponds to the estimated or observed reduction in the rotational speed of the spinner due to the viscous drag of a fluid of a given viscosity.

It will be recognized, therefore, that the "corrected response" line cannot be properly drawn without first establishing its origin to take into account the viscosity of the well bore fluids. This, however, is not ordinarily possible since the true viscosity of the well bore fluids

is rarely known at the time a flowmeter test is being made. Thus, the usual practice heretofore has been to simply assume a nominal viscosity for the particular situation at hand and draw the "corrected response" line on this basis. Those skilled in the art will appreciate, moreover, that this prior-art technique will not be fully reliable in every situation such as those where the fluid viscosity changes in different intervals of a given well bore.

Accordingly, it is an object of the present invention to provide new and improved methods for accurately determining the velocity and flow rate of one or more fluids as they are flowing in a well bore.

This and other objects of the present invention are attained by successively passing a spinner-type flowmeter in opposite directions through a well bore interval containing flowing fluids for obtaining at least one measurement representative of the rotational speed of the spinner while it is turning in one rotational direction and at least one measurement representative of the rotational speed of the spinner while it is rotating in the opposite direction. At least another measurement is secured which is representative of the rotational speed of the spinner in either of its two directions of rotation but at a different relative fluid velocity than either of the previous measurements. These several measurements are then operatively correlated to provide performance data indicative of the corresponding rotational speeds of the flowmeter spinner in both of its rotational directions at different relative fluid velocities for determining the upper and lower limits of the range of relative fluid velocities which are ineffective for inducing rotation of the spinner in each rotational direction in each of the well bore intervals being surveyed. The velocity of each of these fluids can then be determined by establishing the mid-point of the aforementioned relative velocity range in each surveyed interval of the well bore. Where the fluids in the well bore are about the same viscosity, the correlated data may also be used to derive a correction factor which can be applied for correcting measurements obtained with that flowmeter at different intervals throughout the well bore.

The novel features of the present invention are set forth with particularity in the appended claims. The invention, together with further objects and advantages thereof, may be best understood by way of the following description of exemplary methods employing the principles of the invention as illustrated in the accompanying drawings, in which:

FIG. 1 shows a typical flowmeter as it will appear during the practice of the methods of the present invention in a multi-zoned production well;

FIGS. 2-4 respectively depict a series of flow measurements representative of what may be obtained during the practice of the present invention in a well bore such as shown in FIG. 1, with these measurements being presented as they might appear when combined on composite records;

FIG. 5 graphically illustrates one preferred application of the methods of the present invention for correlating the measurements shown in FIGS. 2-4; and

FIG. 6 is an enlarged view of a portion of the graph shown in FIG. 5.

Turning now to FIG. 1, a typical velocity-responsive flowmeter 10 (such as the new and improved tool disclosed in U.S. Pat. No. 3,630,078) is depicted as it will appear while suspended from an electrical logging

cable 11 in a cased well bore 12. As is customary, the cable 11 is spooled on a winch (not shown) at the surface and cooperatively arranged for moving the tool 10 over a range of selected travel speeds either upwardly or downwardly in the well bore 12. A collar locator 13 is preferably included with the tool 10 and coupled to the cable 11 for providing depth-correlation signals as the tool successively passes collars in the string of casing 14 in the well bore 12. To record the output signals of the flowmeter 10 and the collar locator 13 corresponding to the successive depth positions of the tool in the well bore 12, typical surface indicating-and-recording apparatus, such as a CRT or galvanometer recorder 15, is electrically connected to the cable 11 and adapted to be driven in response to its upward and downward movements by means such as a calibrated cable-engaging measuring wheel 16 that is operatively coupled to the recorder as by a pulse generator or mechanical linkage 17.

As fully described, for example, in U.S. Pat. No. 3,630,078 (which is hereby incorporated by reference herein), the flowmeter 10 includes a multi-bladed propeller or velocity-responsive spinner 18 which is coupled to the lower end of a rotatable shaft 19 coaxially mounted in the tool. To maintain the flowmeter 10 in a centered position in the casing 14, typical bow-spring centralizers 20 and 21 are mounted on the tool with the lower one preferably being arranged to also serve as a guard for the spinner 18. As described in the aforementioned patent, the flowmeter 10 is cooperatively arranged for producing an electrical signal which is a substantially-linear function of the rotational speed of the spinner 18. These output signals are transmitted to the surface apparatus 15 by way of the electrical cable 11 where they are successively recorded versus the depth of the flowmeter 10. Although these output signals may, of course, be in any suitable digital or analog form, it will be seen from the aforementioned patent that one convenient arrangement is to produce a series of electrical pulses at a pulse rate which is proportional to the rotational speed of the spinner 18. It should be understood, however, that the new and improved methods of the present invention are equally applicable to any type of flowmeter having an output response that is a substantially-linear function of the relative velocity of fluids across the flowmeter. Thus, a detailed description of the flowmeter 10 is not necessary.

It will, of course, be appreciated that the new and improved methods of the present invention can be successfully employed in any well bore in which monophasic fluids or multi-phasic liquids are flowing in either direction. However, for purposes of fully explaining the principles of the present invention, the well bore 12 is depicted in FIG. 1 as being a typical production well that traverses a number of producing formations 22-25 which have been respectively perforated, as at 26-29, to allow the various connate fluids such as oil or water contained in each formation to enter the well bore 12, as at 30-33, and flow together to the surface for collection. Those skilled in the art will, of course, recognize that although the several formations 22-25 are illustrated as being fairly close to one another in FIG. 1, these formations may well be separated from one another by several hundreds or thousands of feet.

Accordingly, as depicted in FIG. 1, the well bore 12 is divided into four spaced zones or progressively-higher intervals A-D respectively having successively-

greater flow rates which are to be measured by the flowmeter 10 in accordance with the principles of the present invention. Thus, the lowermost well bore interval A is shown as containing only the connate fluids which are produced from the deepest formation 25 and enter the well bore 12, as at 33, by way of the perforations 29. As the fluids 33 produced from the formation 29 flow upwardly from the interval A, they are soon joined by additional connate fluids, as at 32, which are being produced from the next-higher formation 24. Thus, the fluids flowing in the well bore interval B will be a mixture of the flows 32 and 33; and the flow rate in this interval will, of course, be equal to the summation of the respective production flow rates of the formations 24 and 25. In a similar fashion, the overall flow rate in the interval C will be equal to the summation of the flow rates of the respective production flows from the three lower formations; and the overall flow rate in the well bore interval D will be equal to the summation of the production flow rates of the fluids 30-33 flowing from all four of the formations 22-25.

As previously discussed, the usual technique for operating a flowmeter, as at 10, has heretofore been to simply pass the flowmeter at different speeds through a well bore against the direction of fluid flow and then use the resulting relative velocity measurements as a basis for correcting the measurements. In the preferred manner of practicing the present invention, at least one series of velocity measurements are obtained in the same manner while passing the flowmeter, as at 10, at a selected number of different constant travel speeds through the well bore 12 counter to the flow of the fluids, as at 30-33. However, in sharp contrast to the prior art, at least another series of velocity measurements are also made while moving the flowmeter 10 at one or, preferably, a selected number of different but respectively constant velocities through the well bore 12 in the same direction that the fluids, as at 30-33, are flowing. As a further assurance of the accuracy of the results to be attained by practicing the methods of the present invention, it may also be preferred to obtain still another series of measurements while the flowmeter 10 is respectively halted between each of the formations 22-25 as well as at some convenient location in the well bore 12 above the uppermost formation.

As will subsequently be explained in greater detail, the particular sequence that any of the aforementioned measurements are obtained is not at all critical to the successful practice of the present invention. Moreover, as will also be demonstrated, it is not essential that any given number of individual measurements be taken in any run so long as it can be reasonably assumed that those measurements which are taken are accurate. However, as a practical matter, it has been found that the most efficient and reliable practice of the new and improved methods of the present invention is achieved by alternately raising and lowering the flowmeter 10 at three or more different selected travel speeds between convenient locations in the well bore 12 respectively located below the lowermost formation 25 and above the uppermost formation 22. It should be realized, of course, that the travel speeds in any given direction should be substantially different from one another in the interest of securing accurate data. Moreover, there is no requirement that the travel speeds used for raising the tool 10 be the same as those used for lowering the tool. The flowmeter 10 can, of course, also be halted

at any convenient time during the measuring operation for obtaining the aforementioned stationary measurements between each of the well bore intervals A-D. It is also to be understood that the conditions in the well bore 12 should be maintained in a constant condition throughout the entire measuring operation to be certain of the accuracy of the relationships between the various measurements obtained during that time.

Accordingly, if an operating practice such as that briefly described above is followed for obtaining the several series of velocity measurements in the practice of the present invention, it will be realized that the initial logging record (not shown) provided by the recorder 15 will ordinarily be in the form of an extended series of digital or analog output data representative of the speed of the spinner 18 which is recorded versus the depth locations of the tool 10 as it is successively moved back and forth in the well bore 12 to make these measurements. As is typical, this raw data may be stored by the recorder 15 on a suitable recording medium such as, for example, a magnetic tape or a film. Thus, it is to be understood that it is immaterial to the practice of the present invention as to the practical manner in which the primary data is stored or recorded so long as it can be retrieved as necessary for deriving the performance characteristics which are to be subsequently described.

However, as an aid to explaining the practice of the present invention, FIGS. 2-4 have been prepared to schematically illustrate typical flowmeter data in the form of three composite records or simulated flowmeter logs 34-36 that are aligned with the several depth intervals A-D in FIG. 1 and respectively depict on a single log the commonly-related data which was obtained in a random order during the several measuring runs. Accordingly, the composite log 34 in FIG. 2, for example, shows only the continuous measurements 37-39 of the rotational speed of the spinner 18 which were respectively obtained during each of the several measuring runs where the flowmeter 10 was moved downwardly at three different constant travel speeds (V_1 , V_2 and V_3) in the well bore 12 counter to the upwardly-flowing fluids, as at 30-33. Similarly, the composite log 35 in FIG. 3 depicts the continuous data 40-42 respectively taken during each of the measuring runs where the tool 10 was moved upwardly at three selected constant speeds (V'_1 , V'_2 and V'_3). Since the composite log 36 in FIG. 4 depicts the several measurements A_s through D_s obtained as the tool 10 was successively halted in each of the well bore intervals A-D, these measurements simply represent the average speed of the spinner 18 as determined at each depth interval over an adequate time period. It will be realized, of course, that logs such as at 34-36 will not ordinarily be developed; and that these composite logs are presented here solely for better describing the underlying rationale of the present invention regardless of how the measured data is actually recorded and then employed for deriving the performance characteristics of the tool 10 which are used in accurately determining the respective flow rates of the well bore fluids at the several depth intervals A-D.

Since the well bore 12 is a typical production well having a number of producing formations, as at 22-25, the several series of measurements respectively represented by the log traces 37-39 in FIG. 2 are representative of the measurements which are customarily ob-

tained by running the tool 10 at different travel speeds downwardly in the well bore or counter to the upwardly-flowing fluids 30-33. It will, of course, be appreciated that the log trace 37 shows the measurements obtained when the flowmeter 10 is moved at a relatively-low travel speed (V_1); the log trace 38 represents the measurements taken as the tool is moved at a selected higher travel speed (V_2); and the remaining log trace 39 illustrates the measurements at a still-higher travel speed (V_3). In general, the several traces 37-39 respectively illustrate a fairly-constant rotational speed of the spinner 18 while the tool 10 is moving between any two of the producing formations 22-25, with an increase in spinner speed occurring each time the tool passes a group of producing perforations, as at 29, until a higher, but again substantially constant, rotational speed is attained once the tool moves above those perforations.

Accordingly, it will be recognized that for each of the several downward measuring runs of the flowmeter 10, an average measurement will be obtained of the speed of the spinner 18 for each interval A-D of the well bore 12. Where the flowmeter 10 is moving against the flowing fluids, as at 30-33, it will, of course, be recognized that for a given fluid velocity V_f there will always be a correspondingly-higher rotational speed of the spinner 18 as the travel velocity V_t of the tool is increased since the relative velocity across the spinner at any time will be the summation of these two velocities. Thus, in the exemplary practice of the present invention described herein, each of the several downward measuring runs of the tool 10 will respectively provide a different measurement of the rotational speed of the spinner 18 in each of the well bore intervals A-D; with the net result being, of course, that the twelve measurements A_1 through D_3 ideally obtained will respectively represent a function of the apparent or relative fluid velocity in each well bore interval and at each travel speed (V_1 , V_2 and V_3) of the tool.

These several measurements A_1 through D_3 can, of course, be determined from the log traces 37-39 and plotted as shown in the upper right-hand quadrant of the graph 43 depicted in FIG. 5 where the rotational speed of the spinner 18 is scaled along the Y-axis of the graph and the relative velocity of the flowing well bore fluids across the tool 10 is scaled along the X-axis. Thus, the several measurements, as at A_1 through A_3 , respectively taken while the tool 10 is moving downwardly at different travel speeds, V_1 through V_3 , along the lowermost interval A of the well bore 12 will define a line 44 which is representative of the linear relationship of the rotational speeds of the spinner 18 to the summation of the actual fluid velocity, V_f , and the actual travel speed or velocity, V_t , of the tool. Similarly, the other measurements of spinner speeds (as at B_1 through B_3 , C_1 through C_3 and D_1 through D_3) are also determined from the log traces 37-39 and plotted on the graph 43 to respectively define a series of parallel lines, as at 45-47, graphically depicting the performance of the tool 10 as it was successively moved downwardly through the well bore intervals B-D. Moreover, the several measurements of the rotational speed of the spinner 18 while the tool 10 was successively held stationary in the well bore 12 can be plotted, as at A_s through D_s , on the graph 43 to give further confirmation of the positions of the performance lines 44-47.

It will, of course, be recognized that the several performance lines 44-47 shown in the upper right-hand quadrant of the graph 43 are simply representative of the prior-art techniques used heretofore for determining the fluid velocities (and thereby the flow rates) in each interval, as at A-D, in a given well bore, as at 12. However, as previously mentioned, in the practice of the present invention the flowmeter 10 is also successively passed through the well bore 12 at different selected travel speeds but in the same direction that the well bore fluids, as at 30-33, are flowing. Thus, in the exemplary description of the present invention as it is practiced in a producing well bore, as at 12, additional measurements of the rotational speed of the spinner 18 are also taken as the flowmeter 10 is moved upwardly at different travel speeds (V'_1 , V'_2 and V'_3) along with the upwardly-flowing fluids, as at 30-33. These particular measuring runs will, however, not always cause the spinner 18 to rotate in the same direction as it did when the tool 10 was either stationary (e.g., A_s through D_s) or was moving downwardly against the upwardly-flowing fluids 30-33 (e.g., A_1 through D_3).

Instead, it should be realized that when the tool 10 is moving in the same direction as that of the well bore fluids 30-33, the velocity of the tool in relation to the fluid velocity will determine the rotational speed of the spinner 18 as well as its direction of rotation. Thus, if the tool 10 is moved along with the well bore fluids, as at 30-33, and at a velocity considerably less than the actual velocity of the fluids, the spinner 18 will rotate in the same direction as it does when moving counter to the fluids but its rotational speed will be significantly reduced since the relative fluid velocity across the spinner will be equal to the algebraic difference between the actual fluid velocity and the tool velocity. It will be appreciated, therefore, that when the velocity of the tool 10 is equal to the actual fluid velocity, the relative fluid velocity acting across the spinner 18 will be zero and the spinner will be motionless. Conversely, when the tool 10 is moved faster than the well bore fluids 30-33, there will again be relative fluid velocity across the spinner 18 but its effective direction will now be such that the spinner will rotate in the opposite direction.

Accordingly, in the practice of the present invention, it has been found that by successively moving the flowmeter 10 at different speeds (V'_1 , V'_2 and V'_3) in the same direction that the well bore fluids, as at 30-33, are moving, the resulting output measurements will be representative of the rotational speed of the spinner 18 as well as its direction of rotation. In other words, when the flowmeter 10 is moved along with the well bore fluids 30-33, the spinner 18 can be rotating either clockwise or counter-clockwise or it can be halted depending upon the relationship of the tool velocity to the fluid velocity at the time that any particular measurement is taken.

Referring again to FIG. 3, it will be seen on the log 35 that when the flowmeter 10 was moved upwardly in the well bore 12 at its lowest speed (V'_1), the corresponding log trace 40 indicates (as at A'_1) that although the spinner 18 was rotating while the tool was moving through the lowermost well bore interval A, the spinner ultimately halted (as at B'_1) as the tool was moved through the well bore interval B. However, as shown at C'_1 on the log trace 40, the spinner 18 began to rotate again once the tool 10 reached the upper limit

of the perforations 27 and moved on into the well bore interval C. Then, as indicated at D'_1 on the log trace 40, the rotational speed of the spinner 18 increased still further as the flowmeter 10 was moved above the uppermost perforations 26.

Thus, in light of the preceding discussion, it will be appreciated that the log trace 40 clearly shows that when the flowmeter 10 was moved at a relatively-low speed (V'_1), the spinner 18 was rotating in its reverse direction as the tool moved through the interval A and then halted until the tool reaches the well bore interval C. Thereafter, the spinner 18 was rotating at successively-higher speeds in its normal or forward rotational direction as the tool 10 respectively passed upwardly through the well bore intervals C and D.

A similar, but somewhat different, pattern is noted on the next log trace 41 on the log 35. Thus, at the next-higher tool speed (V'_2), as indicated at A'_2 and B'_2 on the trace 41 the spinner 18 was rotating in a reverse direction as the flowmeter 10 was moved through the lower portion of the well bore 12 and did not stop turning (as indicated at C'_2) until the tool was passing the perforations 27 in the well bore interval C. However, the spinner 18 did begin rotating in its forward direction (as shown at D'_2) once the flowmeter 10 reached the uppermost perforations 27 and entered the uppermost well bore interval D.

The last log trace 42 on the log 35 clearly demonstrates that the highest velocity of the tool (V'_3) was always greater than the velocity of the fluids, V_f , in each of the several well bore intervals A-D. Thus, as indicated at A'_3 through C'_3 on the trace 42, the spinner 18 was rotating in its reverse direction and was successively slowed as the flowmeter 10 progressively moved through the well bore intervals A-C. Then, once the flowmeter 10 reached the uppermost well bore interval D, the relative velocity of the fluids 30-33 acting on the spinner 18 at least approached zero so that the spinner stopped rotating as represented by the measurement D'_3 on the trace 42.

Accordingly, it will be appreciated that by successively moving the flowmeter 10 upwardly through the well bore 12 at different tool velocities (V'_1 , V'_2 and V'_3), the log traces 40-42 will respectively indicate the corresponding rotational speeds (A'_1 through D'_3) of the spinner 18 as the tool was moved through each of the various well bore intervals A-D. Moreover, as described above, by comparing or correlating the several measurements A'_1 through D'_3 , the rotational direction of the spinner 18 as well as the points at which it was halted can be readily determined. It should be recalled that although the values of V'_1 , V'_2 and V'_3 are graphically shown in FIG. 5 to be the same as V_1 , V_2 and V_3 , there is no necessity that these selected tool velocities respectively correspond.

Once the information shown on the log 35 has been correlated, the several measurements A'_1 through D'_3 may then be plotted as shown in FIG. 5. As seen there, the several measurements obtained as the tool 10 passed through each of the well bore intervals A-D respectively define an extension of at least some of the lines, as at 46 and 47, as well as a series of parallel lines 48-50 which are entirely located in the lower left-hand quadrant of the graph 43 and extend downwardly to the left. Of particular significance to the practice of the present invention, it will be noted, for example, that the lines 44 and 48 representing the performance of the

flowmeter 10 as it is moved upwardly and downwardly through the well bore interval A would be coincidentally aligned with one another if it were not for their horizontal displacement, as at ΔA , along the X-axis of the graph 43. A similar offset or displacement, as at ΔB and ΔC , is also noted for each associated pair of the other lines 45 and 49 as well as 46 and 50 which together graphically depict the performance of the flowmeter 10 as it was moved through the other well bore intervals B and C respectively. It will also be noted that except for the measurements D'_3 , the other two measurements D'_1 and D'_2 taken as the tool 10 moved through the well bore interval D simply define an extension of the line 47. However, in the particular example described here, it may be reasonably assumed that an upward run of the tool 10 at a still-higher speed would have shown another performance line, as at 15, which is displaced from the line 47 by a distance ΔD .

Accordingly, it will be recognized that the several performance lines 44-51 on the graph 43 collectively represent the actual operational responses of the flowmeter 10 as it was moved at different speeds and in different directions through each of the several well bore intervals A-D. Taking the lines 44 and 48, for example, it is seen that when the flowmeter 10 was moved upwardly through the well bore interval A, there was a minimum tool velocity, as at V_{0A} , where the spinner 18 first stopped turning in one rotational direction. It should be realized that the measurement A'_1 does not necessarily have to coincide with the minimum velocity V_{0A} . Similarly, as depicted in FIGS. 5 and 6, the graph 43 further shows that when the flowmeter 10 was moved downwardly in the interval A, there was also a minimum tool velocity V'_{0A} where the spinner first stopped turning in the opposite rotational direction. Thus, as depicted by the graph 43, the aforementioned ΔA is equal to the range of the relative fluid velocities acting in both directions across the spinner 18 which were ineffective for causing the spinner 18 to rotate when the flowmeter 10 was passed through the well bore interval A. Correspondingly, the other increments ΔB - ΔD are, of course, representative of the response of the spinner 18 when the tool 10 passed through the intervals B-D.

It will be recognized, therefore, that the measured value of ΔA which is established from the graph 43 will be specifically related to the operating characteristics of the particular flowmeter 10 and to the influence of the particular fluids 33 on the performance of this flowmeter. In other words, the magnitude of ΔA will be directly proportional to the combined effects of the frictional losses of the flowmeter 10 as well as the viscous drag of the well bore fluids 33 across the spinner 18. Thus, since it has been found that the performance of a flowmeter such as disclosed in the aforementioned U.S. Pat. No. 3,630,078 is essentially uniform regardless of the direction of the flowmeter 10 is moving, it may be safely assumed that the mid-point of ΔA designates the point at which the relative fluid velocity across the spinner 18 was zero. This, of course, means that one-half of ΔA accurately represents the minimum or threshold velocity required for the well fluids 33 to initiate rotation of the spinner 18 if the flowmeter was held in a stationary position in the well bore interval A. Accordingly, a point "S" can be located on the X-axis of the graph 43 at a distance to the right of the origin of the X and Y axes which is equal to one-half of ΔA .

for accurately determining the origin of a correction line, as at 52, on the graph.

It will be appreciated, therefore, that where the several well bore fluids 30-33 are of about the same viscosity and the internal diameter of the casing 14 passing through the several well bore intervals A-D is at least substantially uniform, the response of the flowmeter 10 will be graphically represented by a corresponding number of parallel performance lines such as collectively shown at 44-51. Thus, under these conditions, it has been found most convenient when a graph, as at 43, is to be employed for correcting the several measurements provided by the flowmeter 10 to simply inscribe a correction line, as at 52, which begins at the point "S" and extends upwardly and to the right paralleling the several performance lines 44-47. Then, as shown by the dashed lines 53 and 54, the true velocity, V_B , of the combined fluids 32 and 33 flowing through the well bore interval B can be readily determined. As illustrated, this graphical solution is made by extending the dashed horizontal line 53 from the Y-axis intercept of the performance line 45 to the correction line 52 and then extending the vertical dashed line 54 from this intersection to its intercept, V_B , with the X-axis. Similar graphical solutions can, of course, be made for respectively determining the true velocities V_C and V_D , of the combined well bore fluids, as at 31-33 and 30-33, respectively passing through the well bore intervals C and D.

It should, of course, be recognized that the graph 43 as shown in FIG. 5 arbitrarily depicts the several offsets ΔA through ΔD as being equal to one another. Those skilled in the art will, however, appreciate that empirical data such as the several measurements A_1 through D_3 and A'_1 through D'_3 will not necessarily be of sufficient accuracy that each pair of the respective performance lines 44-51 defined in this data will always be offset from one another by exactly the same amount as every other pair of performance lines. Thus, where the several fluids, as at 30-33, have substantially the same viscosity and the casing 14 is of a uniform diameter, it has been found advisable to simply average the respective values of ΔA through ΔD and then use one-half of this average value to more accurately locate the position of the point "S" on the X-axis.

The preceding discussion involving the graph 43 has, of course, been directed to an assumed situation where the casing 14 is of a uniform internal diameter and the several well bore fluids 30-33 are of at least about the same viscosity. It will, however, be appreciated that conditions such as these are not always encountered in every situation where flow measurements are to be determined with a flowmeter such as the one shown at 10 in the present drawings. Nevertheless, the basic principles of the present invention can still be reliably employed. Although a graphical solution as described in FIGS. 5 and 6 is not essential for the practice of the present invention, it will be realized from the graph 43 that the performance of the flowmeter 10 as it is moved through each of the several illustrated well bore intervals A-D is separately presented by each of the performance lines as at 44-51.

Thus, should the conditions in the well bore 12 be significantly different at various ones of the several intervals A-D, a plot of the data which is obtained from the several measuring runs of the flowmeter 10 will result in individual performance lines (not shown) which

may not necessarily be parallel to one another as was the case with the depicted performance lines 44-51. It will, of course, be recognized that if the several measurements are reasonably accurate, it will be readily apparent when the data is correlated that the performance of the flowmeter is different in each of the several well bore intervals A-D. For example, if this data is plotted on a graph such as that shown at 43 in FIG. 5, any significant differences in the well bore conditions from one well bore interval to another will be pointed up by such things as non-parallel performance lines at varying slopes or significant differences in the magnitude of the X-axis offsets between the intercepts of each associated set of the performance lines.

Accordingly, if a situation such as this should occur, the principles of the present invention can still be effectively employed to accurately determine the flow rates of the well bore fluids, as at 30-33, at the several intervals A-D of the well bore 12. Using FIG. 6 as an example, it will be seen that the horizontal distance between the mid-point of the offset, as at ΔA , and the origin of the X and Y-axes is equal to the fluid velocity, V_A , in the well bore interval A. Thus, the fluid velocity in each of the several intervals A-D can be respectively determined by simply scaling the distances along the X-axis of the graph 43 to the mid-point of each of the offsets ΔA through ΔD . FIG. 6 graphically illustrates this technique for determining the fluid velocity, V_B , in the well bore interval B.

As previously mentioned, the practice of the present invention is not dependent upon any particular number of measurements being obtained. For example, in those situations where the well bore casing, as at 14, is of a uniform internal diameter and the several fluids flowing therethrough have at least reasonably similar viscosities, it has been shown that the several performance lines, as at 44-51, for a given situation will be substantially parallel and their respective offsets, as at ΔA through ΔD , will be substantially equal. Thus, where a graph as at 43 is used, the true velocities in each of the well bore intervals can be determined so long as the respective intercepts of the several performance lines with the Y-axis can be reliably established and the correction line, as at 52, can be defined with a reasonable degree of accuracy. It will, therefore, be appreciated that various plotting techniques could be employed to make the most out of a minimum amount of data without departing from the scope of the present invention. For example, once the slope of any one of the performance lines, as at 44-51, was established with a reasonable number of measurements, the locations of the other performance lines could be estimated with only one or two measurements so that at least reasonably accurate assumptions could be made of the fluid velocities in the other parts of the well.

More basically, it should also be recognized that the principles of the present invention can also be followed even where there are differences in either casing diameter or fluid viscosities in a given well. For example, as previously described, so long as the upper and lower limits of each of the several offsets, as at ΔA through ΔD , can be established with a fair amount of accuracy, the true velocity in each of the well bore intervals can be reliably determined by scaling the respective distances along the X-axis and the mid-points of each of the offsets. Hereagain, it is, of course, recognized that

the validity of any of these techniques will be wholly dependent upon the accuracy of the several measurements. Thus, as is true with any measuring technique, the statistical reliability of empirical data is always improved by obtaining as many different measurements as are practical for a given situation.

It should also be noted that the discussions to this point have been directed to the determination of the fluid velocities along the central axis of the well bore 12. As is well established, these velocities must be multiplied by a correction factor (ordinarily 0.82 or 0.83) to arrive at an average velocity of the well bore fluids across the entire cross-sectional area of the casing 14. Once this correction is made, it is, of course, elementary to convert these average velocities to their respective flow rates since the cross-sectional flow area of the casing 14 is known.

As previously mentioned, the methods of the present invention are, of course, equally applicable for production wells and injection wells. Thus, where an injection well is being surveyed to determine the flow of the injection fluid (e.g., water) into each of several formation intervals, the same rationale as described above will still apply. However, since the flow in an injection well is downward, it will be appreciated that downward movement of the flowmeter, such as at 10, will be with the flowing fluids and upward movement of the flowmeter will be counter to the direction of flow. Accordingly, in this situation, a composite log such as that shown at 34 in FIG. 2 will instead be provided from the measurements obtained as the tool 10 is moving upwardly and a log, as at 35, will then represent the measurements taken when the flowmeter was moved downwardly. Otherwise, all other procedures as explained by reference to FIGS. 5 and 6 will be followed to practice the new and improved methods of the present invention.

Accordingly, it will be appreciated that the new and improved methods of the present invention are uniquely adapted for accurately determining the flow rates of well bore fluids with velocity-responsive flowmeters. Thus, by successively passing a flowmeter such as the spinner-type tool shown in U.S. Pat. No. 3,630,078 upwardly and downwardly through the fluids flowing in a well bore, the direction and speed of rotation of the spinner can be measured in each well bore interval for each travel speed of the tool. Then, these several measurements are correlated to determine the response or performance of the flowmeter spinner in each well bore interval and over a sufficient range of tool speeds for defining the upper and lower limits of the range of relative fluid velocities where the spinner is not rotating. Once these limits are determined, the actual fluid velocity in each well bore interval can be calculated with accuracy.

While only a particular mode of practicing the invention has been shown and described, it is apparent that changes and modifications may be made without departing from this invention in its broader aspects; and, therefore, the aim in the appended claims is to cover all such changes and modifications as fall within the true spirit and scope of this invention.

What is claimed is:

1. A method for determining the actual velocity of a fluid flowing in a well bore interval with a flowmeter having a rotatable spinner adapted to turn in a rotational direction and at a rotational speed respectively

representative of both the relative direction and the relative velocity of said flowing fluid with respect to said flowmeter and comprising the steps of:

- passing said flowmeter upwardly along said well bore interval at a selected travel speed for obtaining at least one measurement representative of the corresponding rotational speed of said spinner in one of its rotational directions in said flowing fluid;
- passing said flowmeter downwardly along said well bore interval at a selected travel speed for obtaining at least one measurement representative of the corresponding rotational speed of said spinner in the other of its rotational directions in said flowing fluid;
- repeating at least one of the aforespecified steps at a different selected travel speed for obtaining at least another measurement representative of the corresponding rotational speed of said spinner in said flowing fluid;
- correlating said measurements for determining the upper and lower limits of the range of relative fluid velocities which are respectively ineffective for inducing rotation of said spinner in either of its said rotational directions; and, thereafter,
- averaging said upper and lower velocity limits for determining the actual velocity of said flowing fluid in said well bore interval.

2. The method of claim 1 further including the step of:

- multiplying said actual velocity by a factor of about 0.82 times the internal diameter of said well bore interval for determining the actual flow rate of said flowing fluid.

3. The method of claim 1 further including the step of:

- before said measurements are correlated, halting said flowmeter in said well bore interval for obtaining at least another measurement representative of the corresponding rotational speed and rotational direction of said spinner in said flowing fluid.

4. The method of claim 3 further including the step of:

- multiplying said actual velocity by a factor of about 0.82 times the internal diameter of said well bore interval for determining the actual flow rate of said flowing fluid.

5. A method for determining the actual velocity of a fluid flowing in a well bore interval with a flowmeter having a rotatable spinner adapted to turn in a rotational direction and at a rotational speed respectively representative of both the relative direction and the relative velocity of said flowing fluid with respect to said flowmeter and comprising the steps of:

- passing said flowmeter upwardly along said well bore interval at a selected travel speed for obtaining at least one measurement representative of the corresponding rotational speed of said spinner in one of its rotational directions in said flowing fluid;
- passing said flowmeter downwardly along said well bore interval at a selected travel speed for obtaining at least one measurement representative of the corresponding rotational speed of said spinner in the other of its rotational directions in said flowing fluid;
- halting said flowmeter in said well bore interval for obtaining at least another measurement representative of the corresponding rotational speed and rotational direction of said spinner in said flowing fluid;

correlating said measurements for determining the upper and lower limits of the range of relative fluid velocities which are respectively ineffective for inducing rotation of said spinner in either of its said rotational directions; and, thereafter,

averaging said upper and lower velocity limits for determining the actual velocity of said flowing fluid in said well bore interval.

6. The method of claim 5 further including the step of:

multiplying said actual velocity by a factor of about 0.82 times the internal diameter of said well bore interval for determining the actual flow rate of said flowing fluid.

7. A method for determining the actual velocity of a fluid flowing in a well bore interval with a flowmeter having a rotatable spinner adapted to turn in a rotational direction and at a rotational speed respectively representative of both the relative direction and the relative velocity of said flowing fluid with respect to said flowmeter and comprising the steps of:

successively passing said flowmeter at least twice along said well bore interval counter to said flowing fluid and at at least two different travel speeds for obtaining one series of measurements representative of the corresponding rotational speeds of said spinner when rotating in one direction in said flowing fluid;

successively passing said flowmeter at least twice along said well bore interval along with said flowing fluid and at at least two different travel speeds for obtaining another series of measurements representative of the corresponding rotational speeds of said spinner when rotating in the opposite direction in said flowing fluid;

correlating said one series of measurements for determining the relative velocity across said spinner at which said spinner will discontinue rotation in said one direction in said flowing fluid;

correlating said other series of measurements for determining the relative velocity across said spinner at which said spinner will discontinue rotation in said opposite direction in said flowing fluid; and

computing the mid-point of said relative velocities for determining the actual velocity of said flowing fluid in said well bore interval along the rotational axis of said spinner.

8. The method of claim 7 further including the step of:

multiplying said actual velocity by a factor of about 0.82 times the internal diameter of said well bore interval for determining the actual flow rate of said flowing fluid.

9. The method of claim 7 further including the step of:

before said series of measurements are correlated, halting said flowmeter in said well bore interval for obtaining at least another measurement representative of the corresponding rotational speed and rotational direction of said spinner in said flowing fluid.

10. The method of claim 9 further including the step of:

multiplying said actual velocity by a factor of about 0.82 times the internal diameter of said well bore interval for determining the actual flow rate of said flowing fluid.

11. A method for respectively determining the actual velocities of at least a first fluid flowing alone in a lower

interval of a well bore and a second fluid flowing together in a mixture with said first fluid in an upper interval of said well bore by means of a flowmeter having a rotatable spinner adapted to turn in a rotational direction and at a rotational speed respectively representative of both the relative direction and the relative velocity of said flowing fluids with respect to said flowmeter and comprising the steps of:

passing said flowmeter upwardly along said well bore intervals at a selected travel speed for successively obtaining first and second measurements respectively representative of the corresponding rotational speeds of said spinner in one of its rotational directions in both of said well bore intervals;

passing said flowmeter downwardly along said well bore intervals at a selected travel speed for successively obtaining third and fourth measurements respectively representative of the corresponding rotational speeds of said spinner in the other of its rotational directions in both of said well bore intervals; repeating at least one of the aforespecified steps at a different selected travel speed for successively obtaining at least fifth and sixth measurements representative of the corresponding rotational speeds of said spinner in both of said well bore intervals;

correlating said measurements for determining the upper and lower limits of the individual ranges of relative fluid velocities in each of said well bore intervals which are respectively ineffective for inducing rotation of said spinner in either of its said rotational directions; and, thereafter,

averaging said upper and lower velocity limits for each of said well bore intervals for determining the actual velocities of said first and second fluids in said well bore intervals.

12. The method of claim 11 further including the step of:

multiplying each of said actual velocities by a factor of about 0.82 times the respective internal diameter of each of said well bore intervals for respectively determining the actual flow rates of said first and second fluids.

13. The method of claim 11 further including the step of:

before said measurements are correlated, successively halting said flowmeter in each of said well bore intervals for respectively obtaining additional measurements representative of the corresponding rotational speeds and rotational directions of said spinner in each of said well bore intervals.

14. The method of claim 13 further including the step of:

multiplying each of said actual velocities by a factor of about 0.82 times the respective internal diameter of each of said well bore intervals for respectively determining the actual flow rates of said first and second fluids.

15. A method for respectively determining the actual velocities of at least a first fluid flowing alone in a lower interval of a well bore and a second fluid flowing together in a mixture with said first fluid in an upper interval of said well bore by means of a flowmeter having a rotatable spinner adapted to turn in a rotational direction and at a rotational speed respectively representative of both the relative direction and the relative velocity of said flowing fluids with respect to said flowmeter and comprising the steps of:

successively passing said flowmeter at at least two different travel speeds along said well bore intervals counter to said flowing fluids for obtaining first and second measurements respectively representative of the corresponding rotational speeds of said spinner when rotating in one direction in said first fluid and in said mixture;

successively passing said flowmeter at at least two different travel speeds along said well bore intervals with said flowing fluids for obtaining third and fourth measurements respectively representative of the corresponding rotational speeds of said spinner when rotating in the opposite direction in said first fluid and in said mixture;

correlating said first and second measurements for respectively determining the relative fluid velocities across said spinner at which said spinner will discontinue rotating in said one direction in said first fluid and in said mixture;

correlating said third and fourth measurements for respectively determining the relative fluid velocities across said spinner at which said spinner will discontinue rotating in said opposite direction in said first fluid and in said mixture; and

computing the mid-points of each set of said relative velocities in each of said well bore intervals for respectively determining the actual velocities of said first fluid and of said mixture along the rotational axis of said spinner.

16. The method of claim 15 further including the step of:

multiplying each of said actual velocities by a factor of about 0.82 times the respective internal diameter of each of said well bore intervals for respectively determining the actual flow rates of said first fluid and of said mixture.

17. The method of claim 15 further including the step of:

before said measurements are correlated, successively halting said flowmeter in each of said well bore intervals for respectively obtaining additional measurements representative of the corresponding rotational speeds and rotational directions of said spinner in

each of said well bore intervals.

18. The method of claim 17 further including the step of:

multiplying each of said actual velocities by a factor of about 0.82 times the respective internal diameter of each of said well bore intervals for respectively determining the actual flow rates of said first fluid and of said mixture.

19. The method of claim 15 wherein said two travel speeds counter to said flowing fluids are respectively substantially equal to said two travel speeds with said flowing fluids.

20. A method for respectively determining the actual velocities of at least a first fluid flowing alone in a lower interval of a well bore and a second fluid flowing together in a mixture with said first fluid in an upper interval of said well bore by means of a flowmeter having a rotatable spinner adapted to turn in a rotational direction and at a rotational speed respectively representative of both the relative direction and the relative velocity of said flowing fluids with respect to said flowmeter and comprising the steps of:

alternately raising and lowering said flowmeter back and forth in said upper and lower well bore intervals at a sufficient number of different travel speeds in each travel direction for determining the relative fluid velocity across said spinner in each of said well bore intervals where said spinner will respectively stop rotating in each of its said rotational directions; and, thereafter,

averaging said relative fluid velocities determined with respect to each of said well bore intervals for respectively deriving the actual fluid velocities of said flowing fluids in each of said well bore intervals along the rotational axis of said spinner.

21. The method of claim 20 further including the step of:

multiplying each of said actual velocities by a factor of about 0.82 times the respective internal diameter of each of said well bore intervals for respectively determining the actual flow rates of said first and second fluids.

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