FLP-2492/KLP-4492 Impeller Flowmeter

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Golden CO, U. S. A.
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General Information

Overview

The FLP-2492/KLP-4492 impeller flowmeter utilizes a unique fiber-optic sensing mechanism that is designed to minimize the drag associated with other mechanical flowmeters, which use magnets or proximity relays to sense impeller rotation.

Please refer to figure 1 for a general description of the probe. The FLP-2492 is equipped with a standard Mount Sopris single conductor probe top. The KLP-4492 is equipped with a 4-conductor probe top of a customer specified type.

Connectors and Layout

Normal cable assignments are as follows:

Cable line 1 Power and Signal Common (Cable armor on single conductor system)
Cable line 2 Positive (+) Power, Signal (Center conductor on single conductor systems)
Cable line 3 Not used
Cable line 4 Not used

Theory of Operation

The probe requires +30 VDC at the probe top. Pulses from a driver circuit representing impeller rotation (4 pulses per revolution) are sent up the cable. Direction of rotation is not available with this data, so the operator must determine flow direction by logging at different speeds in the same direction and noting whether the impeller rate increases or decreases with respect to changes in rate. See notes in appendix for more information.

The impeller is fitted on rotor which has 2 fiber optic cables imbedded in it which are looped in 180 degree planes in the mounting body. The impeller is held onto the shaft by a nut. The end bearing on the shaft allows the whole assembly (rotor and impeller) to rotate freely on the shaft. Note that the shaft is locked into the probe sensor assembly by a 6/32 set screw (using a 1/16” allen wrench) that is tightened onto the recess on the other end of the shaft.

The sensor assembly has two small openings (lenses) that are aligned 180 degrees apart. They are radially set the same distance from the center axis of the probe as are the ends of the fiber optic loop on the rotor.

When the rotor spins, the light from one of the lenses (led) passes through the loop of fiber optic cable and is received at the other side (photodiode). This occurs 4 times per revolution.

Specifications

Diameter	4.2 cm (depends on cage/impeller configuration)
Weight	9 kg
Length	122 cm
Measuring range	2-70 meters/minute
Resolution	< 0.3 m/min
Pressure	2000 psi
Temperature	70 degrees C

Installation

Installing cages and impellers

Impeller must be removed first before removing or changing cages. They are then re-installed. Cages are simply unscrewed from the weight section. Cages should only be hand tightened. Apply a few wraps of electrical tape to maintain a clean tight connection. Do not allow the housing at the top of the weight section to rotate with respect to the weight, as this may twist off the internal wires.

To change the impeller, unscrew the knurled nut on the end of the impeller and pull it from the shaft. Install the new impeller and replace the nut. Be careful not to apply lateral force on the shaft as this may cause the bearing and rotor to bind.

Operating Procedure

Operation

All impeller flowmeters operate in the same fashion. Generally, up and down passes are logged at different speeds and a calibration curve is constructed to account for different well fluid characteristics and friction effects. See the application notes in the appendix (courtesy of Western Atlas) for more details.

MSLog

1. Select the correct tool driver from the Tool panel selection box. If the correct one is not available run MSLConfig to install it.
2. In the Tool panel, click the Power On button.
3. Click the Depth panel upper right corner icon. Click Zero Tool.
4. If you wish to fill out the header, in the Acquisition panel click Header button.
5. In the Acquisition panel, click Record and select a file name.
6. Turn on the desired, Depth Sampling mode.
7. If you are printing, turn on the printer in MCHCurve.
8. Log to the desired interval as normal. Refer to the MSLog manual for additional information on logging.
9. When done, in the Acquisition panel, click Stop.
10. In the Tool panel, click the Power Off button before removing the probe.

Performance Checks and Calibrations

See Appendix (Applications Notes) for details

Preventative Maintenance

The probe should be thoroughly cleaned after each use, using fresh water, and allowed to dry before storage. The fiber optic-cable ends and diode lenses must be kept clean and clear to operate correctly. The probe should send out 4 pulses per revolution of the impeller, which can be checked on the surface with the logging equipment.

If the rotor or sensor is suspected to be dirty, remove the cage. Then remove the rotor section from the sensor by loosening the 6/32 set screw with a 1/16” Allen wrench. Visually inspect the four windows on the rotor and the two windows on the sensor. Wipe with moist soft cloth. When logging in casing with much rust and scale, it is very likely that the sensor and rotor windows will become coated with iron oxide and will require cleaning. Routine cleaning will keep the probe in optimum condition and provide good data. Cleaning is recommended after every logging operation.

Troubleshooting

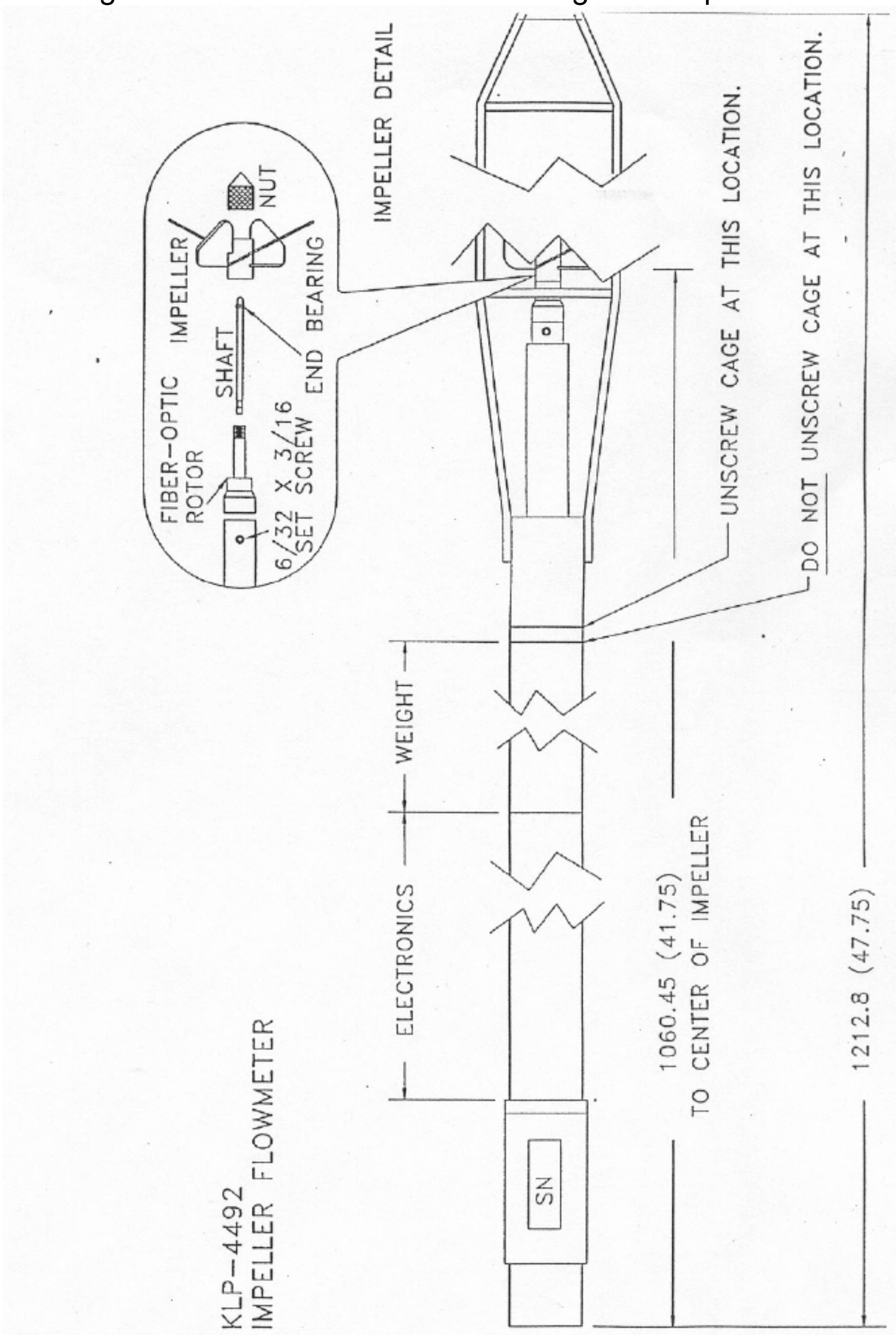
Disassembly Instructions

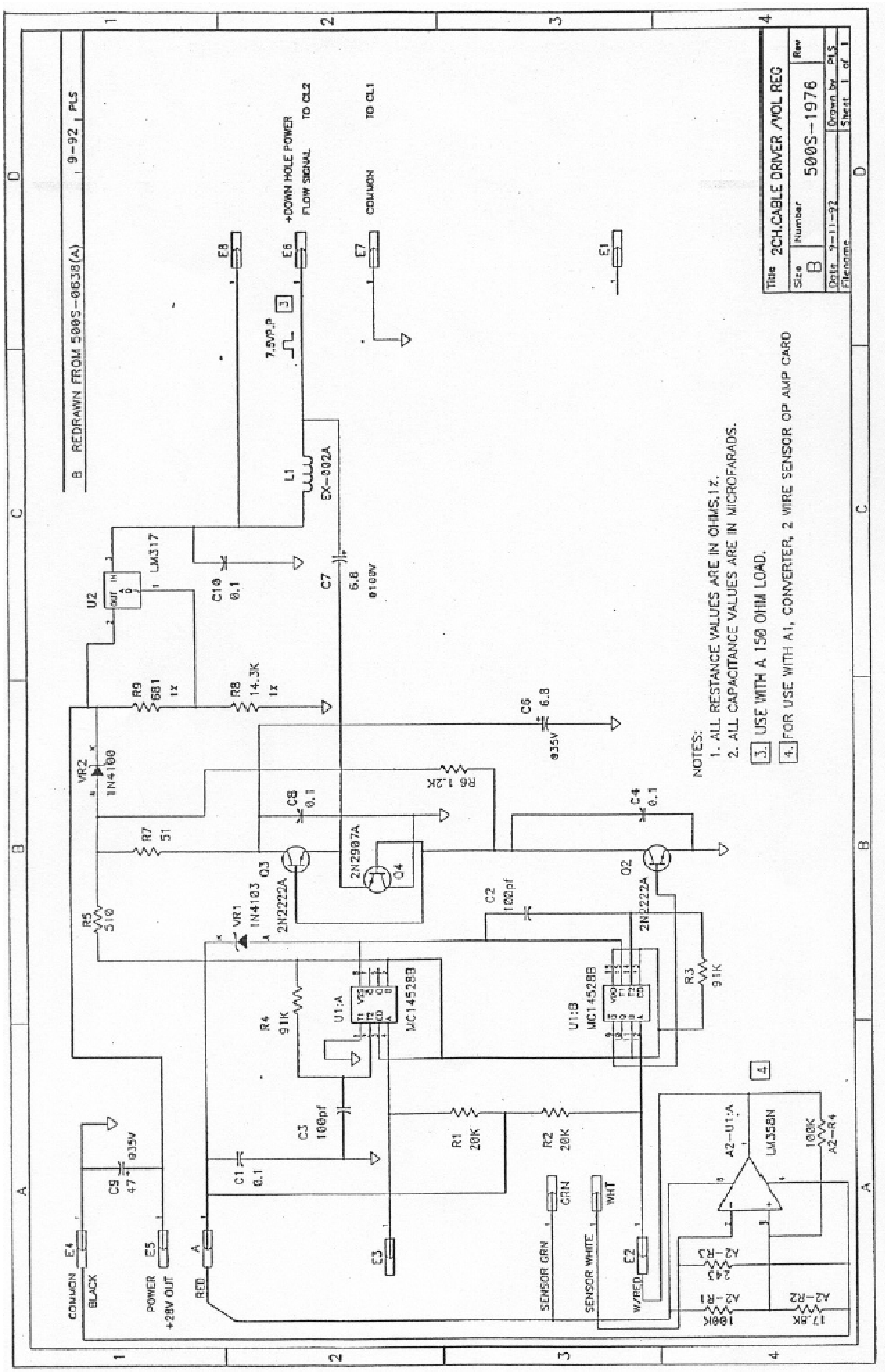
Only qualified personnel should disassemble this probe. Remove the 4 radial screws between the probe top and the electronics housing, and gently pull the probe top off of the housing. Caution should be used in this process as an o-ring is installed on the probe top and will resist this motion until freed. A twist off electrical connector will be exposed, which can be unscrewed, allowing the probe top to be removed. The electronics housing can then be unscrewed to expose the electronics of the pulse driver circuit. There are no user serviceable parts in the sensor, and it cannot be disassembled.

Schematics

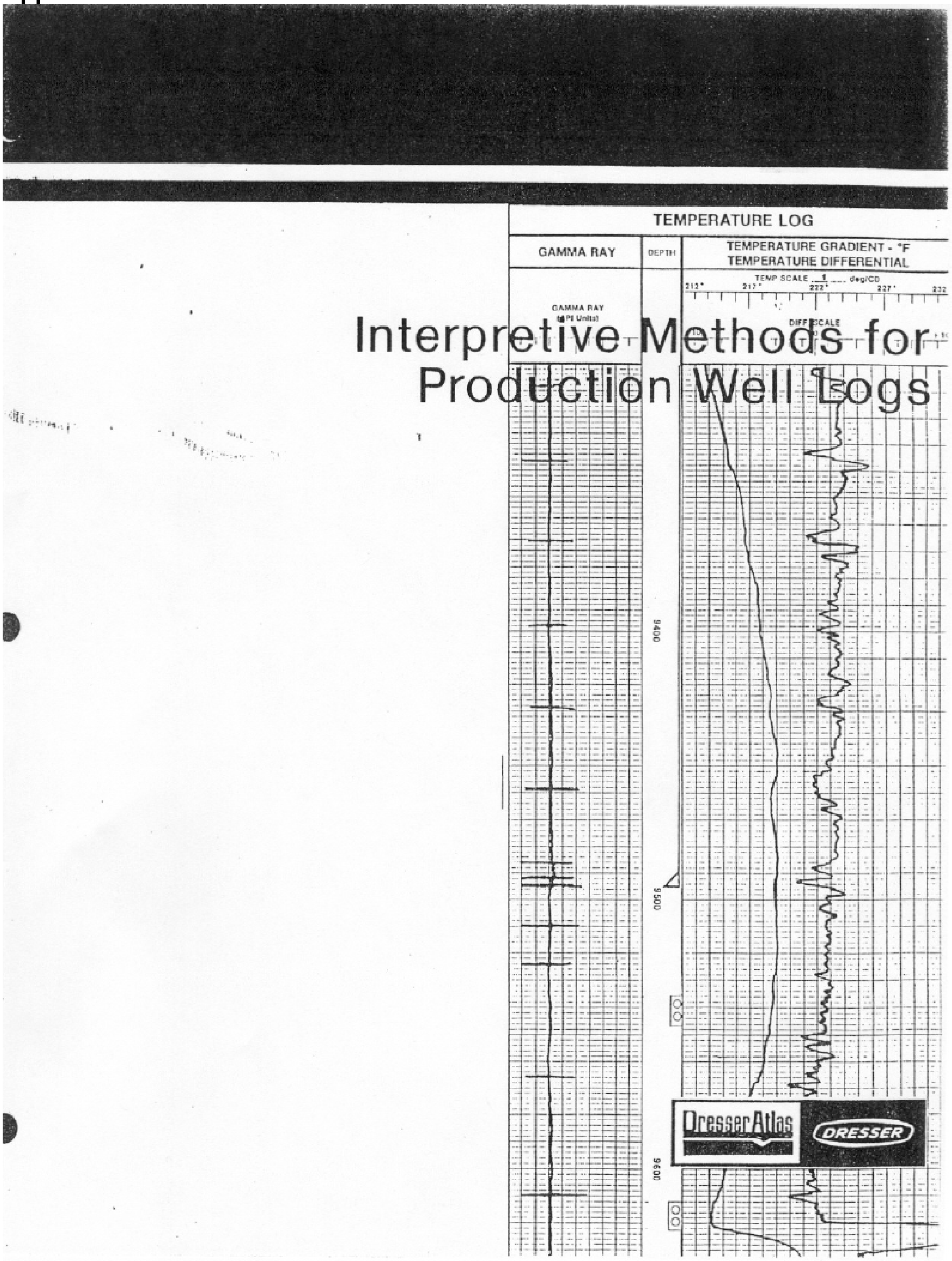
0500S-1976

Drawing Number Title Figure 1 Impeller Flowmeter




B REDRAWN FROM 500S-0638(A) 9-92 PLS
2CH.CABLE DRIVER /VOL REG
Title
Size
B
Number
500S-1976
Rev
Date 9-11-92
Filename
Drawn by PLS
Sheet 1 of 1
NOTES:
1. ALL RESTANCE VALUES ARE IN OHMS,1%.
2. ALL CAPACITANCE VALUES ARE IN MICROFARADS.
3. USE WITH A 150 OHM LOAD.
4. FOR USE WITH A1, CONVERTER, 2 WIRE SENSOR OP AMP CARD
+DOWN HOLE POWER
FLOW SIGNAL
TO CL2
COMMON
TO CL1
E8
E6
E7
E1
7.5VP.P
L1
EX-802A
U2
LM317
C10
0.1
C7
6.8
@100V
R9
681
1%
R8
14.3K
1%
C6
6.8
@35V
VR2
1N4100
R6 1.2K
C8
0.1
C4
0.1
R7
51
Q3
2N2222A
2N2907A
Q4
Q2
2N2222A
R5
510
VR1
1N4103
C2
100pf
R4
91K
U1:A
MC14528B
U1:B
MC14528B
R3
91K
C3
100pf
R1
20K
R2
20K
C5
47
@35V
C1
0.1
A2-U1:A
LM358N
100K
A2-R4
COMMON
BLACK
E4
POWER
+28V OUT
E5
RED
E3
SENSOR GRN
GRN
SENSOR WHITE
WHT
W/RED
E2
A2-R3
A2-R1
100K
A2-R2
17.8K

Application Notes Dresser Atlas



Section 2

THE CONTINUOUS SPINNER FLOWMETER: A VELOCITY MEASURING INSTRUMENT

INTRODUCTION

The Continuous Spinner Flowmeter (CSF) incorporates an impeller that is rotated by a moving fluid (Fig. 2-1). The rotating impeller is arranged to generate a series of electrical pulses which are transmitted by the wireline for receipt by surface equipment. At the surface, the pulse frequency is detected, permitting measurement of the number of revolutions per second (RPS) of the impeller. The Continuous Spinner Flowmeter continuously generates useful measurements even as the wireline (cable) is moved with or against the direction of fluid flow.

Because the purpose of the Continuous Spinner Flowmeter is to measure the velocity of the moving fluid, it is necessary to relate revolutions per second to fluid velocity. This relationship, called the response curve, is presented in Figure 2-2, where revolutions per second are represented on the vertical axis and fluid velocity appears on the horizontal. It should be noted that until the fluid velocity reaches or exceeds the value, V_T (the threshold velocity), the impeller does not rotate. As the fluid velocity increases above V_T, the RPS values increase linearly with fluid velocity; therefore, the fluid velocity is readily obtained from a measured RPS value, provided that the relationship depicted by the response curve is known.

There are a number of important considerations related to the response curve, which are summarized here. First, the response curve is somewhat idealized, especially at low fluid velocities. Second, the response curve relates revolutions per second to fluid velocity when the Continuous Spinner Flowmeter is stationary in the moving fluid. Third, the slope of the response curve depends on the diameter of the pipe in which the fluid moves. Also, the slope of the response curve is significantly affected by the viscosity of the moving fluid. Finally, the value of V_T varies somewhat with the adjustment of the impeller shaft bearings and with the viscosity and density of the moving fluid.

It is possible to derive response curves from surface data that are applicable generally to all Continuous

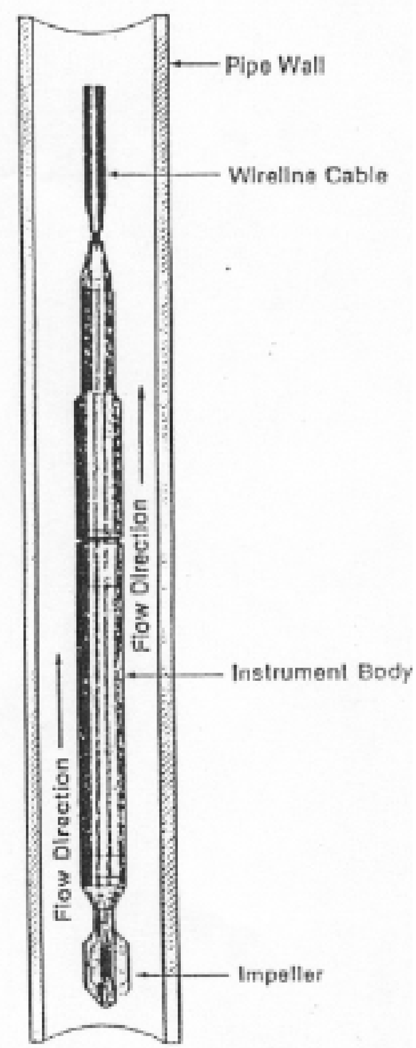


FIGURE 2-1
Continuous Spinner Flowmeter, production mode.

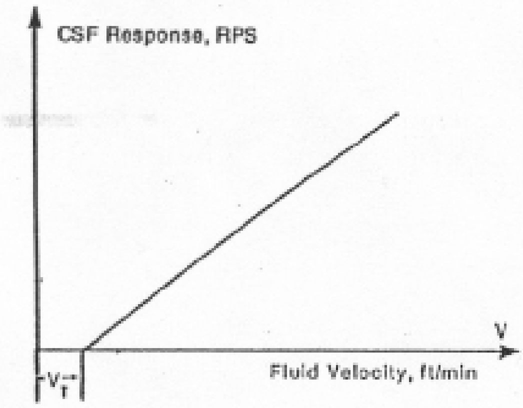


FIGURE 2-2
Typical CSF response curve, instrument stationary in moving fluid.

Spinners in all surveys. But one of the most accurate response curves is derived by calibrating a particular CSF in its downhole environment, whereby the effects of diameter, viscosity, etc., are compensated automatically. Later, calibration and presentation of the results of a Continuous Spinner Flowmeter survey are discussed in detail, but prior to such discussion the following topic considers some additional aspects of operating a CSF.

OPERATIONAL ASPECTS

Turbulent Flow

Experience has shown that the CSF measures fluid velocity very satisfactorily in single-phase, turbulent fluid flow. Therefore, the CSF is useful in injection wells and in many production wells, where the requirements of single phase and turbulence are satisfied. With regard to turbulence, the Reynold's Number is a widely used index that predicts whether turbulent fluid flow occurs.

$$N_{Re} = \frac{\rho \bar{V} d}{\mu} \qquad (2\text{-}1)$$

where

ρ = fluid density, g/cm^3

$\bar{V}$ = average fluid velocity, cm/sec

d = inside pipe diameter, cm

μ = fluid viscosity, poise

N_{Re} = Reynold's Number

Reynold's Number is dimensionless; therefore, any consistent set of units may be used, and the value of N_{Re} is transparent to the particular set of unit used, as long as the units are consistent. Because ρ and μ are frequently stated as grams per cubic centimeter and poise, consistency requires that d be measured in centimeters and $\bar{V}$ in centimeters per second. Frequently, μ is stated in centipoise. But note that the value of μ that is used in Equation (2-1) is stated in poise, not **centipoise.**

Before computing the value of N_{Re}, it is necessary to compute a value of $\bar{V}$. Usually the flow rate is expressed in barrels per day, while Equation (2-1) includes average velocity in centimeters per second. The following equation accomplishes the conversion of barrels per day to $\bar{V}$:

$$\bar{V} = (0.3637)\frac{Q}{D^2} \qquad (2\text{-}2)$$

$\bar{V}$ = average velocity, cm/sec

D = inner diameter of pipe, in.

Q = flow rate, B/D

The literature of fluid flow states that flow is laminar if the value of N_{Re} is 2000 or less, and turbulent if the value of N_{Re} is 3000 or more. For values of N_{Re} between 2000 and 3000, the flow is laminar or turbulent depending on the particular fluid and other circumstances. The response curve is valid when the flow is turbulent.

Velocity Profiles

Figure 2-3 illustrates the velocity profiles for laminar and turbulent flow. In each case the velocity at the center of the pipe, V_f, is greater than the velocities away from the center, an effect which is more pronounced for laminar flow than for turbulent. Thus, there is an average velocity across a section of the pipe, and the average velocity, $\bar{V}$, is approximately 0.83 times the value of the velocity at the center, V_f. Because the CSF is usually operated with centralizers, the velocity that is obtained from the response curve is a measure of the maximum velocity, V_f. If velocity (as measured by the CSF) is used for calculating volumetric flow rates, then the correction factor (CF) of 0.83 usually must be applied to the CSF-measured value before volumetric flow calculations proceed. Moreover, 0.83 is a typical value, and the variation of the correction factor with Reynold's Number is depicted in Figure 2-4.

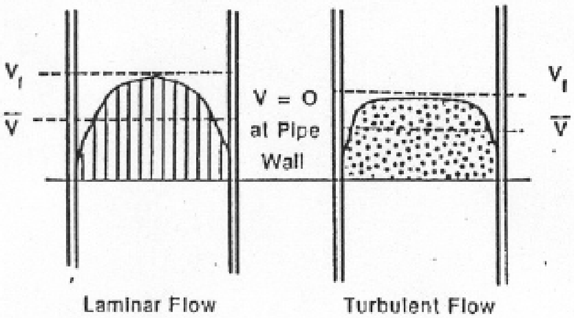


FIGURE 2-3
Velocity profiles depend on type of flow.

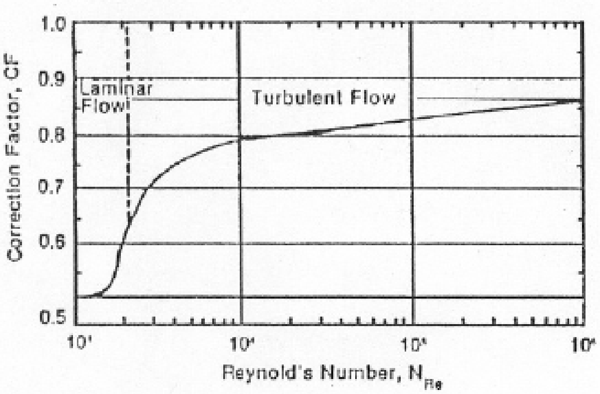


FIGURE 2-4
Correction factor variation with Reynold's Number.

Operational Modes

Referring again to Figure 2-1, the CSF is depicted in the production mode. In this mode, the direction of flow is toward the impeller end of the instrument. After passing the impeller, the flow passes the instrument body. The production mode occurs when the CSF is stationary or moves downward in a production well.

Another operational mode of the CSF is the injection mode, in which the flow moves toward the wireline end of the instrument, then along the instrument body, and finally past the impeller. The injection mode occurs when the CSF is stationary or moves upward in an injection well.

Whether in the production or in the injection mode, the occupancy required by the impeller is not significant; therefore, Equations (1-9) and (1-10) should be used for performing velocity conversions when the measured velocity is obtained with the CSF. These equations are preferred because they neglect tool occupancy.

RPS-Cable Velocity Relationship

Because the CSF may be used when stationary and in motion, it is helpful to consider the relationship of the RPS value to cable velocity as the CSF is moved at various speeds through a moving fluid of constant velocity profile. This relationship is shown in Figure 2-5, which is not a response curve, because the horizontal axis now represents the cable velocity in feet per minute.

As the cable velocity increases in the direction against fluid flow, the RPS value increases. As the cable velocity increases in the direction with fluid flow, the RPS value decreases to zero and remains at zero for an interval of cable velocities that is twice V_T ($2 \times V_T$) long. Then as the cable velocity further increases in the direction with fluid flow, the RPS value begins increasing negatively, which merely means that the impeller's direction of rotation is reversed. The design of the CSF is such that the instrument generates useful RPS measurements regardless of rotational direction. A further advantage of the CSF is that the magnitude of the electrical pulses from the instrument is greater for rotation in one direction than for the other. By monitoring the pulse magnitude, the surface equipment monitors not only the RPS value but also the rotational direction.

Also note in Figure 2-5 that the cable velocity interval of length $2 \times V_T$, over which the RPS value is zero, is centered around a cable velocity whose value is

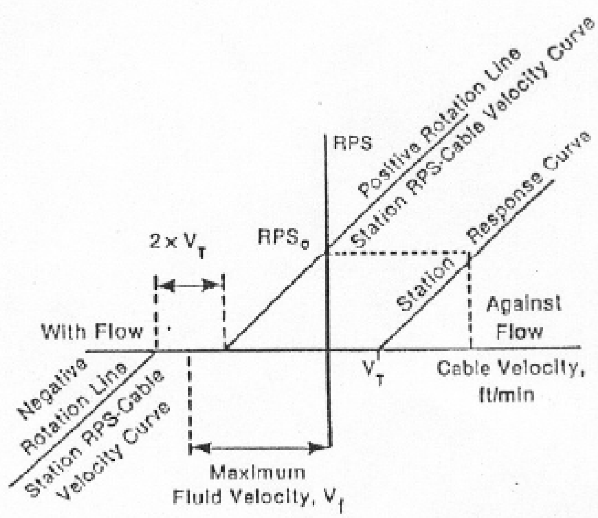


FIGURE 2-5
RPS-cable velocity curve for a single station.

equal to the maximum fluid velocity, V_f. As mentioned, the fluid velocity profile is constant for the purposes of Figure 2-5.

As will be shown, the CSF may be moved through a moving fluid at various cable velocities, simultaneously obtaining data for a determination of the response curve in the instrument's downhole environment, as well as data indicative of the desired fluid velocity measurements. While data obtained with the CSF in motion are essential for determining the response curve downhole, accurate data for measuring fluid velocity may be obtained with the CSF stationary. In Figure 2-5, the RPS value corresponding to the CSF stationary is indicated by RPS_o. If a value of RPS_o is not available, data obtained with the CSF in motion may be used, as will be explained.

PRESENTATION OF RESULTS AND DOWNHOLE CALIBRATION

There are three basic methods of presenting the results of a CSF survey or calibrating the CSF in its downhole environment. The three methods are presented below.

Method 1

In Method 1, flow rates are presented as a percentage of the total flow rate. There are some variations of this basic scheme.

First Variation: Downhole flow rates are presented as a variable ranging from 0% to 100%, but no B/D value is attributed to any rate.

Second Variation: 100% flow rate is known in barrels per day at the surface, and percentages of the total flow rate from the downhole survey are converted to their corresponding B/D values (at surface conditions). Therefore, the downhole flow rates are presented as barrels per day, adjusted to surface conditions.

Third Variation: 100% flow rate is known in barrels per day at downhole conditions, and percentages of the total flow rate from the downhole survey are converted to their corresponding B/D values. Therefore the downhole flow rates are presented as barrels per day at downhole conditions.

In both the second and third variations, the total flow rate in barrels per day must be known independently of the survey. In these variations, the accuracy of the presentation is no better than the accuracy with which 100% flow rate is stated as barrels per day.

To perform the survey, the CSF is moved through the fluid at constant cable velocity until the entire vertical interval of the survey is measured and recorded. In particular, this phase of the survey measures revolutions per second of the CSF corresponding to 100% flow. To complete the survey, it is necessary to record revolutions per second of the CSF while it is moving at the same constant cable velocity through a stationary column of the fluid. This may be accomplished during the survey if there is a standing column of fluid in the wellbore. If there is no standing column, the well may be shut in, upon which the desired RPS value may be measured. One or the other of these measurements provides the measured revolutions per second of the CSF corresponding to 0% flow.

To convert measured RPS values to percentages of total flow rate, the following equation is used:

$$PTF(M) = \frac{RPS(M) - RPS(0)}{RPS(100) - RPS(0)} \times 100 \qquad (2\text{-}3)$$

where

RPS(0) = RPS at 0% flow rate

RPS(100) = RPS at 100% flow rate

RPS(M) = measured value of the revolutions per second of the CSF for which the percentage of total flow rate is desired

PTF(M) = percentage of total flow rate that corresponds to RPS(M)

By inspection, it is evident that the equation calculates PTF(0) = 0 when RPS(M) is set equal to RPS(0). Also the equation calculates PTF(100) = 100 when RPS(M) is set equal to RPS(100).

Use of Equation (2-3) results in values of percentage of the total flow rate. If a B/D value corresponding to 100% flow rate is known, a percentage obtained from the above equation should be divided by 100 and the resulting fraction multiplied by the barrels per day associated with total flow, to calculate the number of barrels per day corresponding to the percentage value.

Method 1 tacitly assumes that the inside pipe diameter is constant over the entire vertical range of the flow survey. If the diameter varies significantly, the percentages obtained from measured RPS values using Equation (2-3) are subject to significant error. For varying diameters, the following procedure should be used. A final point is that Method 1 assumes that the viscosity of the moving fluid is constant over the vertical interval of the flow survey. The requirement of constant viscosity is usually satisfied in injection wells and wells that produce a single fluid from a single reservoir. If more than one reservoir is producing, the constant viscosity requirements may not be fulfilled.

Compensation For Varying Diameter

The following equation compensates Method 1 for varying inside pipe diameters:

$$PTF(M) = \frac{RPS(M) - RPS(0)}{RPS(100) - RPS(0)} \times 100 \quad (2\text{-}4)$$

$$\times \left(\frac{D_2}{D_1}\right)^2$$

where

$RPS(100)$ = CSF response in 100% flow, diameter, D_1, in.

$RPS(0)$ = CSF response in zero flow, diameter preferably D_1, in.

$RPS(M)$ = CSF response in intermediate flow, diameter D_2, in.

Example

Referring to Figure 2-6, calculate the flow rate of water to Zone A after treatment, using Equation (2-3).

At Station 1,

$$PTF(M) = \frac{33 - 5}{33 - 5} \times 100 = 100\%$$

At Station 2,

$$PTF(M) = \frac{23 - 5}{33 - 5} \times 100 = 64.3\%$$

The flow rate to Zone A therefore is 100% − 64.3% = 35.7% (of total flow rate). To determine the flow rate to Zone A in barrels per day, use 23,000 B/D as the rate in 100% flow. Then the flow rate to Zone A is:

$$\frac{35.7 \times 23000}{100} = 8211 \text{ B/D}$$

Problem

Figure 2-6 shows the results of two CSF surveys of a water injection well. We are interested in the distribution of injected water among the various zones after treatment, when the total injection rate is 23,000 B/D.

1. By inspection of the CSF profile, which zones probably are not taking water?

2. Using Equation (2-3), calculate the flow rate in barrels per day to each of the following:

   Q to Zone A____________________ B/D

   Q to Zone D____________________ B/D

   Q to Zone E____________________ B/D

3. What is the likelihood of a standing water column below Zone E?

4. Sum the barrels per day to Zones A, D, and E:

   ____________________ B/D.

   How much is the difference between your answer and 23,000?

   ____________________ B/D.

5. Is the rate of flow to Zone A greater than or less than the rate before treatment? How much different is the rate of flow to Zone A after treatment than before?

   ____________________ B/D.

Method 2

Method 2 permits presentation of the downhole flow rates in barrels per day without reliance upon an independent measurement of the number of barrels per day corresponding to 100% flow. Furthermore, Method 2 does not rely upon the assumption of constant pipe diameter, which is tacitly made in Method 1. Although Method 2 results in volumetric flow rates stated in bottomhole barrels per day, these rates may be converted to surface barrels per day by application of the appropriate formation volume factors. While Method 2 has distinct advantages over Method 1, it also requires more data, as described below.

Method 2 frequently is referred to as the downhole calibration of the CSF. The difference between Methods 1 and 2 is largely a difference in degree of the amount of data that is acquired for downhole calibration purposes. Also, Method 2 requires more computation to arrive at a final presentation of the survey results stated in barrels per day at downhole conditions.

As a first step, a series of stations is defined. A station is a specific depth at which the flow rate is to be measured. The stations usually are at depth intervals above or below perforated zones as shown in Figure 2-6. Then the CSF is moved through the fluid at various constant cable velocities, and the RPS

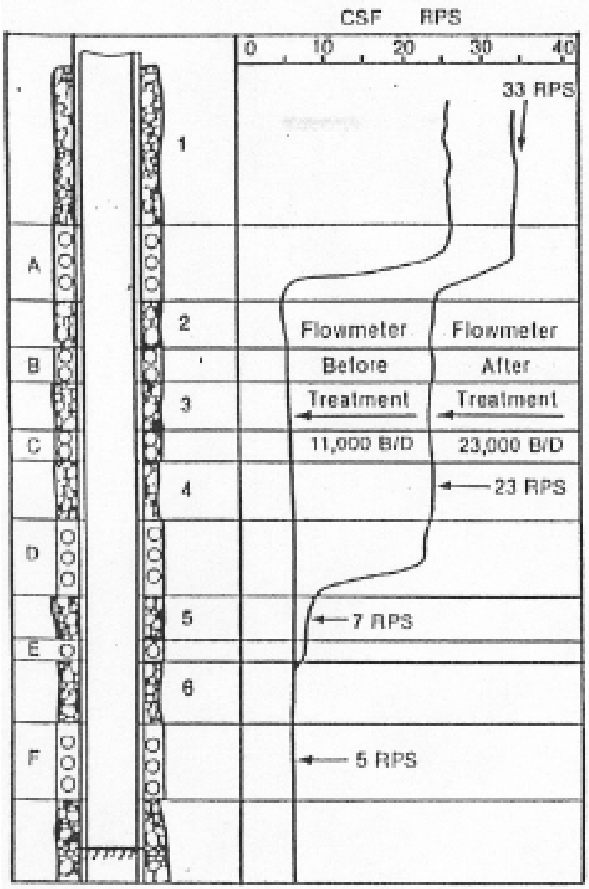


FIGURE 2-8
Water Injection well with CSF survey before and after treatment.

response at each station is recorded for each cable velocity. Recorded RPS values thus are associated with specific stations. The process of recording RPS values at defined stations is performed at two or three distinct cable velocities both with and against the direction of fluid flow. If it is desired to determine V_T in the downhole environment, then RPS data must be recorded for impeller rotation in both directions to define the interval $2 \times V_T$ shown in Figure 2-5. Preferably, although not absolutely necessary, the RPS response also is recorded at each station with the CSF stationary (RPS_0 in Fig. 2-5).

Because Method 2 relies upon the response curve previously discussed with respect to Figure 2-2, the RPS values associated with each station are plotted against cable velocity. When RPS values are plotted against cable velocity for a station, the plotted points lie essentially on a straight line whose slope is the slope of the response curve for the station (see Fig. 2-5). To define the response curve for the station, a straight line is drawn having the slope just discussed, but intersecting the fluid velocity axis at V_T, the value of the threshold velocity. The value of V_T may be measured downhole or a surface-measured value may be used.

In the preferred application of Method 2, a response curve is defined for each station. Thus, there is a one-on-one correspondence between the response curves and the stations. A response curve should be defined for each station whenever it is suspected that there are viscosity variations among the stations or that the inner pipe diameter varies among the stations. If there are no such variations, the plots of the RPS values against cable velocity should be reasonably parallel (see Fig. 2-7), and it is justified to use a single response curve that applies universally to all stations. If the plots are not parallel, this is a strong indication that the variations just described do exist, in which case individual response curves are advisable.

Having defined the response curve or curves, the next step is to determine the fluid velocity at each station. If a stationary RPS measurement has been recorded for a station, that value should be used with the station's response curve to obtain the fluid velocity at the station (see dashed line, Fig. 2-5). If there is no stationary RPS value, the RPS-cable velocity curve for the station intersects the RPS-axis at a value which approximates the stationary RPS response, as in

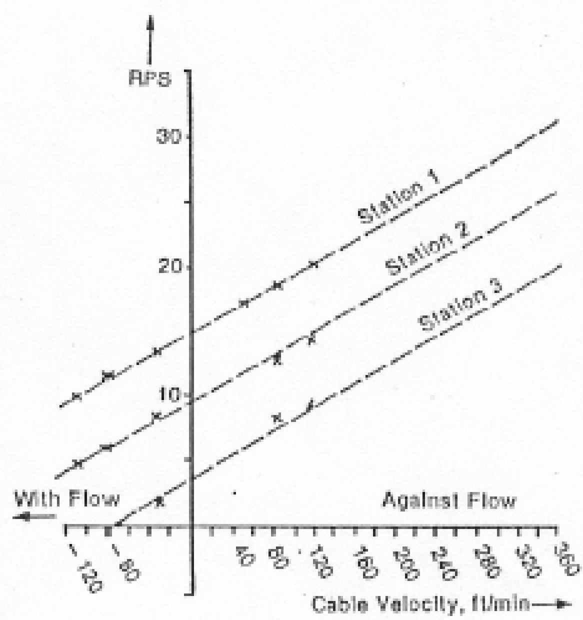


FIGURE 2-7
RPS-cable velocity data for multiple stations in a production well. Station 1 is above all of the perforations. Station 2 is below Station 1. Station 3 is below Station 2. Stations 2 and 3 should be located between perforated intervals.

Figure 2-7. In absence of a stationary RPS value, use the RPS-axis intercept value for the station in combination with the station's response curve to determine the fluid velocity at the station.

Because the CSF is usually operated with centralizers, the fluid velocities obtained for the stations must be adjusted to determine the average fluid velocities. A good first approximation is to multiply each velocity by 0.83 to define the corresponding average velocity, $\bar{V}$. If more accuracy is desired, the Reynold's Number may be used to determine the value of the correction factor, as previously described (see Fig. 2-4).

A final computation transforms average velocity values into B/D values for the defined stations. An average velocity, $\bar{V}$ (ft/min), is multiplied by the cross-sectional area, A, of the inside of the pipe or casing expressed in square feet, and the product is divided by a factor of 5.615 to obtain volumetric flow in barrels per minute, which is proportional to the desired B/D value. Briefly,

$$Q = \frac{\bar{V} \times A}{5.615} \times (60 \times 24) \qquad (2\text{-}5)$$

$$= \bar{V} \times A \times 256.46 \text{ B/D}$$

where $\bar{V}$ is obtained from operations described above, while A is calculated as follows:

$$A = \frac{\pi D^2}{4 \times 144}$$

$$A = 0.005454\,(D^2) \qquad (2\text{-}6)$$

where A is stated in square feet, and D is the inner pipe diameter in inches.

Procedure For Using Method 2

The following procedure is useful when Method 2 is applied to data from a CSF survey. For an RPS-cable velocity line at a station:

$$RPS = a + b \times \text{ cable velocity,} \qquad (2\text{-}7)$$

a and b constants defining the line's intercept and slope

Equation (2-7) defines a line corresponding to positive or negative rotation at a station, but not both rotations. Again, see Figure 2-5.

Y_i = RPS of CSF at the station, from CSF survey

X_i = cable velocity, ft/min, corresponding to Y_i (values of X_i against flow are positive, values of X_i with flow are negative)

i = 1, 2, ... N, where N is the total number of data points being used to define the RPS-cable velocity line at a station.

$$b = \frac{N\Sigma X_i Y_i - \Sigma X_i \Sigma Y_i}{N\Sigma X_i^2 - (\Sigma X_i)^2} \qquad (2\text{-}8)$$

$$a = \frac{(\Sigma X_i)(\Sigma X_i Y_i) - (\Sigma Y_i)(\Sigma X_i^2)}{(\Sigma X_i)^2 - N\Sigma X_i^2} \qquad (2\text{-}9)$$

For the response curve corresponding to the RPS-cable velocity line defined by Equations (2-8) and (2-9), assuming V_T is known:

$$RPS = b \times (V_f - V_T), \text{ for fluid velocity} > V_T \qquad (2\text{-}10)$$

$$RPS = 0 \text{ for fluid velocity} \leq V_T \qquad (2\text{-}11)$$

V_f = maximum fluid velocity

For the fluid velocity at the station, using the response curve for the station defined by Equation (2-10): let RPS_o be the measured RPS at the station with the CSF stationary.

$$\frac{RPS_o}{b} + V_T = \text{maximum fluid velocity} \qquad (2\text{-}12)$$

$$= V_f$$

However, if no stationary RPS measurement is available, use (a) for the station from Equation (2-9).

$$\frac{a}{b} + V_T = V_f = \text{maximum fluid velocity} \qquad (2\text{-}13)$$

For volumetric flow in barrels per day (downhole):

$$V_{fc} = V_f \times \text{correction factor,} \qquad (2\text{-}14)$$

where the correction factor is typically 0.83, or may be determined from Reynold's Number and Figure 2-4, and:

$$Q = V_{fc} \times D^2 \times 1.4 \qquad (2\text{-}15)$$

D = inner pipe diameter, in.

For emphasis, it is restated that Equation (2-7) represents a station's RPS-cable velocity line, either for positive rotation or for negative rotation, but not both. If it is desired to represent both RPS-cable velocity lines, then the parameters a and b must be determined for the positive rotation line, and separately for the negative rotation line (Fig. 2-5). It is necessary to represent both lines only if V_T is to be determined from the downhole environment, in which case the CSF survey data must be sufficient to define the station's RPS-cable velocity lines for positive and negative rotation. If the value of V_T is derived from surface-measured data, it is necessary to define only one of the RPS-cable velocity lines for the station. Usually, the positive rotation line is used. The procedure just stated for using Method 2 is designed to represent one of the RPS-cable velocity lines at a subject station. An example using Method 2 appears under "Example Logs."

Method 3

In Method 3, RPS values are related to effective velocity at the impeller through a standard response curve. First, an RPS value is used to determine the corresponding value of effective velocity from the standard response curve. Then the corresponding cable velocity is added to or subtracted from the effective velocity to obtain the fluid velocity. Finally, the volumetric flow rate in barrels per day is calculated as in Method 2.

Procedure For Using Method 3

The standard response curve is defined as:

$$RPS = -b \times V_T + b \times \text{effective velocity}$$

where

V_T = threshold velocity, ft/min

b = slope of standard response line, RPS/ft/min

RPS(M) is a measured RPS value at a corresponding cable velocity, CV(M), in ft/min. Therefore,

$$\frac{RPS(M) + bV_T}{b} = \text{effective velocity}(M) \quad (2\text{-}16)$$

If the cable is moving against flow, then the cable velocity is subtracted from the effective, to obtain the maximum fluid velocity:

$$V_f = \text{effective velocity (M)} - CV(M) \quad (2\text{-}17)$$

This assumes CV(M) is positive.

If the cable is moving with the flow, then the cable velocity is added to the effective to obtain the maximum fluid velocity:

$$V_f = \text{effective velocity (M)} + CV(M) \quad (2\text{-}18)$$

This assumes CV(M) is positive.

Then Q is calculated according to:

$$Q = V_f \times \text{correction factor} \times (D)^2 \quad (2\text{-}19)$$

$$\times\ 1.4,\ B/D$$

D = inner pipe diameter, in.

Of course, Method 3 may be used for RPS values recorded with the CSF stationary, in which case the calculated effective velocity is the same as the maximum fluid velocity, V_f.

A point to be noted with respect to Method 3 is that the slope of the standard response curve, (b), typically is greater in the production mode than in the injection mode. For a 1-11/16 in. CSF in water, the value of (b) in the production mode exceeds the value of (b) in the injection mode by approximately 10%. An example using Method 3 appears under "Example Logs."

Problem

The data in the table below were derived from an actual CSF survey. RPS_0 means that the RPS values were measured with the CSF stationary. RPS values designated down and up indicate responses obtained with the CSF in motion.

1. Are the data for an injection or a production well?
2. For Station 1, determine the slope of the RPS-cable velocity line, (b), using Equation (2-8).

   Note: When using Equation (2-8), velocities against flow are positive; velocities with flow are negative.
3. Using V_T = 2 ft/min and the station reading for Station 1, what is the velocity of flow, V_f, at Station 1?
4. If the inner pipe diameter is 6.276 in., how many barrels per day are flowing at Station 1?
5. Compute the value of (a) using Equation (2-9), and then compute the flow velocity and barrels per day for Station 1 based on (a).

TABLE 2-1

Logging Speed and Direction	CSF RPS Station 1	Station 2	Station 3	Station 4
Down 115 ft/min	20.15	14.60	9.20	5.10
Down 82 ft/min	18.50	13.00	8.35	3.50
Down 50 ft/min	17.20	11.60	5.40	2.10
RPS_o	14.65	9.65	3.15	—
Up 32 ft/min	13.30	8.30	1.85	−1.05
Up 80 ft/min	11.50	6.30	—	−3.05
Up 110 ft/min	9.85	4.75	—	−4.60

1. Well is injection __________, production __________. Check one.
2. At Station 1 the value of (b) is __________ RPS/ft/min.
3. At Station 1 the value of V_f is __________ ft/min.
4. At Station 1 the flow rate is __________ B/D.
5. At Station 1 the value of (a) is __________ RPS.
6. Based on (a), the flow rate at Station 1 is __________ B/D.

EXAMPLE LOGS

A Continuous Spinner Flowmeter was run in an oil well that was producing some water. At a depth of 6470 ft, a companion Fluid Density Log showed that the fluid was salt water (see Fig. 2-8). The CSF was run downward at 6470 ft, and was also stationary. The following responses of the CSF were recorded (see Fig. 2-9):

RPS	CABLE VELOCITY, ft/min
1	0
2.5	40
5.5	80
6.8	120

All CSF responses with the instrument in motion were recorded with the instrument moving against the direction of flow. The internal diameter of the casing at 6470 ft was 2.5 in.

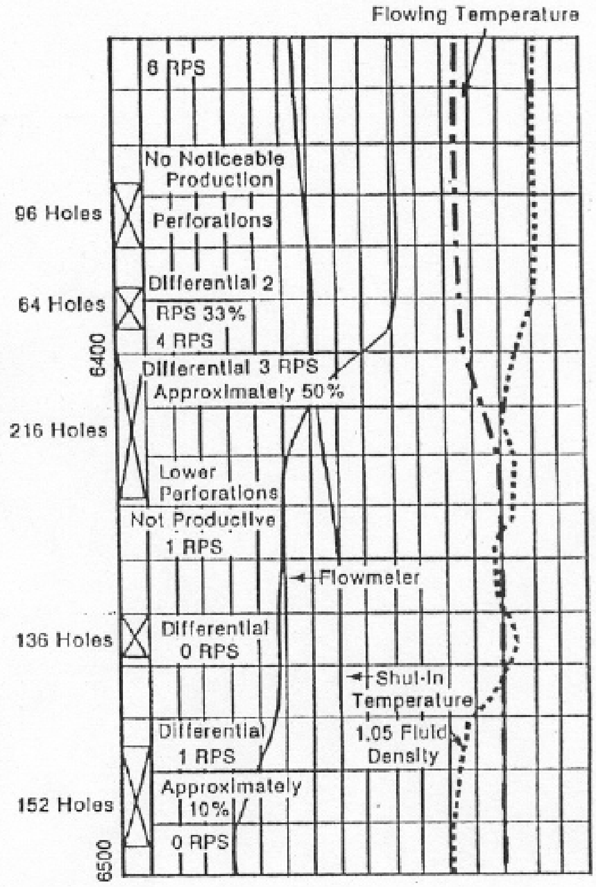


FIGURE 2-8
Logs of oil well producing water.

The CSF responses are plotted against cable speed in Figure 2-10, and a solid straight line is drawn as an approximate "fit" to the response data. The equation of this approximate fit is:

$$RPS = 0.75 + 0.055 \times \text{cable velocity}$$

This approximate fit is not the response curve at 6470 ft however.

A more accurate fit is obtained by using Equations (2-8) and (2-9) of Method 2, as follows. The data are arranged as X_i and Y_i data pairs:

X_i	Y_i
0	1.0
(+) 40	2.5
(+) 80	5.5
(+)120	6.8

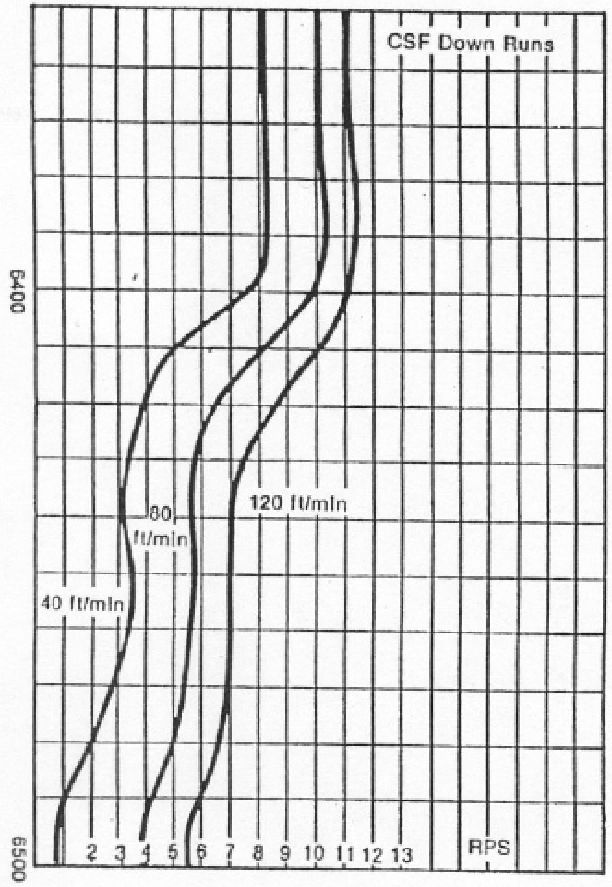


FIGURE 2-9

CSF down runs in oil well producing water.

Cable velocities against flow are assigned positive values, as shown. The following summations result in the values shown:

$$\Sigma X_i = 240 \qquad \Sigma X_i Y_i = 1356$$

$$\Sigma Y_i = 15.8 \qquad \Sigma X_i^2 = 22{,}400$$

Then evaluation of Equation (2-8) results in b = 0.051 RPS/ft/min. Equation (2-9) results in a = 0.890 RPS. Therefore, the best fit to the RPS-cable velocity data is:

$$\text{RPS} = 0.890 + 0.051 \times \text{cable velocity}$$

Note that the best fit is not the response curve at 6470 ft, but that the value of b is the slope of the response curve. The best fit is shown in Figure 2-10 by a dashed straight line.

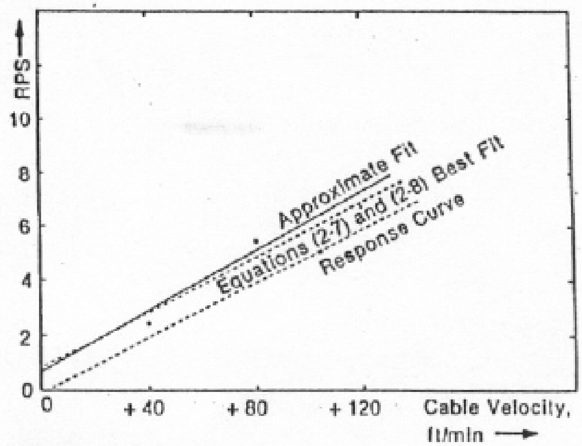


FIGURE 2-10

Best fit and response curve, CSF field example.

The value of V_T, the threshold velocity, is approximately 2-3 ft/min. Therefore, the response curve is drawn on Figure 2-10 with a slope of 0.051 (parallel to the dashed line) and with an X-axis intercept of 2.5 ft/min.

Using Equation (2-12), the fluid velocity at 6470 ft is estimated as:

$$1/0.051 + 2.5 = 22.11 \text{ ft/min}$$

This estimate is based on the response curve, and the RPS recorded with the CSF stationary at 6470 ft (RPS_o).

Using Equation (2-13), which is based on the response curve and the best fit value for (a) (a = 0.89), the fluid velocity is estimated as:

$$0.89/0.051 + 2.5 = 19.95 \text{ ft/min}$$

Also, the fluid velocity at 6470 ft may be estimated using the recorded RPS values with the cable moving, together with the response curve. However, the value from the response curve must be adjusted for the cable velocity to obtain the estimated fluid velocity, as in Method 3:

$$2.5/0.051 + 2.5 - 40 = 11.52 \text{ ft/min}$$

$$5.5/0.051 + 2.5 - 80 = 30.34 \text{ ft/min}$$

$$6.8/0.051 + 2.5 - 120 = 15.83 \text{ ft/min}$$

It is evident that the estimates of fluid velocity at 6470 ft vary considerably when Method 3 is used.

As between the approximate fit and the best fit, the best fit (using Equations 2-8 and 2-9) is preferred, the approximate fit being merely a check on the accuracy of computation. Therefore, the best fit is the preferred method of estimating the slope and intercept of the straight line relating RPS to cable velocity.

With respect to estimating the fluid velocity at 6470 ft, either the stationary response or the best fit intercept (a) is preferred over RPS values recorded with the instrument moving. In other words, Equations (2-12) and (2-13) are the preferred methods of calculating the fluid velocity, V_f. Notice that the results obtained from Equations (2-12) and (2-13) agree within 10%.

Using Equations (2-14) and (2-15), the flow of salt water at 6470 ft is calculated on the basis of a 2.5-in. inside casing diameter, and 20 ft/min fluid velocity:

$$20 \times 0.83 \times (2.5)^2 \times 1.4$$

$$= 145.3 \text{ B/D, downhole conditions}$$

The recorded water production at the surface is 150 B/D; therefore, it is reasonable to conclude that all of the water is produced below 6470 ft. To verify that the flow at 6470 ft is turbulent,

$$\bar{V} = (0.3637)\,\frac{150}{(2.5)^2}$$

$$= 8.73 \text{ cm/sec, using Equation (2-2).}$$

Then Reynold's Number is calculated from Equation (2-1) as:

$$N_{Re} = \frac{1.05 \times 8.73 \times 6.35}{10^{-2}} = 5821,$$

using one centipoise as a typical viscosity of water, and converting 2.5 in. to 6.35 cm. Therefore, the flow is turbulent.

Stationary CSF responses also were recorded at 6440 ft, 1 RPS; 6395 ft, 4 RPS; and 6380 ft, 6 RPS. Because the stationary response at 6470 ft is 1 RPS, a perforated interval between 6440 ft and 6470 ft is not producing significantly. An interval between 6395 ft and 6430 ft causes the RPS to increase from 1 to 4 (oil and dissolved gas production). A second interval of oil and dissolved gas production between 6394 ft and 6386 ft raises the RPS response from 4 to 6. Therefore, the first interval produces 3/5, or 60% of the oil, and the second interval produces 2/5, or 40%. The CSF response does not increase from 6 RPS across a top-most interval above 6380 ft, leading to the conclusion that the top-most interval also is not producing significantly.

The following summarizes the CSF down runs at a depth in total flow:

RPS	CABLE VELOCITY (ft/min)
6.00	0
7.85	40
10.15	80
11.50	120

Using Equations (2-8) and (2-9), the intercept and slope of the straight line best describing the relationship of RPS to cable velocity are:

$$a = 6.055$$

$$b = 0.047$$

based upon

$$\Sigma X_i = 240$$

$$\Sigma Y_i = 35.5$$

$$\Sigma X_i^2 = 22{,}400$$

$$\Sigma X_i Y_i = 2506$$

Using Equation (2-13), the velocity, V_f, in total flow is:

$$\frac{6.055}{0.047} + 2.5 = 131.33 \text{ ft/min}$$

Then the total flow rate from Equations (2-14) and (2-15) is:

$$131.33 \times 0.83 \times (2.5)^2 \times 1.4 = 953.8 \text{ B/D}$$

The total flow rate is the combined flow rate of water and oil with dissolved gas at downhole conditons. At the surface the reported production is 800 BOPD and 150 B/D (water), plus free gas.