WIERTNICTWO NAFTA GAZ • TOM 24 • ZESZYT 1 • 2007

Ali Qureshi*, Stefan Miska, Włodzimierz Miska*****

ANALYSIS OF THE USE OF A DOWN-HOLE MECHANICAL CLEANING DEVICE FOR EFFICIENT WELLBORE CLEANING

1. INTRODUCTION AND EXPERIMENTAL SETUP

The tool analyzed for this study is called the Mechanical Cleaning Device (MCD, see Fig. A-1) and is an integral drill string component consisting of a short mandrel with no moving parts, shaped in such a way so as to stimulate any cuttings which have a tendency to settle out of the mud in the high angled sections of the well bore. These sections could be inside the casing or in open hole; the tool is adaptable to suit several environments.

Testing on the MCD was carried out on the Tulsa University Drilling Research Projects' Low Pressure Ambient Temperature (LPAT) flow loop (Fig. A-2). The LPAT flow loop is a well bore simulator which can be used to carry out experiments for a wide range of input parameters like flow rate, drilling fluid type, cuttings size and type, rate of penetration (ROP), drill string rotational speed (RPM), and different hole inclination angles. It consists of a 100 feet long transparent test section with a 4-1/2″ OD drill pipe in an 8″ ID outer acrylic pipe. The use of acrylic for the outer pipe facilitates visual observations of flow patterns in the annulus. A centrifugal pump is used to establish the flow of the drilling fluid from the mud tank. The injection tank and the auger are used to inject cuttings into the fluid stream, at a specified rate of penetration, into the test section. This closely simulates a drilling process. The cuttings travel and form a bed in the test section. They flow through the upper end of the flow loop into the shale shaker, which separates the cuttings and the fluid. The cuttings fall into the cuttings collection tank and the drilling fluid goes into the mud tank. At steady state, the rate of injection (ROI) equals the rate of collection (ROC) and, depending upon the flow rate and inclination angle, a cuttings bed is formed in the test

* OMV
** University of Tulsa
*** Drilling, Oil and Gas Faculty AGH-UST, Kraków

section. Data pertaining to pressure drops across three locations on the test section, flow rate, rates of injection and collection, collection tank weight, injection tank weight, torque, and other parameters is recorded in the form of an excel spreadsheet by the data acquisition system. Pertinent information from this spreadsheet can be filtered out and analyzed by generating plots from the data. The discussion that appears later in the report follows this methodology of data analysis.

Experiments on the MCDs were performed with two drilling fluids, water and polymer, at various flow rates, pipe rotation speeds and inclination angles. The test matrix is given in Table A-1 while the polymer rheological parameters are provided in Table A-2. The database obtained from the experiments provided a comparison of in-situ cuttings concentration with and without the MCDs installed and was used to quantify the cleaning efficiency of this tool.

2. DISCUSSION OF RESULTS

One of the most important parameters studied was the *in-situ* volumetric cuttings concentration (C_c). C_c is a dimensionless parameter which can be calculated from the steady--state weight of the cuttings inside the test-section. It is expressed as a percentage and is given by

$$C_c = \frac{V_c}{V_A} \cdot 100,$$

where:

V_c – volume (in ft^3) of cuttings inside the annulus at steady state,
V_A – volume (in ft^3) of the annular test section.

Plotting C_c against flow rate and pipe rotational speeds provides quantitative results for the improvement in cuttings transport achieved. These graphs are provided in the appendix and are referred to in the discussion that follows. The analysis in this report focuses on the effect of flow rate and pipe rotational speed on volumetric cuttings concentration and bed heights.

3. EFFECT OF FLOW RATE AND PIPE ROTATIONAL SPEED ON VOLUMETRIC CUTTINGS CONCENTRATION

Tool Performance with Water at 90° Inclination Angle

Figures A-3 and A-4 show C_c *vs*. water flow rate at 90° inclination angle and 40 rpm and 80 rpm pipe rotational speeds respectively. A decrease in C_c is obtained with increasing water flow rate, which is expected. Additionally, these plots indicate that higher cuttings concentration is obtained when 1 MCD is placed in the drill string. This behavior is unexpected and possible reasons to explain it can only be speculated upon.

Tool Performance with Water at 45° Inclination Angle

At 45° inclination angle, no appreciable difference in C_c is obtained by the use of the MCDs even at higher flow rates and pipe rotational speeds (Fig. A-5). Data for polymer at 45° could not be obtained because of a break-down on the flow loop.

Tool Performance with Polymer at 90° Inclination Angle

Figures A-6 and A-7 show the cuttings concentration plotted against polymer flow rate at 90° inclination angle and 40 rpm and 80 rpm pipe rotational speeds respectively. It can be seen that the cuttings concentration drops with increase in the flow rate both with and without the MCDs. This is expected because a higher flow rate results in higher turbulence and higher interfacial shear stress at the surface of the bed. As a result, more cuttings are removed and a decrease in C_c with increasing flow rate is registered. The presence of the tools reduces C_c, although increasing the number of tools did not significantly reduce the cuttings concentration.

An important reason for using a cleaning device is to reduce the cuttings concentration in the hole without having to increase the pumping rate. The MCDs under investigation show such a saving in pumping rate as is seen in Figures A-6 and A-7. In Figure A-6, at flow rate of 300 gpm, a C_c of approximately 20% is obtained. It can be seen that the same C_c can be maintained with 2 MCDs with only 260 gpm flow rate. This means that the presence of the devices resulted in approximately 13% reduction in the flow rate. In case of Figure A-7, the reduction is 33%.

Comparison between Water and Polymeric Fluid

Figure A-8 shows the effect of flow rate on the cuttings concentration when two different fluids are used (at 80 rpm pipe rotational speed and with 1 tool in the drill-string). As before, a decrease in volumetric cuttings concentration (C_c) is seen with increase in the flow rate, which is in agreement with the expected behavior. At the same time, a significant decrease in C_c is obtained with the use of polymeric drilling fluid. From this graph, it is concluded that the polymer is a better fluid for cuttings transport than water for this case. Because of its higher viscosity and cuttings carrying capacity as compared to water, the polymer removes more cuttings and is able to suspend them for a longer duration.

The mechanical cleaning device functions in such a way that it agitates the cuttings bed and helps to bring the cuttings into suspension for removal by the flowing fluid. If the fluid does not have the capability to suspend and transport the agitated cuttings then these will fall back and the effect of the tool will be mitigated. Therefore, it is a combination of the MCD agitation as well as the fluid carrying capacity which will dictate how efficiently the hole is cleaned.

Additionally, the flow rates at which the testing was performed results in a turbulent flow regime for water and a laminar/transition flow regime for the polymer. As is seen above, better cleaning is observed with polymer than with water, which indicates that tool performance is better in laminar or close to laminar regimes with a fluid having a higher viscosity and better cuttings carrying capacity.

C_c *vs*. Pipe Rotation Speed

The effect of pipe rotation on cuttings concentration, at a given flow rate, is shown in Figure A-9. As can be expected, C_c drops as the pipe rotation is increased; higher agitation of the cuttings bed leads to better hole-cleaning. Without rotation (zero rpm) approximately the same amount of cuttings are deposited and therefore the curves originate at almost the same location on the graph. The presence of the tools in the drill string serves to reduce C_c as compared to no tools at all.

4. BED HEIGHTS

Bed heights with and without the device were recorded at 10 different locations on the 90 ft. long transparent test section in the horizontal position. At 45 degrees inclination, it was not possible to read the measuring tapes and therefore this data is not available. The tapes were not spaced equally; rather they were placed closer together in the vicinity of the MCDs to capture the exact profile of the bed.

Figure A-10 shows the bed height profile along the test section with 400 gpm of water and 80 rpm. The drop in the bed height in the immediate vicinity of the tools can clearly be seen. Bed heights obtained for polymer with the same flow rate and pipe rotational speed are shown in Figure A-11. Figure A-12 shows the effect of increasing flow rate of polymer on the bed height while having two MCDs in the drill-string and rotating the pipe at 80 rpm. The steady decrease in the bed height is clearly indicated. The effect of using two different fluids on the bed height is shown in Figure A-13. Again, there are two MCDs in the drill-string and the pipe is rotated at 80 rpm.

The bed height graphs clearly indicate the decrease in the bed height in the immediate vicinity of the cleaning tools, as well as the cuttings re-deposition distance. The cuttings re-deposition distance is the length downstream of the tool after which the bed height becomes essentially constant. The distance varies depending upon the flow rate and the pipe rotation speed; the maximum obtained was 14 ft.

5. REGRESSION MODELING

In many engineering applications involving fluid mechanics, it is not possible to develop an analytical solution to a problem because of the complexity of the system. In such a case, engineers rely on both analysis and experimentation to arrive to a conclusion. The system of a cleaning tool in an annulus with an inner, eccentric rotating pipe with partial blockage (cuttings bed) as well as Newtonian and non-Newtonian fluid flow is indeed one such problem for which the development of a pure analytical model is a challenging task. In such a case, correlating the experimental data and obtaining equations which describe it can yield practical results. One of the first steps in this approach is dimensional analysis wherein dimensionless groups are formed taking into consideration the key system variables that directly effect its functionality. The variables considered for this study are shown in Table 1.

Table 1
Dimensional Analysis Variables

S. No	Variable	Symbol	Units	S. No	Variable	Symbol	Units
1	Hole Inclination angle	θ	Degree	7	Fluid velocity	V	LT^{-1}
2	Vol. Cuttings Conc.	C_c	–	8	Cuttings bed height	h	L
3	No. of Tools	N_T	–	9	Rate of Penetration	ROP	LT^{-1}
4	Annular Clearance	D	L	10	Dist. traveled by cuttings	X	L
5	Density of Mud	ρ	ML^{-3}	11	Pipe RPM	ω	T^{-1}
6	Viscosity of Mud	μ_{eff}	$ML^{-1}T^{-1}$				

Next, dimensionless groups (pi terms) are formed following the well known Buckingham Pi theorem. These are given in Table 2.

Table 2
Dimensionless groups

S. No	Dimensionless Group	Remarks	S. No	Dimensionless Group	Remarks
π_1	$\frac{\omega\rho D^2}{\mu_{eff}}$	Taylor's Number	π_5	$\frac{\rho D(ROP)}{\mu_{eff}}$	
π_2	$\frac{\rho V^{2-n} D^n}{K\, 8^{n-1}}$	Generalized Reynolds' Number	π_6	N_T	No. of tools
π_3	$\frac{X}{D}$	Difficult to record for inclined sections	π_7	C_c	Cuttings concentration
π_4	$\frac{h}{D}$	Difficult to record for inclined sections	π_8	α	Dimensionless inclination angle

An important parameter obtained in the analysis is the percent volumetric cuttings concentration, C_c, which is a measure of the amount of cuttings present in the test section at steady state. C_c has a functional dependence upon several Pi terms

$$C_c = f(\alpha, N, N_{Re}, N_{Ta}, N_{ROP}).$$

π_3 and π_4 do not appear in this functionality because the bed height and the distance traveled by the cuttings are difficult to record in inclined test sections. Only a qualitative estimate is available in these cases.

The relationship between C_c and other dimensionless parameters can be established using multivariate regression and non-linear estimation in Statistica®. This relationship will give the correlation which can be used to predict C_c under a different set of conditions provided geometric and kinematic similarities are maintained between the two systems. The R^2 test (coefficient of determination) was taken as the standard for evaluating the closeness of fit. The R^2 value should be close to 1 for a good match. Also, a difference of 10% between the observed and the predicted values of C_c was chosen as the maximum allowable error.

For the case of polymer as the drilling fluid, 90° inclination angle and one MCD in the drill string, the correlation is given as

$$C_c = -5.22 \cdot 10^{-5} N_{Ta}^{1.36} + 605.714 N_{\mathrm{Re}}^{-0.0124} + 8.86 e^{230.43} N_{ROP}^{-77.58} - 529.4 \quad (1)$$

$1450 < N_{Re} < 3700$, $0 < N_{Ta} < 5800$, $19.7 < N_{ROP} < 23$, $\alpha = 1$, $N_T = 1$, $R^2 = 0.997$, max_err < 4%.

The R^2 value is 0.997 and the maximum error obtained between the observed and predicted values of C_c is less than 4%.

For 45° inclination angle and 1 MCD in the drill string, the correlation is

$$C_c = 3.22\,(1 + N_{Ta})^{-0.472} + 5703.6 N_{Re}^{-0.776} + 69.3 N_{ROP}^{-0.051} - 63.3 \quad (2)$$

$1450 < N_{Re} < 3700$, $0 < N_{Ta} < 5800$, $19.7 < N_{ROP} < 23$, $\alpha = 0.5$, $N_T = 1$, $R^2 = 0.97$, max_err < 10%

The graph of Predicted *vs*. Observed C_c is shown in Figure A-14 together with + 10% error bars. Clearly, the predicted values are very close to the observed values, which means that the correlations of Equations (1) and (2) are quite accurate. The residuals, which are the difference between the predicted and observed values, when plotted against the fitted dependent variable can also be used to evaluate the goodness of fit. They give an indication of the variance and bias in predicted values. Residuals for the correlations of Eqs (1) and (2) are plotted in Figure A-15 and are evenly distributed above and below zero. This means that no bias is present and again establishes the goodness of fit.

For the case of polymer as the drilling fluid and no tools in the drill string, the correlations are as follows:

– for 90° inclination angle:

$$C_c = -14.04 e^{-316} (1 + N_{Ta})^{36.33} + 284.96 N_{Re}^{-0.073} + 58.2 e^{30.9} N_{ROP}^{-12.46} - 140.88 \quad (3)$$

$1450 < N_{Re} < 3700$, $0 < N_{Ta} < 5800$, $19.7 < N_{ROP} < 23$, $\alpha = 1$, $N_T = 0$, $R^2 = 0.9899$, max_err < 9%;

– for 45° inclination angle:

$$C_c = 1.8 (1 + N_{Ta})^{-8.13} + 21.25 e^{177.57} N_{Re}^{-24.63} + 15.7 e^{3.54} N_{ROP}^{-0.03} - 487.67 \quad (4)$$

$1450 < N_{Re} < 3700$, $0 < N_{Ta} < 5800$, $19.7 < N_{ROP} < 23$, $\alpha = 0.5$, $N_T = 0$, $R^2 = 0.99$, max_err < 6%.

For the case of water as the drilling fluid and no tools in the drill string, the correlations are as follows:

– for 90° inclination angle:

$$C_c = 2.196\,(1 + N_{Ta})^{-1.014} + 1.11e^{17.5423}\,N_{Re}^{-1.42} + 1.46\cdot 10^{-3}\,N_{ROP}^{0.96} + 7.486 \tag{5}$$

$33900 < N_{Re} < 68{,}000$, $0 < N_{Ta} < 67{,}000$, $190 < N_{ROP} < 327$, $\alpha = 1$, $N_T = 0$, $R^2 = 0.97$, max_err < 10%

– for 45° inclination angle:

$$C_c = 1.71\,(1 + N_{Ta})^{-1} + 794.94\,N_{Re}^{-0.078} - 0.32e^{38.54}\,N_{ROP}^{-6.68} - 325.83 \tag{6}$$

$33900 < N_{Re} < 68{,}000$, $0 < N_{Ta} < 67{,}000$, $190 < N_{ROP} < 327$, $\alpha = 0.5$, $N_T = 0$, $R^2 = 0.988$, max_err < 10%

The correlations of Eqs (1)–(3) and (4) provide a good estimate of the cuttings concentration in the test section at steady state when polymer is used as the drilling fluid with and without the cleaning tools. However, the difference of C_c between these two cases holds more significance than the individual estimates of C_c and will show how efficiently the tool performs. For example, at a flow rate of 200 gpm, 80 rpm pipe rotation, and 90° inclination angle, C_c is 17% with one MCD and 22% without MCD. This means that the tool made a difference of 23%. In an actual drilling scenario, the correlations will predict the difference that one MCD will create in a 100 ft. section of the bore-hole, given that the ratio of outer to the inner pipe diameters is 1.78. Some error in predictions will still be encountered because the tests were conducted at low pressure and ambient temperature conditions which are considerably different from those actually encountered while drilling. Also the bore-hole wall is acrylic for the flow loop which means that the friction at the wall will differ from that of an actual well-bore.

6. CONCLUSIONS

Provided below are some concluding remarks for this experimental study which highlight some important features of this device as well as the vital aspects of the fluid mechanics related to it. They provide a firm basis for future research and encourage further study of cleaning tools to completely characterize their use.

1) The MCDs make little difference when used with water.
2) Significant improvement in cuttings removal and pumping requirements is seen with polymer.
3) The MCD alone cannot significantly improve hole-cleaning; selection of appropriate drilling fluid is essential.
4) At 45 degrees inclination, the effect of the MCDs on cuttings concentration is not felt.

7. NOMENCLATURE

ω	–	Pipe rotational speed
ROP	–	Rate of Penetration
ρ	–	Fluid density
N_{Re}	–	Reynolds number
D	–	Diameter
N_{Ta}	–	Taylor's number
n	–	Flow behavior index
N_T	–	No. of tools
K	–	Consistency index
α	–	Dimensionless angle
μ_{eff}	–	Effective viscosity
θ	–	Inclination angle

APPENDIX A

Fig. A-1. Mechanical Cleaning Device Length: 2.5 ft (0.76 m), Dia. at ends: 5 in (0.127 m)

Test Section Length	100 ft (30.5 m)
Wellbore Diameter	8 in i.d. (20.5cm)
Drillpipe Diameter	4.5 in o.d. (11.5 cm)
Drillpipe Rotation	0–140 rpm (14.66 rad/s)
Liquid Flow Rate	0–650 gpm (0.041 m^3/s)
Gas Flow Rate	0–1250 scfm (6.6 m^3/s)
Angle of Inclination	10–90° (from vertical)

Fig. A-2. TUDRP Low Pressure Ambient Temperature Flow Loop which simulates a well bore in a drilling operation

Table A-1

Experimentation Test Matrix

Fluid Type	Flow Rate GPM (m^3/s)	Drill Pipe Rotation RPM (rad/s)	Rate of Penetration ft/hr (m/hr)	Inclination Angles (degrees)	Number of MCDs
Fluid A (Water) Fluid B (1.5 ppb PAC-R)	200 (0.013) 300 (0.019) 400 (0.025)	0, 40 (4.2), 80 (8,4)	25 (8)–35 (11)	45, 90	0, 1, 2

Table A-2

Rheology of the polymeric fluid used in experiments

Concentration lbs per barrel (kg/m^3)	Flow Behavior Index (n)	Consistency Index (K) $lb\text{-}s^n/100\ ft^2$ ($Pa\cdot s^n$)	Rheological Model
1.5 (4.28)	0.6–0.7	0.1–0.2 (0.0478–0.0956)	Power Law

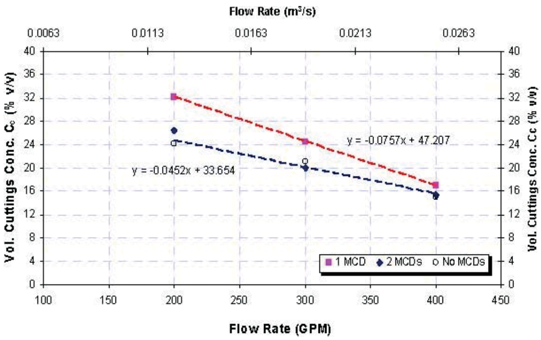

Fig. A-3. C_c *vs*. Flow Rate of Water with 40 rpm pipe rotational speed (90° incl.)

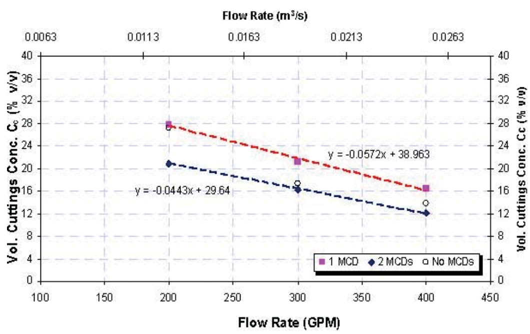

Fig. A-4. C_c *vs*. Flow Rate of Water with 80 rpm pipe rotational speed (90° incl.)

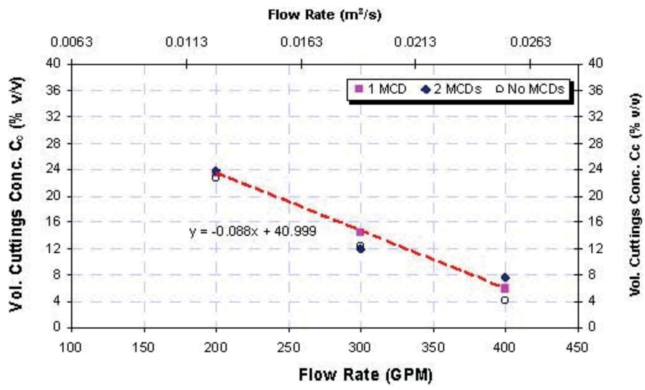

Fig. A-5. C_c *vs*. Water Flow Rate at 45° incl. (40 rpm)

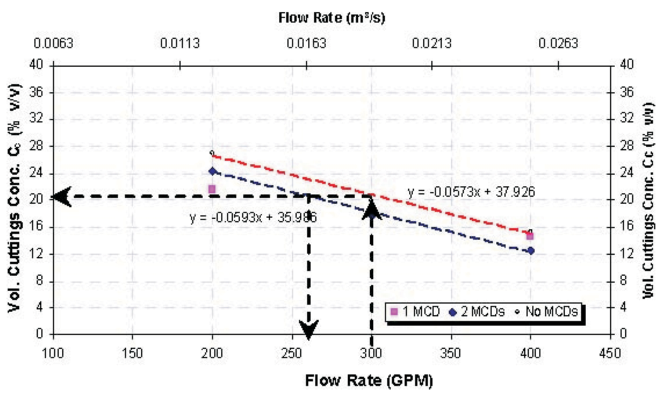

Fig. A-6. C_c *vs*. Polymer Flow Rate at 90° incl. (40 rpm)

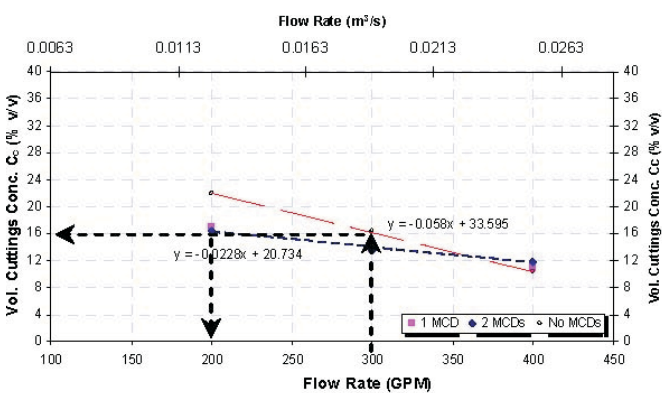

Fig. A-7. C_c *vs*. Polymer Flow Rate at 90° incl. (80 rpm)

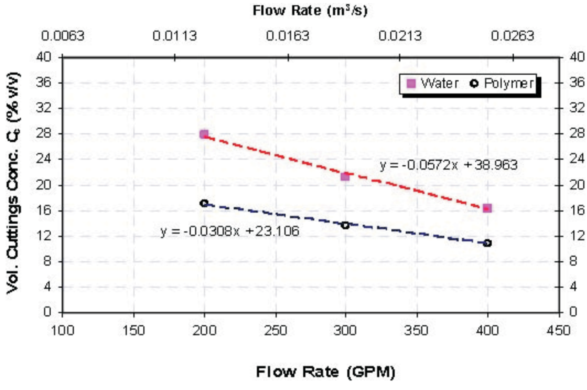

Fig. A-8. C_c *vs*. Flow Rate of Water and Polymer with 1 MCD (90° inc., 80 rpm)

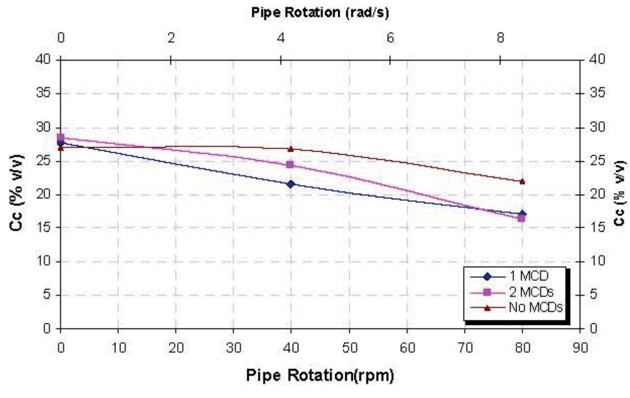

Fig. A-9. C_c *vs*. Pipe rotational speed at 200 gpm (polymer drilling fluid, 90° inc.)

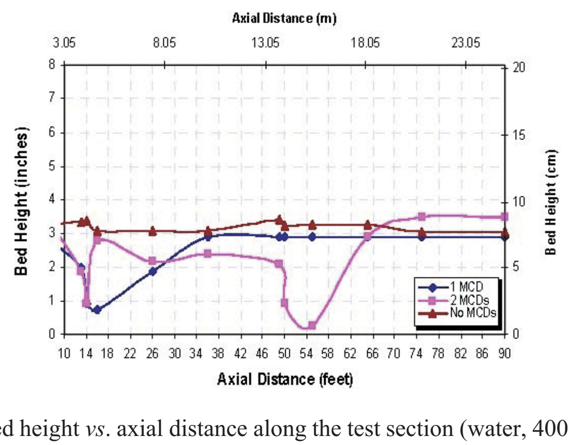

Fig. A-10. Bed height *vs*. axial distance along the test section (water, 400 gpm, 80 rpm)

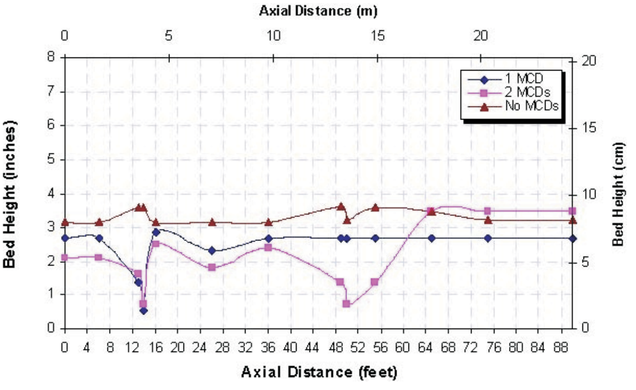

Fig. A-11. Bed height *vs.* axial distance along the test section (polymer, 400 gpm, 80 rpm)

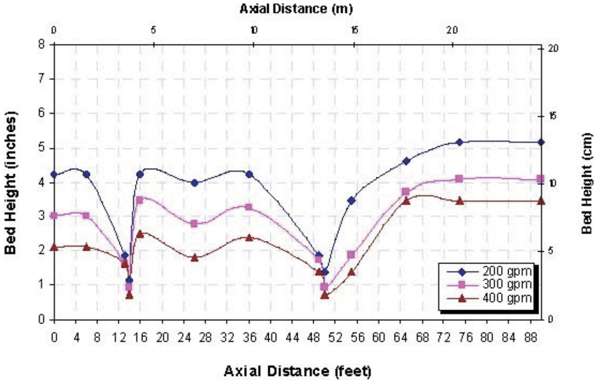

Fig. A-12. Bed height *vs.* axial distance along the test section (polymer, 2 × MCDs, 80 rpm)

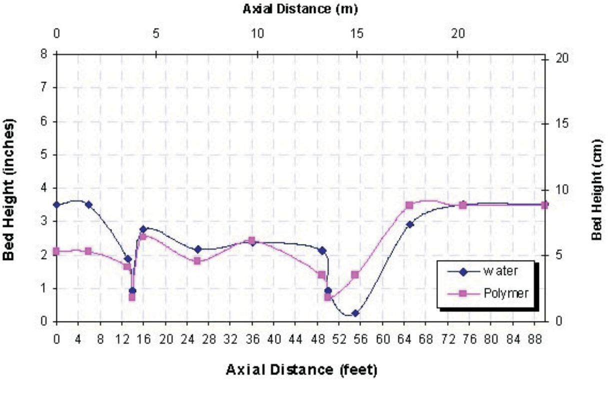

Fig. A-13. Bed height *vs*. axial distance along the test section for water and polymer (400 gpm, 2 × MCDs, 80 rpm)

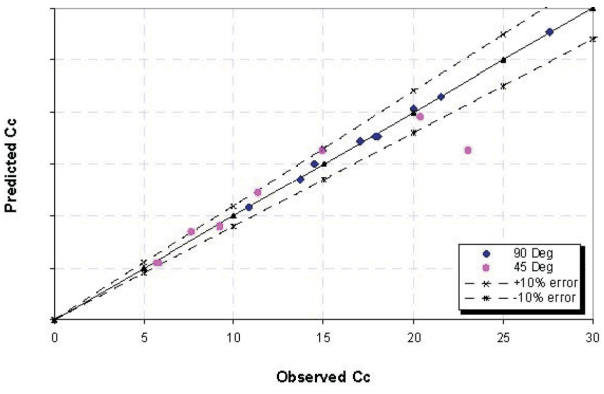

Fig. A-14. Predicted C_c *vs*. observed C_c for polymer fluid and 1 MCD in the drill string

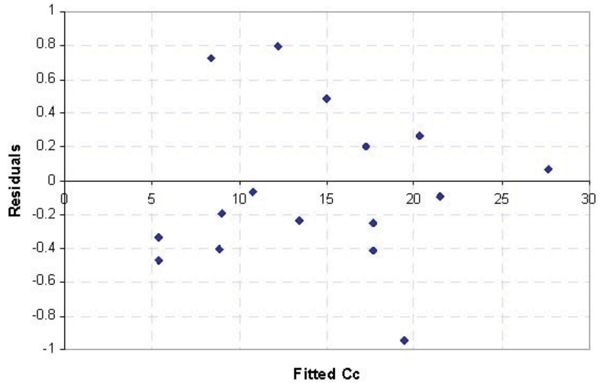

Fig. A-15. Residuals *vs.* fitted C_c for polymer fluid and 1 MCD in drill string