Pakistan Journal of Hydrocarbon Research
Vol.3, No.2(July 1991), P.81-86, 2 Figs., 3 Tables

Optimization of Rotary Drilling Hydraulics: Some Aspects of Computer Applications

Abdel Sattar M. El Saghir[1]

ABSTRACT

The effectiveness with which a rotary drilling rig performs affects on economical profitability of whole oil and gas production process. The nature of the bottom-hole cleaning for rotary drilling is still not sufficiently elucidated. To achieve good bottom-hole cleaning an optimal drilling mud circulation program (hydraulics program) is required. Discussion presented in this paper is focused on bit hydraulic horsepower and impact force criterions. A mathematical model of drilling hydraulics and its computer application for use in field practice is presented. Selected data are included in tabular form and some hard copy protocols from computer are attached.

INTRODUCTION

The use of jet bits belonging to fluid circulation system requires properly designed bottom-hole cleaning. Otherwise, the poor bottom-hole cleaning can restrict the sufficient rate of penetration.

The amount of bottom-hole cleaning required may be determined directly in field operations. In certain series of tests it was proved that rate of penetration improves with simultaneous increase of bit hydraulic horsepower and hydraulic impact force (Moore, 1974).

The rate of penetration is directly proportional to bit weight if bottom-hole cleaning is adequate. In coastal operations using mill-tooth bits, 5.2 bit hydraulic horsepower (BHHP) per square inch of hole is recommended by rule-of-the-thumb. Less bottom-hole cleaning is required for hard formations than in the soft formations. IMCO recommends 2.5 to 5 BHHP/sq.in. as a guideline for adequate jet horse power (IMCO, 1979). For penetration rates less than 10 ft/hr, 2.5 to 3 BHHP/sq.in. is the maximum figure recommended. In general, the BHHP requirements depend upon formation, mud weight, penetration rate and the pressure difference between hydraulic pressure and formation pressure.

The design of a hydraulic program is based on maximizing bottom-hole cleaning and efficient lifting of formation cuttings to the surface (Brouse, 1982; Robinson, 1982; Eckel, 1968; Sutko and Myers, 1970; Eckel and Bielstein, 1951). The drilling cuttings generally have a specific gravity of 2.3 to 3.0 and an average of 2.5 can be assumed.

[1]Department of Petroleum Engineering, Bright Star University, Libya.

Base Assumption of Optimizing Criterion for Hydraulic Program

Optimizing of drilling hydraulics is accomplished in this paper by maximizing of bit hydraulic horsepower or maximizing of hydraulic impact force. This form of optimization was assumed for this purpose because:

- The use of maximizing of mud nozzle velocity in drilling industry is rarely applied.
- The use of maximizing of rate of penetration (ROP) is very prospective but still not certain. Determination of diameter of nozzles for the first and sequent bits run below the surface or intermediate casing requires the development of micro-computer program for a better comfort, high speed and good accuracy. Design of this program is based on work out of Hughes Tool Co. "Simplified Hydraulics", and Scott's method which can be recommended (Hughes Tool Company, 1958; Scott, 1971; Smith Tool Co., 1979).

The total pressure losses in the circulating system are defined by the formula:

$$P_s = K\,Q^n \text{, Psi} \qquad (1)$$

where:

Q = flow rate of mud, gpm

K = constant affected by geometry of circulating system and density of mud

n = hydraulic exponent, primarily a function of the mud properties. This exponent as a slope of straight line plot of P_s Vs Q on log-log paper can be measured while preparing drilling of the interval.

Table 1. Determination of surface equipment loss coefficient.

Case	Stand pipe		Hose		Swivel		Kelly		Coefficient
	L	ID	L	ID	L	ID	L	ID	C_e
1	40	3.0	45	2.0	4	2.0	40	2.25	19
2	40	3.5	55	2.5	5	2.5	40	3.25	7
3	43	4.0	55	3.0	5	2.5	40	3.25	4
4	45	4.0	55	3.0	6	3.0	40	4.00	3

L = Length in feet
ID = Inside diameter in inch

Optimizing Drilling Hydraulics Procedure

This procedure involves:

- Selection of optimizing criterion.
- Calculation of system pressure losses
- Determining of initial circulation rate
- Determining of system circulation rate
- Sizing of bit nozzles
- Determining of pump circulation rate

Selection of Optimizing Criterion

Maximum hydraulic horse-power is described by:

$P_b = [n/(n+1)]\, P_{sp}$ .... (2)

But maximum impact force is determined by:

$P_b = [n/(n+1)]\, P_{sp}$ .... (3)

where:

P_b = pressure drop across the bit, Psi

P_{sp} = standpipe pressure or maximum allowable surface pressure.

n = hydraulic exponent primarily a function of the mud properties can vary from 1.0 to 2.0. IMCO service assumed 1.78, Reed Tool Co.-1.82, H.A. Kendal and W.C. Goins-1.9 and Hughes Tool Co. uses 1.86 (rule used in this paper).

System Pressure Losses

These pressure losses can be determined from:

$P_s = P_{sp} - P_b$ .... (4)

In the case of shortage of field data to estimate an exponent, it can be assumed as 1.86 and for this case the system pressure losses P_s for BHHP are given by:

$P_s = 0.35\, P_{sp}$ .... (5)

while the system pressure losses P_s for IF are determined by:

$P_s = 0.52\, P_{sp}$ .... (6)

Initial Circulation Rate

This circulation rate is determined by transforming equation (7) to (8) as follows:

$P_s = K\, Q^{1.86}$, Psi .... (7)

$Q = (P/K)^{1/1.86}$, gal/min. .... (8)

where:

K = Constant affected by geometry of circulating system and density of mud.

$K = 10^{(-5)}[Ce + [C_3 + C_4]*L_c + [C_5 + C_6]L_h + L_p/C_p]w$ .... (9)

w = Weight density of mud, lb/gal

C_e = Surface equipment loss coefficient determined from Table 1

Drill collar bore loss coefficient is calculated from:

$$C_3 = 6.1/D_{cb}^{4.86} \quad (10)$$

and drill collar annular loss coefficient from:

$$C_4 = 8.6\,B / [[D_o - D_1]\,[D_o^2 - D_1^2]^2] \quad (11)$$

Heavy weight pipe bore loss coefficient is given by:

$$C_5 = 6.1/D_{hb}^{4.86} \quad (12)$$

and heavy weight pipe annular loss coefficient by:

$$C_6 = 8.6\,B / [[D_o - D_{hw}]\,[D_o^2 - D_{hw}^2]^2] \quad (13)$$

Drill pipe loss coefficient is give by:

$$C_p = 1/[5.68/D_{pb}^{4.86} + 8.17B/x_1 + 0.41/D_{jb}^{4.85} + 0.43B/x_2] \quad (14)$$

where:

$$x_1 = (D_o - D_p)\,(D_o^2 - D_p^2)^2$$

$$x_2 = (D_o - D_j)\,(D_o^2 - D_j^2)^2$$

Values of B parameter are taken as follows:

Hole Diameter	Parameter B
4 3/4"	2.0
5 5/8" - 6 3/4"	2.2
7 3/8" - 7 3/4"	2.3
7 7/8" - 11"	2.4
12" - 18 1/2"	2.5

Inside diameter of casing is put in place of diameter of hole, if the considered section of drill string is inside casing.
Pressure losses through and around the drill string and through the surface equipment are given by:

$$P_s = 10^{(-5)}[C_e + [C_3 + C_3]\,L_c + [C_5 + C_6]\,L_h + L_p/C_p]\,w\,Q^{1.86} \quad (15)$$

System Circulation Rate

The initial circulation rate should be checked, whether its value is greater than circulation rate providing minimum annular velocity. This minimum circulation rate is calculated from:

$$Q_m = 0.041\,(D_o^2 - D_p^2)\,V_m \quad (16)$$

Minimum annular velocity V_m is required to carry the cutting from the bottom of the hole to the surface. Recommended hydraulic practice by Hughes Tool Co. gives the following values for V_m.

Hole Size inch	Annular Velocity ft/min.
15	80
12 1/4	90
10 5/8	110
8 3/4	120
7	130
6	140

Sizing of Bit Nozzles

Using the formula for bit pressure drop (17), it is easy to determine total area of nozzles (18) and nozzle size (19):

$$P_b = Q^2\,w/[\,12031A^2\,C^2\,],\ \text{Psi} \quad (17)$$

$$A = Q\,[w/(12031 * P_b * 0.95^2)]^{1/2},\ \text{sq.in.} \quad (18)$$

$$D = [32 * 4A/3\,Pi]^{1/2},\ 1/32\ \text{in.} \quad (19)$$

where Pi = 3.1415

Diameter of every nozzle is calculated by routine which optimizes feasible size selection.

Pump Circulation Rate

Total frequency of double acting duplex pump is given by equation (21) as follows:

$$F_r = Q/[0.0136\,S\,[L_s^2 - (R_s/2)^2]\,E_f],\ \text{Stk/min.} \quad (20)$$

$$F_r = Q/[0.01\,S\,L_s^2\,E_f],\ \text{Stk/min.} \quad (21)$$

where:
S = Length of stroke, inch
L_s = Diameter of liner, inch
R_s = Diameter of piston rod, inch
E_f = Volumetric efficiency of pump.

If total frequency exceeds maximum frequency of the pump, then larger diameter of linear or multiplication of pumps should be considered. Since the mud pump is a source of discharge rate and pressure in circulating system, a special attention should be paid on its operational performance.

Table 2. Hydraulic parameters at maximum hydraulic horse-power criterion.

Depth (ft)	Stand pipe pressure (Psi)	Circ. rate (GMP)	Pump HHP (HP)	Bit HHP (HP)	Impact force (Ib)	Nozzle sizes (1/32")	No of pump	Pump frequency. (strokes/ minute)
2000	3000	870	1693	990	2103	16,16,16	2	67
2500	3000	811	1577	922	1959	15,16,16	2	62
3000	3000	761	1481	866	1840	15,15,15	2	59
3500	3000	720	1400	819	1739	14,15,15	2	55
4000	3000	684	1331	778	1653	14,14,15	2	53
4500	3000	653	1270	743	1578	14,14,14	2	50
5000	3000	626	1217	712	1512	13,14,14	2	48
5500	3000	602	1170	684	1453	13,13,14	2	46
6000	3000	580	1128	660	1401	13,13,13	2	44
6500	3000	560	1089	637	1453	13,13,13	2	43
7000	3000	542	1055	617	1310	12,13,13	2	42
7500	3000	526	1023	598	1271	12,13,13	2	40
8000	3000	511	994	581	1234	12,12,13	2	39

SKETCH OF COMPUTER PROGRAM FOR SELECTION OF NOZZLE SIZE

There are different opinions to optimize hydraulics i.e. maximize BHHP of IF. Since there is no conclusive evidence that either of the methods is the best, it was assumed that both methods should be available in the program. The data selected in this program fall into following two categories: (1) Pump data i.e. max. pump frequency, type of pump, linear size, rod size, stroke length, volumetric efficiency, and max. surface pressure; (2) Drilling system data i.e. mud weight, diameter of hole, inside diameter of casing, casing setting depth, minimum annular velocity, type of surface equipment, outside diameter of drilling pipe, inside diameter of drilling pipe, outside diameter of tool joint, inside diameter of tool joint, length of drill pipe string, outside diameter of heavy weight pipe, inside diameter of heavy weight pipe, length of heavy weight pipe string, outside diameter of drill collars, inside diameter of drill collars, length of collar string, and optimizing criterion. This part of the program is prepared in dialogue manner which effectively facilitates its usage.

Next block of program consists of statement which allows to reckon demanded total area of nozzles. Distribution of this area into specific nozzles is optimized. There are two versions of solution considered: Bit with three and two nozzles. Optimization criterion ratio based on minimized difference between demanded total area of nozzle and the sum of feasible nozzles area. Accuracy of the calculation of the program is characterized by differential area given as output data.

Program is equipped with subroutine which allows to modify input data. This part of program has dialogue form. Service by this subroutine is initialized by negative answer on computer ask for approval of finished series of calculation. Modification can take place for simple correction of some data or in case of necessity to change of full input data set (24 data). Modification subroutine is running in loop which is ended on distinct request of user.

It was thought of to simulate bit penetration progress in program. Assuming arbitrary step of progress equals 250 ft and max length of open hole equals 6000 ft, it was reckoned data for BHHP and IF hydraulic optimization program ending each step by optionally printing protocol. Two random protocols are attached to this paper as examples (I and II). The 250 ft step in this simulation was assumed as a depth which can be obtained in average circumstances with one bit trip. If it is required, this value can be changed by substituting new value into the program.

HYDRAULIC PROGRAM - I

INPUT DATA

MF = 70	LS = 6.25	RS = 3.5
S = 16	VE = .9	PSP = 3000
W = 10	DO = 12.25	DC = 12.515
CSD = 2000	VM = 110	CASE = 4
DP = 4.5	DBP = 3.826	DJ = 6.25
DJB = 3.25	LP = 1100	DHW = 4.5
DHB = 3	LH = 450	DC1 = 9.5
DCB = 3.5	LC = 360	OPT = HHP
LO = 4000	TD = 6000	

OUTPUT DATA

Pressure drop across bit = 1950 (Psi)
System pressure loss = 1050 (Psi)
Hydraulic horse power in bit = 660 (HP)
Impact force = 1401 (lb)
Circulation rate = 579.845 (GPM)
Nozzle area = 0.3985 (Sq. Inch.)
Nozzle sizes = 13/32, 13/32, 13/32 (in.)
Differential area = 9.628E-03 (Sq. in.)
Number of pumps = 2
Pump frequency = 44 (Strokes/min.)
Pump Hydr. Horse Power = 1127.67 (HP)
Protocol of hydraulic program at maximum HHP in bit criterion.

HYDRAULIC PROGRAM - II

INPUT DATA

MF = 70	LS = 6.25	RS = 3.5
S = 16	VE = 0.9	PSP = 3000
W = 10	DO = 12.25	DC = 12.515
CSD = 2000	VM = 110	CASE = 4
DP = 4.5	DBP = 3.826	DJ = 6.25
DJB = 3.25	LP = 1100	DHW = 4.5
DHB = 3	LH = 540	DC1 = 9.5
DCB = 3.5	LC = 360	OPT = IF
LO = 4000	TD = 6000	

OUTPUT DATA

Pressure drop across bit = 1440 (Psi)
System pressure loss = 1560 (Psi)
Hydraulic horse power in bit = 603 (HP)
Impact force = 1489 (lb)
Circulation rate = 717.382 (GPM)
Nozzle area = .5737 (Sq. Inch)
Nozzle sizes 15/32, 16/32, 16/32 (in.)
Differential area = 8.441E-03 (Sq. in.)
Number of pumps = 2
Pump frequency = 55 (Strokes/min.)
Pump hydr. horse power = 1395.14 (HP)
Protocol of hydraulic program at maximum IF criterion.

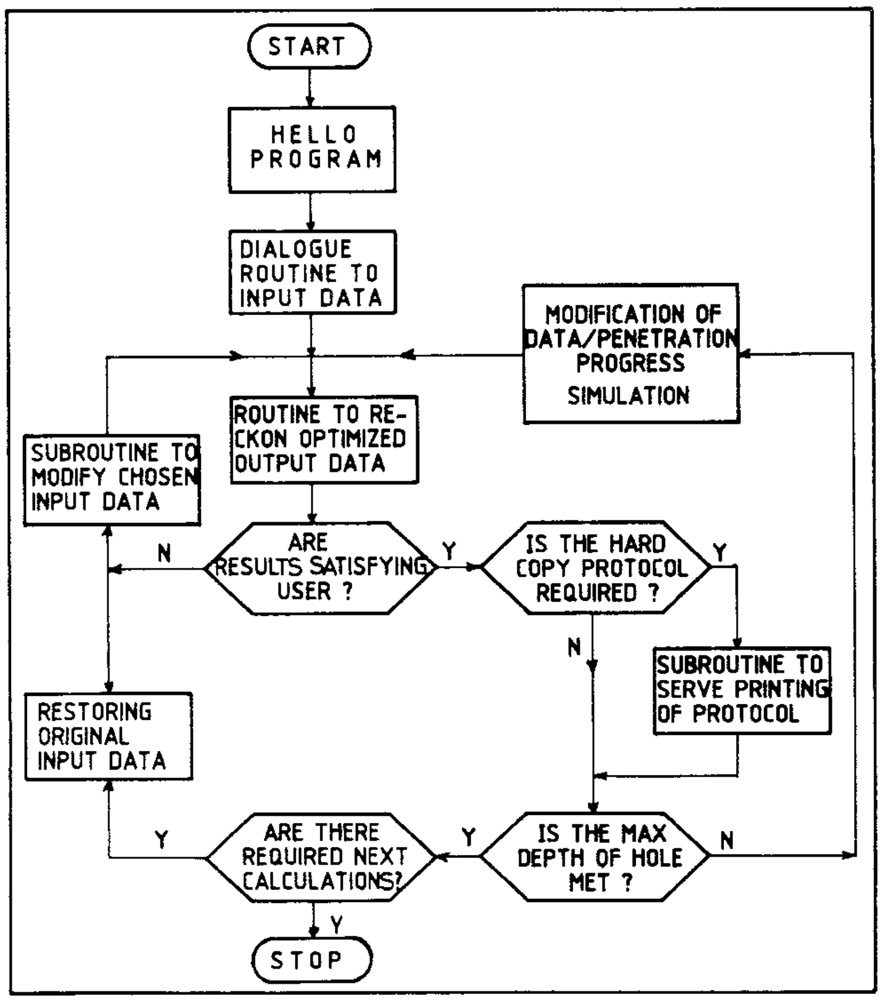

Figure 1— General program flowchart.

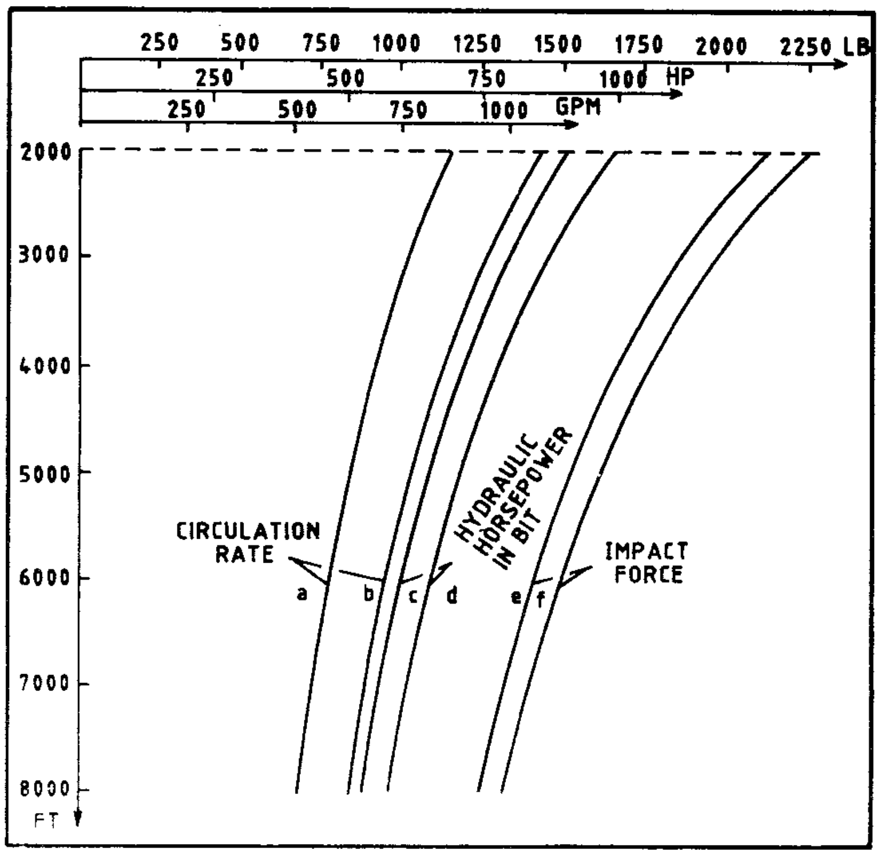

Figure 2— Circulation Rate, hudraulic horsepower in bit and impact force versus depth at maximum hydraulic horsepower in bit criterion (a,d,e) and at maximum impact force criterion (b, c, f).

Table 3. Hydraulic parameters at maximum impact force criterion.

Depth (ft)	Stand pipe pressure (Psi)	Circ. rate (GMP)	Pump HHP (HP)	Bit HHP (HP)	Impact force (Ib)	Nozzle sizes (1/32")	No of pump	Pump frq. (strokes/ minute)
2000	3000	1070	2094	905	2236	18,20,20	3	55
2500	3000	1003	1951	843	2082	18,18,20	3	51
3000	3000	942	1832	791	1956	18,18,18	3	48
3500	3000	891	1732	748	1849	16,18,18	2	69
4000	3000	847	1646	711	1757	16,18,18	2	65
4500	3000	808	1572	679	1678	16,16,18	2	62
5000	3000	774	1506	651	1608	16,16,18	2	60
5500	3000	744	1448	625	1545	16,16,16	2	57
6000	3000	717	1395	603	1489	15,16,16	2	55
6500	3000	693	1348	582	1439	15,16,16	2	53
7000	3000	671	1305	564	1393	15,15,16	2	52
7500	3000	651	1266	547	1351	15,15,15	2	50
8000	3000	632	1229	531	1312	14,15,15	2	49

General sketch of program is depicted on program flow chart (Figure 1). Compressed form of results calculated for the presented paper is given in Tables 2 and 3 and Figure 2.

CONCLUSIONS

Relationship between the nature of the bottom-hole cleaning and bit hydraulic horse-power is however still not well understood. Further, numerical computer aided studies of field and lab data should help to elucidate this problem.

Experiences in application of the hydraulic program presented in this paper provide the certainty of its benefits and usage in field practice.

At the first phase of 12.25" hole drilling and required increased annular velocity of 110 ft/min. fulfillment of BHHP criterion conditions requires running of two pumps within hydraulic system. In case of IF criterion above drilling conditions demand running of as many as three mud pumps. Thus, under these conditions, only BHHP criterion can be applied.

REFERENCES

Brouse, M., 1982, Practical Hydraulics: A key to efficient drilling: World Oil.

Eckel, J., R., 1968, (June 17), How mud and hydraulics affect drilling rate: The Oil and Gas Journal.

---------- and W. J. Bielstein, (1951), Nozzle design and its effect on drilling rate and pump operation drilling and production practice: API, p. 28.

Hughes Tool Company, 1958, Bulletin No. I-C, Houston, p. 14.

IMCO, 1979., Applied mud technology (Manual): IMCO Services publications.

Moore, P.L., 1974, Drilling practices manual, Penn Well Books, Tulsa.

Robinson, L. 1982, (July) Optimizing bit hydraulics increases penetration rate: World Oil.

Scott, K. F., 1971 (October) A new practical approach to rotary drilling hydraulics: SPE paper no. 3530, New Orleans, Louisiana, Oct. 1971.

Smith Tool Co., 1979, Drilling and bit Technology Seminar.

Sutko, A.A., and G.M. Myers, 1970 (October). The effect of nozzle size, number and extension on the pressure distribution under a tricone bit: SPE paper no. 3109, fall meeting of SPE of AIME. Houston, Texas.