A Comprehensive Comparison Study of Empirical Cutting Transport Models in Inclined and Horizontal Wells

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Abstract. In deviated and horizontal drilling, hole-cleaning issues are a common and complex problem. This study explored the effect of various parameters in drilling operations and how they affect the flow rate required for effective cutting transport. Three models, developed following an empirical approach, were employed: Rudi-Shindu's model, Hopkins', and Tobenna's model. Rudi-Shindu's model needs iteration in the calculation. Firstly, the three models were compared using a sensitivity analysis of drilling parameters affecting cutting transport. The result shows that the models have similar trends but different values for minimum flow velocity. Analysis was conducted to examine the feasibility of using Rudi-Shindu's, Hopkins', and Tobenna's models. The result showed that Hopkins' model is limited by cutting size and revolution per minute (RPM). The minimum flow rate from Tobenna's model is affected only by well inclination, drilling fluid weight and drilling fluid rheological property. Meanwhile, Rudi-Shindu's model is limited by inclinations above 45°. The study showed that the investigated models are not suitable for horizontal wells because they do not include the effect of lateral section.

Keywords: *cutting transport; drilling parameters; hole cleaning; Hopkins' model; horizontal wells; inclined wells; Rudi-Shindu's model; Tobenna's model.*

1 Introduction

Hole cleaning is one of the major considerations in both the design and execution of drilling operations. Especially in wells that have a high inclination, if the fluid velocity is lower than a critical value, a stationary bed develops, which may cause several problems, such as a higher probability of stuck pipe, high drag, higher hydraulic requirements, etc., if not removed properly [1-5]. In order to avoid such problems, generated cuttings have to be removed from the wellbore with the help of drilling fluid. Factors that influence cutting transport are drilling fluid flow rate, drilling fluid viscosity, drilling fluid weight, drilling

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fluid type, hole size, rotational speed, eccentricity, penetration rate, and cutting size. Efficient cutting transport is presumed to be achieved when the pump flow rate is above the critical flow rate. An inadequate pump flow rate may cause cuttings to fall back to the bottom of the hole. In highly inclined and horizontal wells, cutting beds frequently occur, i.e. fall-back cuttings that pile up on the surface of the wellbore.

Many cutting transportation models have been developed. Nowadays, it is common to recognize two main approaches: an empirical approach and a mechanistic approach [6]. This study employed three models, developed using an empirical approach, i.e. Rudi-Shindu's model [7], Hopkins' model [8], and Tobenna's model [9]. In 1995, Hopkins listed all variables that are required to determine the minimum flow rate. After several years, Rudi-Shindu introduced slip velocity and a correction factor for drilling fluid weight and angle of inclination. Tobenna developed a model in 2010 to calculate the critical flow rate for deviated wells based on Bern-Lou's method. The models were compared using case-study wells. Two example wells that mimic operational conditions were considered.

2 Basics of Cutting Transport

Cutting transport represents the quality of hole cleaning during the drilling process. Nazari [10] found that there are several drilling variables that affect cutting transport in directional wells. These variables are the following:

1. Drilling fluid flow rate
2. Drilling fluid rheological property
3. Hole angle
4. Drilling fluid weight
5. Drilling fluid type
6. Hole size
7. Rotational speed
8. Eccentricity
9. Penetration rate
10. Cutting size

3 Cutting Bed Formation in Highly Inclined and Horizontal Wells

When a highly deviated section is being drilled, cuttings generated at the drill bit tend to fall to the lower side of the hole because of the gravitational effect. This leads to the formation of a cutting bed. Cutting beds cause several problems in drilling, such as increase of torque and drag, limited reach of the target, pipe sticking, difficulties in cementing and logging, and increased well cost [11].

Two models have been introduced by Gavignet to model cutting-bed concentration in wellbores, namely a two-layer model and a three-layer model [12]. The main difference between both models is based on the cutting settling condition in the drilling fluid. The two-layer model considers a suspension layer and a cutting-bed layer, while the three-layer model considers a cutting-bed layer, a suspension layer and a liquid-phase layer.

4 Cutting Transport Model – Empirical Approach

In this study, three empirical cutting transport models were used to evaluate cutting transfer in several case-study wells, i.e. Rudi-Shindu's, Hopkins', and Tobenna's model. Drilling parameters (flow rate, drilling fluid density, drilling fluid viscosity, drill pipe rotation, hole angle, penetration rate, and cutting properties) were introduced into the models as influencing factors. The result of all three models were compared and analyzed.

4.1 Rudi-Shindu's Model

Rudi-Shindu introduced a new equation for determination of the drilling fluid minimum flow rate necessary to lift the cuttings in inclined to horizontal wellbores. The correlation is a development of Moore's model [13], Larsen's model, and an experiment conducted by Peden. The equation is stated as follows.

Cutting velocity (v_{cut}) can be expressed as in Eq. (1):

$$V_{cut} = \frac{1}{\left[1-\left(\frac{d_{pipe}}{d_{hole}}\right)^2\right]\left(0.64+\frac{18.16}{ROP}\right)} \tag{1}$$

Slip velocity (V_{slip}) is determined by calculating apparent viscosity. Based on experimental data in the following Eqs. (2) and (3):

$$V_{slip} = 0.00516\ \mu_a + 3.006, \text{ for } \mu_a < 53 \text{ cp} \tag{2}$$

$$V_{slip} = 0.02554\ (\mu_a + 53) + 3.28, \text{ for } \mu_a > 53 \text{ cp} \tag{3}$$

In this method, Rudi-Shindu included corrections for inclination, drilling fluid density, and rotational speed (RPM).

For inclinations below 45° the correction is calculated with Eq. (4):

$$C_{inc} = \left(1 + \frac{2\theta}{45}\right) \quad (4)$$

For inclinations above 45°, a correction is calculated with the following equation:

$$C_{inc} = 3$$

Drilling fluid density correction can be determined with Eq. (5):

$$C_{dens} = \frac{3 + \rho_m}{15} \quad (5)$$

And rotational speed correction can be expressed with Eq. (6):

$$C_{RPM} = \left(1 - \frac{RPM}{600}\right) \quad (6)$$

Rudi-Shindu's model is applied for inclination angles between 0° and 90°. At 0°, Rudi-Shindu's model corresponds to Moore's model for vertical wellbores. The minimum flow velocity defined by Rudi-Shindu's model shows a gradual increase at the inclination interval between 0° and 45°. However, at the inclination angle interval between 45° and 90°, Rudi-Shindu's minimum flow velocity is a constant value.

4.2 Hopkins' Model

Hopkins found that the slip velocity of bit cuttings is reduced by increasing the drilling fluid density. However, unless the density is required to counter formation pressures, the use of high-density drilling fluids to clean a drilling hole is normally impractical. For inclination angles smaller than 35°, the minimum flow rates correspond to the pump output at which cutting accumulation in the annulus is 5% or less by volume. Meanwhile, for inclination angles greater than 35°, the critical flow is defined as the minimum velocity required to maintain continuous movement of the cuttings in the upward direction toward the surface.

The effect of drilling fluid weight on the slip velocity can be obtained with the following Eq. (7):

$$F_{mw} = 2.117 - 0.1648 \times \rho_m + 0.003681 \times \rho_m^{\ 2} \quad (7)$$

Slip velocity in ft/min for the vertical (V_{sv}) condition can be obtained from Figure 1 by inputting the yield point value and assuming an average cutting size. The adjusted vertical slip velocity considering the effect of drilling fluid weight and yield point is calculated using Eq. (8):

$$V_s = F_{mw} \times V_{sv} \tag{8}$$

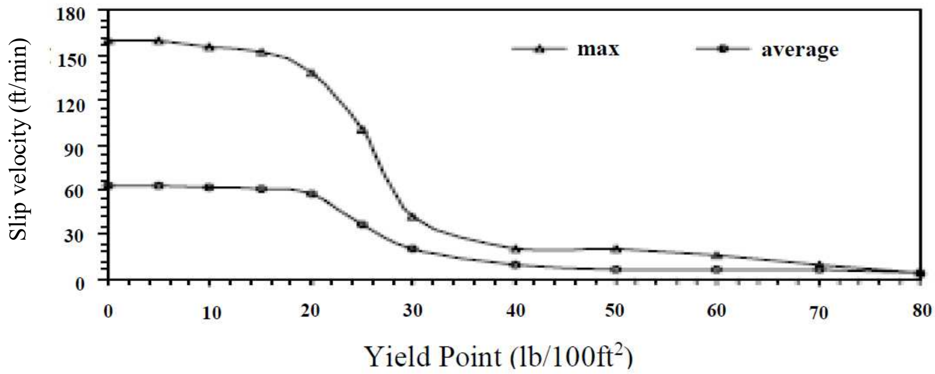

Figure 1 Hopkins' velocity chart [15].

The minimum drilling fluid velocity in the non-vertical section is outlined as follows in Eq. (9):

$$V_{min} = (V_s \times \cos\emptyset) + (V_2 \times \sin\emptyset) \tag{9}$$

where

$$V_2 = C \times \left[\left(\frac{\rho_s - \rho_m}{\rho_m} \right) \times g^3 \times \left(\frac{d_h - d_p}{12} \right)^3 \right]^{\frac{1}{6}} \tag{10}$$

and C in Eq. (10) is an empirical constant based on laboratory data that varies from 40 to 60. Therefore, the minimum flow in gal/min can be calculated as in Eq. (11):

$$Q_{crit} = 0.04079 \times \left({d_h}^2 - {d_p}^2 \right) \times V_{min} \tag{11}$$

4.3 Tobenna's Model

Tobenna developed a model to calculate the critical flow rate for deviated wells based on Bern-Lou's method. In advance, Bern-Lou established a model to calculate the critical flow rate for hole cleaning in vertical wells by considering the drilling fluid rheological property, drilling fluid density, and hole diameter. Bern-Lou used the Power Law's rheological model into their model. The critical flow rate for vertical wells can be calculated with Eq. (12) and the conditions with Eqs. (13) to (15).

$$Q_{vertical} = \frac{400{,}000 A_a}{\rho k (0.13369)} \tag{12}$$

where,

$$A_a = \frac{\pi}{4}\frac{(D_o^2 - D_i^2)}{144} \tag{13}$$

and,

$$k = 510\ \frac{PV+YP}{511^n} \tag{14}$$

and,

$$n = 3.32\ \log\frac{2PV+YP}{PV+YP} \tag{15}$$

A_a is in ft^2, ρ is in ppg, PV is in cp, and YP is in $lb/100ft^2$.

Tobenna established a correction factor, called the angle factor, so that the critical flow rate for deviated wells can be stated as follows in Eq. (16):

$$Q_{deviated} = \frac{1}{AF} Q_{vertical} \tag{16}$$

The angle factor is provided by the graph of angle factor vs. hole angle (Figure 2). This model provides a simple calculation that can be implemented in the field.

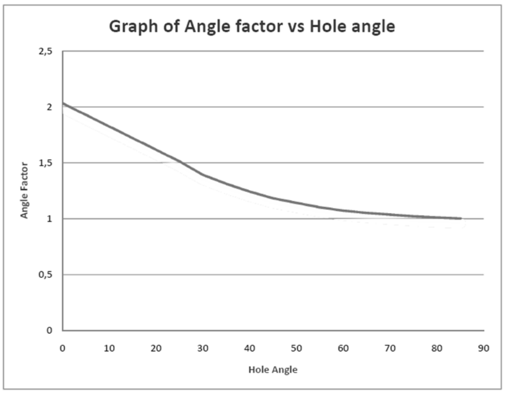

Figure 2 Graph of angle factor vs. hole angle [6].

4.4 Cutting-Bed Concentration Prediction

Larsen, *et al.*[1] developed a model to predict the cutting-bed concentration. When drilling fluid flow velocity in the wellbore is equal to minimum drilling fluid velocity, cuttings will start to accumulate on the wellbore surface with inclination > 25° until the area open to flow above the bed is so restricted that the fluid is capable of transporting out all the cuttings. This results in a steady state condition when the cutting bed neither grows nor erodes. In Eq. (17) they used the assumption that:

$$v_{open} = v_{crit} \tag{17}$$

The equation above can be expressed in terms of flow rate and area open to flow and then becomes the following Eq. (18):

$$\frac{Q_{pump}}{A_{open}} = \frac{Q_{crit}}{A_{ann}} \tag{18}$$

The area that is occupied by deposited cuttings is called the bed area (A_{bed}).
It can be calculated with Eqs. (19) and (20):

$$A_{bed} = A_{ann} - A_{open} \tag{19}$$

$$A_{bed} = A_{ann}\left(1 - \frac{Q_{pump}}{Q_{crit}}\right) \tag{20}$$

Thus, the cutting-bed concentration, neglecting cutting-bed porosity, can be expressed as follows in Eqs. (21) and (22):

$$C_{bconc} = \frac{A_{bed}}{A_{ann}} \tag{21}$$

$$C_{bconc} = \left(1 - \frac{Q_{pump}}{Q_{crit}}\right) \tag{22}$$

5 Case Study

5.1 Well "X" – Horizontal Well

In this study, cutting transport evaluation for every section was evaluated by calculating critical drilling fluid velocity with Rudi-Shindu's [1] and Hopkins' methods and then calculations were done to predict the cutting-bed concentration. All input data are listed in Tables 1 and 2.

Table 1 Well "X" data.

Well classification	Horizontal well
Total inclination	88.3°
Total depth	14,205 ftMD (12,014 ftTVD)

Table 1 Continued. Well "X" data.

Hole section	26"	17.5"	12.25"	8.5"	5.75"
Formation	Claystone	Claystone-sandstone	Claystone-sandstone	Claystone-sandstone	Limestone
Section inclination (^{o})	0	0	32.7	49.5	88.3
Drilling fluid	WBM	OBM	OBM	OBM	OBM
MW (ppg)	9.2 – 10	10.8 – 11.2	11.3 – 13.7	15.4	15.8
PV (cp)	11 – 23	18 – 24	20 – 28	29 – 33	30 – 37
YP (lb/100ft^2)	15 - 26	24 – 27	23 – 25	21 – 25	14 – 23
ROP (ft/hr)	20 – 86	60 – 86	12 – 20	20	13 – 23
RPM	75 – 210	100 – 110	80 – 120	80 – 195	170 – 260

Lateral specifications

Lateral length (ft)	1,500	**Drilling fluid**	OBM
Lateral inclination (^{o})	81 – 88	**MW (ppg)**	15.8
Pump rate (gpm)	245	**PV (cp)**	30 – 37
ROP (ft/hr)	13 – 50	**YP (lb/100ft^2)**	14 – 23
RPM	170 – 260	**Cutting SG**	2.7

Table 2 Drilling parameter data of Well "X".

MD (ft)	Inclination	ROP (ft/hr)	RPM	Drilling fluid weight (ppg)	PV (cp)	YP (lb/100ft^2)	GS 10s/10m (lb/100ft^2)	Cutting transport condition		
								Rudi-Shindu	Hopkin	Tobenna
1,000	0.8	20	75	9.2	11	15	7/18	Not Lifted	Not Lifted	Not Lifted
2,000	2.7	120	125	10	23	27	8/20	Not Lifted	Not Lifted	Lifted
3,000	0.7	85.7	210	10	23	26	11/17	Not Lifted	Not Lifted	Lifted
4,000	0.5	85.7	100	10.8	24	27	12/18	Not Lifted	Not Lifted	Lifted
5,000	0.2	66.7	100	10.3	20	25	12/18	Not Lifted	Lifted	Lifted
6,000	0.8	30	100	10.5	19	25	11/17	Not Lifted	Lifted	Lifted
7,000	0.5	60	100	10.8	18	25	11/17	Not Lifted	Lifted	Lifted
8,000	0.4	60	110	11.2	18	24	11/17	Not Lifted	Lifted	Lifted
9,000	0.6	20	120	11.3	20	25	14/17	Lifted	Lifted	Lifted
10,000	12.9	20	90	13.5	28	24	12/18	Lifted	Lifted	Lifted
11,000	32.7	12	80	13.7	28	23	16/24	Lifted	Lifted	Lifted
11,500	42	20	80	13.9	29	25	17/26	Lifted	Lifted	Lifted
12,000	49.5	20	195	15.4	33	21	9/31	Lifted	Lifted	Lifted

MD (ft)	Inclination	ROP (ft/hr)	RPM	Drilling fluid weight (ppg)	PV (cp)	YP (lb/100ft²)	GS 10s/10m (lb/100ft²)	Cutting transport condition		
								Rudi-Shindu	Hopkin	Tobenna
12,600	76.7	13	175	15.8	30	14	15/46	Lifted	Lifted	Lifted
12,650	78	21.4	225	15.8	30	14	15/38	Lifted	Lifted	Lifted
12,700	81	16.2	170	15.8	30	14	15/38	Lifted	Lifted	Lifted
12,750	82.5	13	170	15.8	30	14	7/19	Lifted	Lifted	Lifted
12,800	85.5	13	175	15.8	30	14	7/19	Lifted	Lifted	Lifted
12,850	86	21.4	235	15.8	30	14	8/19	Lifted	Lifted	Lifted
12,900	86.5	31.6	220	15.8	30	14	8/20	Lifted	Lifted	Lifted
12,950	87	50.9	250	15.8	30	14	9/20	Lifted	Lifted	Lifted
13,000	86.5	50.9	250	15.8	29	15	9/21	Lifted	Lifted	Lifted
13,050	86	21.4	175	15.8	29	15	10/20	Lifted	Lifted	Lifted
13,100	86	21.4	240	15.8	29	15	11/21	Lifted	Lifted	Lifted
13,150	86	22.2	250	15.8	31	15	12/22	Lifted	Lifted	Lifted
13,200	86	21	250	15.8	31	15	12/22	Lifted	Lifted	Lifted
13,250	86.5	21.4	250	15.8	31	15	12/24	Lifted	Lifted	Lifted
13,300	86	21	250	15.8	31	15	11/23	Lifted	Lifted	Lifted
13,350	85.5	21.4	175	15.8	32	18	10/22	Lifted	Lifted	Lifted
13,400	85.6	22.2	260	15.8	32	18	10/22	Lifted	Lifted	Lifted
13,450	85.7	21.4	225	15.8	32	18	12/25	Lifted	Lifted	Lifted
13,500	85.8	21.4	235	15.8	32	18	12/27	Lifted	Lifted	Lifted
13,550	86	21.4	235	15.8	32	18	13/28	Lifted	Lifted	Lifted
13,600	86	21.4	240	15.8	32	18	14/29	Lifted	Lifted	Lifted
13,650	86.5	13	240	15.8	34	17	13/29	Lifted	Lifted	Lifted
13,700	86.6	21.4	180	15.8	34	17	14/29	Lifted	Lifted	Lifted
13,750	86.7	20.7	240	15.8	34	17	14/29	Lifted	Lifted	Lifted
13,800	86.8	20.7	240	15.8	36	19	13/30	Lifted	Lifted	Lifted
13,850	87	23.1	230	15.8	36	19	14/29	Lifted	Lifted	Lifted
13900	86.1	21.4	235	15.8	36	19	14/30	Lifted	Lifted	Lifted
13,950	87.8	23.1	220	15.8	36	19	15/30	Lifted	Lifted	Lifted
14,000	87.9	21.1	245	15.8	36	19	15/30	Lifted	Lifted	Lifted
14,050	88.1	20	245	15.8	37	24	16/29	Lifted	Lifted	Lifted
14,100	88.1	20	250	15.8	37	24	16/29	Lifted	Lifted	Lifted
14,150	88.1	17.7	250	15.8	37	24	15/28	Lifted	Lifted	Lifted
14,200	88.3	21.1	225	15.8	37	23	16/27	Lifted	Lifted	Lifted

5.2 Well "Y" – Inclined Well

Well "Y" was designed to reach a target depth of 10,861 ftMD with hold inclination 58°. This well was sidetracked at 5,063 ftMD and finally was abandoned with plug-back cementing at 8,710 ftMD due to several cases of stuck pipe. Stuck pipe in this well was experienced due to pack-off. This indicated that hole cleaning was poor. Fishing operations were conducted 3 times at 3,170 ftMD (section hole 17.5", shale formation, MW in 10 ppg, pump flow rate 850 GPM), 5,168 ftMD (section hole 12.25", shale formation, MW in 12.9 ppg, pump flow rate 700 GPM), and at sidetrack hole 6,622 ftMD (section 12.25", shale formation, 12.7 ppg, pump flow rate 700 GPM) when the company decided to plug back the well. The company used a pump with maximum pump displacement 772 GPM. All input data are listed in Tables 3 and 4.

Table 3 Well "Y" data.

Well classification	Directional well		
Total inclination	58^{o}		
Total depth	7,200 ftMD		
Hole section	26"	17.5"	12.25"
Formation	Claystone, sandstone, limestone	Claystone, sandstone, limestone	Claystone
Section inclination (^{o})	0	65	58
Drilling fluid	WBM	OBM	OBM
MW (ppg)	8.7-9.05	9-10	11-12.9
PV (cp)	10-12	15-51	25-50
YP (lb/100ft^2)	12-18	16-81	19-30
ROP (ft/hr)	110.2	13.91	35.5
RPM	82	176	80

Table 4 Drilling parameter data of Well "Y".

MD (ft)	**Inclination**	**ROP (ft/hr)**	**RPM**	**Drilling fluid weight (ppg)**	**PV (cp)**	**YP (lb/100ft^2)**	**GS 10s/10m (lb/100ft^2)**	**Cutting transport condition**		
								Rudi-Shindu	**Hopkin**	**Tobenna**
500	0.4	148.6	120	9.3	15	20	5/10	Not Lifted	Not Lifted	Lifted
1,000	1.7	132.1	89	9.3	15	20	5/10	Not Lifted	Lifted	Lifted

MD (ft)	Inclination	ROP (ft/hr)	RPM	Drilling fluid weight (ppg)	PV (cp)	YP (lb/100ft^2)	GS 10s/10m (lb/100ft^2)	Cutting transport condition		
								Rudi-Shindu	Hopkin	Tobenna
1,500	13	157.1	151	9.3	15	20	7/13	Not Lifted	Not Lifted	Lifted
2,000	17.6	106.7	102	9.3	15	22	6/12	Not Lifted	Not Lifted	Lifted
2,500	31.5	105.6	102	9.3	15	22	7/14	Not Lifted	Not Lifted	Lifted
3,000	42.3	116.6	168	9.3	15	22	7/14	Not Lifted	Not Lifted	Lifted
3,500	59	71.7	166	9.4	15	22	7/14	Not Lifted	Not Lifted	Lifted
4,000	64.9	46	102	9.7	16	22	7/14	Not Lifted	Not Lifted	Lifted
4,500	63.5	100	155	9.9	17	22	10/22	Not Lifted	Not Lifted	Lifted
5,000	66	51.5	168	10	41	25	10/22	Lifted	Not Lifted	Lifted
5,500	69	73	213	11	44	27	19/51	Lifted	Not Lifted	Lifted
6,000	67	73.8	208	11	44	27	18/49	Lifted	Not Lifted	Lifted
6,500	66.5	63	100	11.3	42	25	11/46	Lifted	Not Lifted	Lifted
7,000	59	71	100	11.3	42	25	12/49	Lifted	Not Lifted	Lifted
7,200	58	75	100	11.3	42	25	13/37	Lifted	Not Lifted	Lifted

6 Calculation

In this section, calculation examples of minimum drilling fluid velocity and cutting-bed concentration prediction are elaborated using data from the case-study wells. The differences between each model can be represented by the calculation results yielded from each model with certain parameters used. The calculation steps shown in Table 5 may illustrate the sensitivity of the parameters to each model. Calculation examples of minimum drilling fluid velocity and cutting-bed concentration prediction are elaborated using data from the case-study wells. The calculation results are summarized in Table 5 below.

Table 5 Calculation Results of Rudi-Shindhu, Hopkins and Tobenna Methods

Well Data	Rudi – Shindu's	Hopkins'	Tobenna's
MD = 7200 MDft	V_{cut} = 1.4181 ft/s	ρ_s = 17.493 ppg	n = 0.702
Inclination = 58 deg	V_{min} = 1.7643 ft/s	F_{mw} = 0.724787	k = 429.7
Dh = 12.25 inch	μ_a = 638.964 cp	V_{sv} = 54.649 ft/min	A_a = 0.682 ft^2
Dp = 5 inch	N_{Re} = 0.004759	V_s = 39.6088 ft/min	$Q_{vertical}$ = 420.3 GPM
ROP = 75 ft/hr	f = 8404.502	V_2 = 159.849 ft/min	AF = 1.08
RPM = 100	V_{slip}= 0.4358 ft/s	V_{min} = 156.549 ft/min	$Q_{deviated}$ = 388.8 GPM
PV = 42 cp	$V_{slip\ correction}$ = 0.3462 ft/s	Q_{min} = 798.60431 GPM	
YP = 25 lb/100ft^2	A = 5.0996 gal/ft		

ρ_m = 11.3 ppg	Q_{min} = 539.838 gpm
d_c = 0.0029 inch	
C_c = 1.8385 %	
Tp = 25 lb/100 ft^2	
SG Cutting = 2.1	
Pw = 8.33 ppg	
C = 40 (assumed)	

7 Discussion

Based on this study, each of the three models has its own limitations. However, Rudi-Shindu's model covers more drilling parameters than Hopkins' and Tobenna's models. Hopkins' and Tobenna's give a simpler model to determine the minimum flow rate. All three models have a similar trend in sensitivity to drilling fluid weight, specific gravity of cutting, and hole diameter. For yield point, Tobenna's model is the most sensitive, for which Hopkins' model is only slightly sensitive, while Rudi-Shindu's model is not sensitive to it at all. Both Rudi-Shindu's and Hopkins' models are not sensitive to plastic viscosity. In contrast, Tobenna's model is affected by plastic viscosity. Sensitivity to ROP and RPM could not be measured for Hopkins' and Tobenna's models since those parameters are neglected in both models. Table 6 summarizes the parameters used and not used by each model.

Table 6 Drilling parameter comparison of Rudi-Shindu's and Hopkins' Models.

	Rudi-Shindu's	**Hopkins'**	**Tobenna's**
Inclination	Yes	Yes	Yes
Hole diameter	Yes	Yes	No
MW	Yes	Yes	Yes
PV	No	No	Yes
YP	No	Yes	Yes
ROP	Yes	No	No
RPM	Yes	No	No
Cutting diameter	Yes	Yes	No
Cutting concentration	Yes	Yes	No
Cutting density	Yes	Yes	No
Lateral length	No	No	No

8 Conclusions

In large holes (26 inches), minimum flow velocity from Hopkins' model tends to have a lower value than from Rudi-Shindu's model. Meanwhile, in small holes (5-3/4 inches), minimum flow velocity from Rudi-Shindu's model tends to have a lower value than from Hopkins' model. However, minimum flow velocity from Tobenna's model is not sensitive to hole diameter.

At low inclinations (< 30°), Hopkins' and Tobenna's models give lower minimum flow velocity than Rudi-Shindu's. Meanwhile, at higher inclinations (> 30°), Hopkins' model gives a higher minimum flow velocity than Rudi-Shindu's.

The type of formation influences cutting transport. Higher SG cuttings, i.e. limestone, give more difficulty in hole cleaning since they need a higher minimum flow velocity.

Rudi-Shindu's and Hopkins' models gave a very high minimum pump velocity in large holes (26 and 17.5 inches). Hopkins' model can be used only for cutting size between 0.4-0.95 inches and when drillpipe rotation is not desired (i.e. coiled tubing drilling). Hopkins' model is more suited for inclinations above 45° since Rudi-Shindu's model neglects the effect of inclinations above 45°. Tobenna's model is not recommended for designing cutting transport since the drilling parameters considered in the model are not adequate.

Flow rate is the major factor for cutting transport. Meanwhile, cutting transport can be improved by manipulating other drilling parameters as well.

Nomenclature

A_a	=	annulus area, ft^2
A_{bed}	=	cutting bed area, ft^2
$A_{wellbore}$	=	area of wellbore, ft^2
C	=	empirical constant of laboratory = 40
C_{bconc}	=	cutting bed concentration, %
C_c	=	cutting concentration, %
C_{inc}	=	Rubiandini's inclination correction
C_{dens}	=	Rubiandini's drilling fluid density correction
C_{RPM}	=	Rubiandini's drillpipe rotation correction
D_{hyd}	=	hydraullic diameter, in

D_i	=	inner diameter, in
D_o	=	outer diameter, in
d_c	=	cutting diameter, in
d_{pipe}	=	drillpipe OD, in
d_{hole}	=	hole diameter, in
F	=	friction factor
F_{mw}	=	correction factor of drilling fluid weight for Hopkins'
g	=	gravitational accelaration, $lb_m ft/lb_f s^2$
k	=	drilling drilling fluid consistency parameter (Power Law)
n	=	drilling drilling fluid behavior index (Power Law)
N_{Re}	=	Reynold's number
PV	=	plastic viscosity of drilling fluid, cp
Q_{pump}	=	pump flow rate, gpm
Q_{crit}	=	critical flow rate, gpm
$Q_{deviated}$	=	flow rate for deviated well, gpm
$Q_{vertical}$	=	flow rate for vertical well, gpm
ROP	=	penetration rate, ft/hr
RPM	=	drillpipe rotation
Rt	=	transport ratio
V_2	=	cutting velocity for Hopkins' model, ft/min
V_{min}	=	minimum flow velocity, ft/min
V_s	=	slip velocity, ft/min
V_{sv}	=	vertical slip velocity, ft/min
v_{cut}	=	cutting velocity, ft/s
v_{crit}	=	critical/drilling fluid minimum velocity, ft/s
V_{slip}	=	slip velocity, ft/s
YP	=	yield point of drilling fluid, lb/100ft^2
μ_a	=	apparent viscosity of drilling fluid, cp
ρ_m	=	drilling fluid density, ppg
ρ_s	=	cutting density, ppg
θ	=	Inclination, °

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