GHGfrack: A model for estimating greenhouse gas emissions from drilling and hydraulic fracturing

User Guide for GHGfrack version 1.0

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Contents

1. What is GHGfrack?

GHGfrack models the greenhouse gas (GHG) emissions from oil and natural gas well drilling and hydraulic fracturing operations. GHGfrack estimates the direct energy consumption for drilling of vertical, directional, and horizontal wells. This includes the energy consumed for the rotation of the drill string and drilling mud circulation. GHGfrack also calculates the energy requirement for injection of water during fracturing, considering the strength of the rock formation being fractured and the hydraulic properties of injection.

Flow back process and under balanced drilling can be significant sources of greenhouse gas (GHG) emissions. The current version of GHGfrack is limited to calculation of GHG emissions from combustion of fuels to supply energy for drilling (including mud circulation) and fracturing pumps.

Development of GHGfrack was sponsored by the California Air Resources Board (funded under ARB contract 13-408). GHGfrack is developed to augment and improve the OPGEE model of Stanford University. OPGEE stands for Oil Production Greenhouse Gas Emissions Estimator, and is an open-source model for estimating GHG emissions from oil and gas operations. The goal of developing GHGfrack is to enhance the accuracy of estimating the air emissions from directional well drilling (including horizontal wells) and hydraulic fracturing. GHGfrack is an open-source computer program, which is written in Microsoft Excel using the Visual Basic for Applications (VBA) language. Microsoft Excel is used in order to ensure that the model is readable and accessible by the largest possible community (Microsoft Excel is popular in the life cycle assessment and regulatory government community). Because GHGfrack is an open-source code, users can modify, improve, or customize it for their own particular application. It can be tailored with simple VBA code to be run on large datasets for thousands of oil and gas wells.

Estimation of the energy use and emissions during drilling is a challenge for life cycle assessment studies. While GHGfrack makes realistic estimates of energy use in drilling

a well, it is not intended to be used as a drilling engineering software (e.g. performing detailed torque and drag calculations).

GHGfrack can provide estimates of some of the input parameters for a particular case if the user chooses the “automatic” mode instead of the manual mode. The idea is to let the user start with values which are not out of range of physical reality. It is the responsibility of the user to use appropriate input parameters for the particular study at hand based on the field data or the literature.

Users with experience in college-level physics who have a general idea of the process of drilling oil wells and hydraulic fracturing should be able to readily use GHGfrack. The theory of the non-Newtonian fluids is briefly reviewed in this user guide, to enable those who are not familiar with the subject of fluid mechanics to use GHGfrack properly.

2. The theoretical foundation of GHGfrack

The theoretical concepts and formulation for drilling and mud circulation is mainly taken from a reference text by Azar and Samuel.[1] This document explains the mathematics and algorithms of calculations of the three modules: drilling, mud circulation, and hydraulic fracturing.

GHGfrack uses only explicit equations, which guarantees a solution providing that the user does not enter data that are mathematically or physically impossible. In some cases, GHGfrack implements less complex formulae to avoid iterative methods that might not always converge to a solution. In practice when we use any drilling engineering model, many of the parameters and conditions are either unknown or uncertain, e.g., exact well bore geometry and position of the pipe in the hole. When it comes to the non-Newtonian fluids, even the complex correlations which appear in the literature are only approximations[2]. Thus, for the purpose of GHGfrack the choice of simpler explicit methods is not likely to be a notable source of inaccuracy, and using more complex or implicit equations would not necessarily lead to higher accuracy.

We use oil field units (mixed Imperial) instead of SI units (with few exceptions). Firstly, the governing equations of the hydraulic system are developed and derived from reference works using this system of measurement. Secondly, these units are prevalently used in the related literature about oilfield development at the time that we have been developing GHGfrack (in the USA). This avoids redundant conversions when both the reported field data and equations are in field units. The open-source nature of GHGfrack let this program be easily modified to use SI units.

2.1 Drilling

Figure 1 shows the input variables for top-drive drilling model, as entered in Drilling Power worksheet in GHGfrack. The example input values are taken either from the key reference text .[1] The example values are just for giving an idea and are not supposed to be copied as the real model inputs. The model input values should be set under "User", based on the values taken from the reliable reports and literature, or field data. Figure 2 shows how results from the top-drive (rotation) model are reported.

Rotational Energy via Rotary Table: Input Data — Rotary Table

	User	Example	Units	Notes	
Is rotary table active?	Yes	Yes		Yes/No	
User defined torque value	Yes	Yes		Yes/No	No for automatic mode: automatic estimation based on Azar and Samuel method pages 23 and 24
Length of drill string at top of the section	10855	50	ft		
Length of drill string at bottom of the section	14500	4250	ft		
Rate of drill penetration (ROP)	1.25	1	ft/min		
Rotationl speed	60	60	rpm		
Inclination angle	90	0	degree	Vertical =0 , Horizontal = 90, Directional > 0	
Engine Efficiency	45	45	%		
Torque factors:	1.625	1.625		for shallow holes less than 10,000 ft with light drill string = 1.5 to 1.75	
(Automatic mode)	1.875	1.875		for 10,000 ft - 15,000 ft wells with average conditions = 1.75 to 2.0	
	2.125	2.125		for deep holes with heavy drill string = 2.0 to 2.25	
	2.625	2.625		for high torque torque = 2.25 to 3.0	
Torque values:	13000	8500	ft-lbf	vertical	less than 15,000 ft-lbf
(Applied torque is known)	15000	15800	ft-lbf	horizontal	may exceed 80,000 ft-lbf
	15000	13700	ft-lbf	inclined	

Figure 1. The input parameters of the drilling module

Rotaional Energy via Rotary Table: Results			
Drilling time	48.6	h	
Drilling power segment 1	380.6	hp	Drilling string length less than 10,000 ft or directional well
Drilling power segment 2	NA	hp	Drilling string length 10,000 to 15,000 ft
Drilling power segment 3	NA	hp	Drilling string length more than 15,000 ft
Drilling energy required	47.1	MMBtu	
Max HP	380.6	hp	

Figure 2. The output of the drilling module

In drilling operations, the power to drill the rock is supplied by either a driver at the surface (top driver) or a downhole motor or both[3]. GHGfrack let the user select either or both of these means. The downhole motor is discussed in section 2.2 where we explain the hydraulic model. The power requirement for rotation of the drill string depends on the rotational speed, the applied torque at the top driver, and the efficiencies of the diesel engine and the mechanical design to transmit work to the top driver. The rotary power requirement (before applying the efficiencies) is calculated by equation 1.[1]

$$H_{rp} = \frac{2\pi NT}{33{,}000} \tag{1}$$

in which H_{rp} = rotary power [horsepower], N = rotary table speed [rpm], and T = torque [ft-lb_f].

The rotary power requirement is generally smaller in drilling vertical wells compared with drilling directional well segments. The required torque is generally less than 15,000 ft-lb_f in vertical well drilling while in directional drilling it may exceed 80,000 ft-lb_f.[1] The required torque for drilling is difficult to predict since there are many factors that can influence the drill pipe torque, including: hole size, depth, type of bit, drill collar size, drill pipe size, bit weight, rotational speed, mud properties, hole inclination angle, severity and location of the doglegs, use of reamers, stabilizers, and formation characteristics.[1]

The top-drive drilling module has two modes for input of torque requirements. The *user defined* mode and *automatic* mode. The user defined mode lets the user define the

average torque value for each drilling section. This torque value is applied to the entire drilling section to calculate power using equation 1. If the drilling section is so deep that the torque requirement may change significantly along the section, the user can split the drilling section into smaller pieces, each with a different torque value.

The automatic mode uses an empirical approach.[1] Instead of the torque value an empirical parameter named torque factor is used in this method. The definition of torque factor is given by equation 2:[1]

$$H_{rp} = FN \tag{2}$$

in which *F* is the torque factor and *N* is the rotational speed [rpm]. GHGfrack uses the torque factors in Table 1, as suggested by Azar and Samuel.[1,2]

Table 1. Range of torque value, F, given by Azar and Samuel [1,2].

1.50 - 1.75	for shallow holes less than 10,000 ft with light drill string
1.75 - 2.00	for 10,000 – 15,000 ft wells with average conditions
2.00 - 2.25	for deep holes with heavy drill string
2.25 - 3.00	for high torque

Azar and Samuel suggests that these values are reasonable estimates of rotary requirements. However, for highly deviated wells, they suggest that the torque requirement must be calculated using computer software programs.[1]

The automatic mode in drilling module uses the average of value of torque factor for each range by default. The user can change the torque factor and enter any desired value from Table 1 or out of the suggested ranges if desired. This mode choses the torque factors based on the inclination angle of the well which is a model parameters.

The default torque factor for directional wells (including horizontal) is set to the range for high torque from Table 1, but the user can modify the torque value for vertical, inclined, and horizontal wells and assign a desired value to each separate drilling section. The

automatic mode can split a vertical well up to three segments and uses the designated torque factor for each range of the depth based on Table 1. Consequently, three different horse power values can be reported for each of these three segments as it is depicted in Figure 2. The model considers only one single torque factor for the entire length of an inclined or a horizontal section. If the directional well is very long and use of a single average torque factor can be insufficient for accurate evaluation of the required power. In this case, the user can split that particular long section to smaller parts using different torque factor for each. Users should calibrate the automatic module with field torque data if they are available.

Comparing equation 1 and 2, one can see that the torque factor, F, can be calculated if the torque T is known. This can be used to calibrate the automatic module while the torque values in drilling operation are reported and available. While these two modes are similar, there is one algorithmic difference. The automatic mode detects the depth as drilling progresses and applies different torque factors from the torque factor table in Figure 1 according to the instantaneous depth of drilling. In contrast, the user-defined torque mode applies the defined torque to the entire length of the drilling section. Therefore, the users are also responsible to choose the smallest length of the drilling section for which the defined torque value is representative. The automatic mode does not split the length for the directional wells.

For example, in drilling a vertical section of a well from 9,000 to 16,000 ft, the automatic mode breaks down this distance to three segments: less than 10,000 ft, 10,000 to 15,000 ft, and above 15,000 ft. The automatic mode applies different torque factors for each segment from the torque factor table. In the user-defined torque mode a single torque value from the table in Figure 1 is used to calculate the rotational power for the entire length of the drilling section. In the example above, such a large length is not a reasonable choice for calculating the rotational power as the required torque is expected to change. Nevertheless, the user-defined torque value mode is intentionally designed to give more freedom and control for the user who is an expert in the area.

The power calculated by equation 1 or 2 is the theoretical value, and the real energy use depends on the efficiency of the electrical generator and the conversion to mechanical energy and transmission to the rotary table (top driver). The efficiency in the drilling module is an overall efficiency that contain all the losses from generation of the electricity to the mechanical losses in transmission of work to the rotary table and rotation of the drill string at the surface couplings or joints. The brake horsepower (BHP) is calculated by dividing the total theoretical rotational and transmission power by the overall efficiency. This is BHP for the diesel engine and is used to evaluate the fuel consumption and GHG emissions upon combustion.

In order to calculate the energy consumption, the drilling time is required. The drilling time can be calculated based on reported values of the rate of penetration (ROP) of the drill bit for each drilling section, typically reported in units of [ft/hr]. ROP near the surface is usually higher than deep in the formation and in the directional segments. Energy consumption is calculated by multiplying the BHP and the drilling time for each section. The drilling module also reports the maximum required BHP in case the automatic model splits the section to smaller subsections and applying different torque factors as explained earlier.

To calculate the required diesel fuel and the greenhouse gas emissions we use data from OPGEE version 1.1 Draft D.[4] The fuel efficiency of the diesel engine is calculated based on the empirical equation suggested in OPGEE worksheet *Fuel Spec*. The emission factor for combustion of the diesel fuel is also taken from OPGEE in worksheet *Drivers*.

GHGfrack version 1.0 does not model the energy consumed by an idling engine. One set of drilling cost data reports zero idling time for evaluation of the cost of the diesel fuel.[5] While this will not be strictly true in a real operation, and some idle time is likely inevitable, in a well-managed drilling operation the idle time of the engine should be kept to a minimum. If idle time is comparable to the time of drilling (e.g., of order of a week to a

month or more), then the model can be easily modified to include the time of the idling and the fuel efficiency of the idling engine.

Draw work is work required to pull the drill string out of the well to change the drill bit and making other necessary changes to the drill string. In GHGfrack version 1.0 the energy required for draw work is estimated to be insignificant compared with the drilling energy. The overall duration of the draw work is much smaller than the time in which drilling actually takes place, so we neglect it here.

1.2. Mud circulation

Use of drilling fluids is necessary in drilling a gas or oil well. Some important functions of a drilling fluid are:[1]

- Cleaning drill bit and removing drilling cuttings;
- Containing subsurface formation fluid pressures
- Stabilizing the hole prior to casing and cementing
- Cooling and lubricating the drill string and drill bit

Drilling fluid can be in gas or liquid phase and is made of many different compositions in practice. Drilling mud is a liquid (water or oil or a combination) that is mixed with a clay or clay-like substance, such as bentonite clay or a polymer[1]. Drilling mud is a common drilling fluid.

The energy required to circulate drilling muds is the largest source of drilling energy consumption for most wells. The mud circulation module of GHGfrack is a hydraulic module that calculates the pressure drop during flow of the mud inside the drill string and through the annulus where the mud flow back to the surface. GHGfrack models the hydraulics of the drilling muds assuming that their rheology follows either a *Bingham plastic* or *power law* model. These models are used commonly in the literature to describe the rheology of drilling mud. We will give a brief review of the rheology of mud later in this section.

Figure 3 shows the flow of mud in a vertical well. The drill string consists of drill pipe, and bottom hole assembly (BHA). The BHA consists of the drill bit, drill collar, mud motor (or downhole motor), measurement-while-drilling (MWD), and other tools (Figure 3 does not show the details of the BHA). The hydraulic model considers two annuli, one between the wall of the hole and outer wall of the drill collar and the second, between the wall of the hole and the outer wall of the drill string. The BHA and drill collar are assumed to have the same outside diameter (OD) or an average OD is used if OD is varied along BHA. In GHGfrack this OD is referred to as drill collar OD.

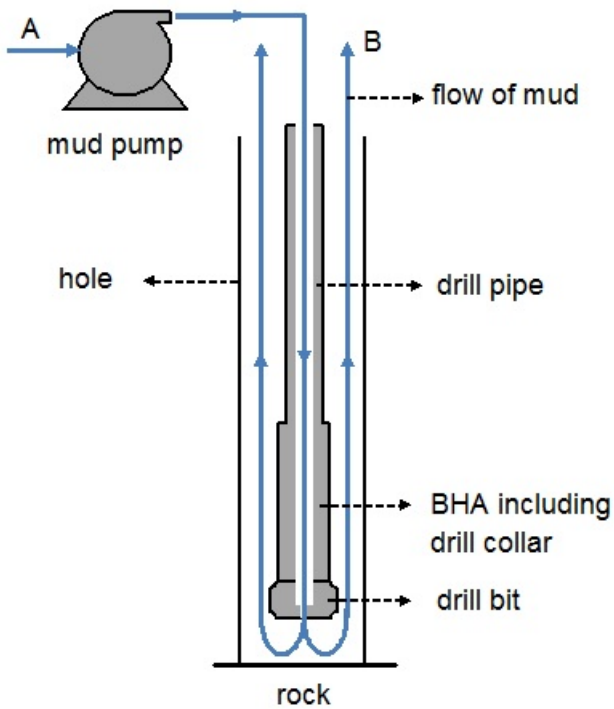

Figure 3. Mud circulation

We assume that for each drilling section, the diameter of the hole from the drill bit up to the surface changes insignificantly. In many cases when the operator drills a hole, they put a casing that extends to the surface and then cement the area between the hole and

that casing. The next segment of hole to drill has an OD close to the ID of the installed casing and thus the mud flow through a reasonably constant hole and casing diameter from the bit to the surface (see Figure 4). Future versions of GHGfrack will be designed to handle wells in which mud flows through an annulus of varied diameter.

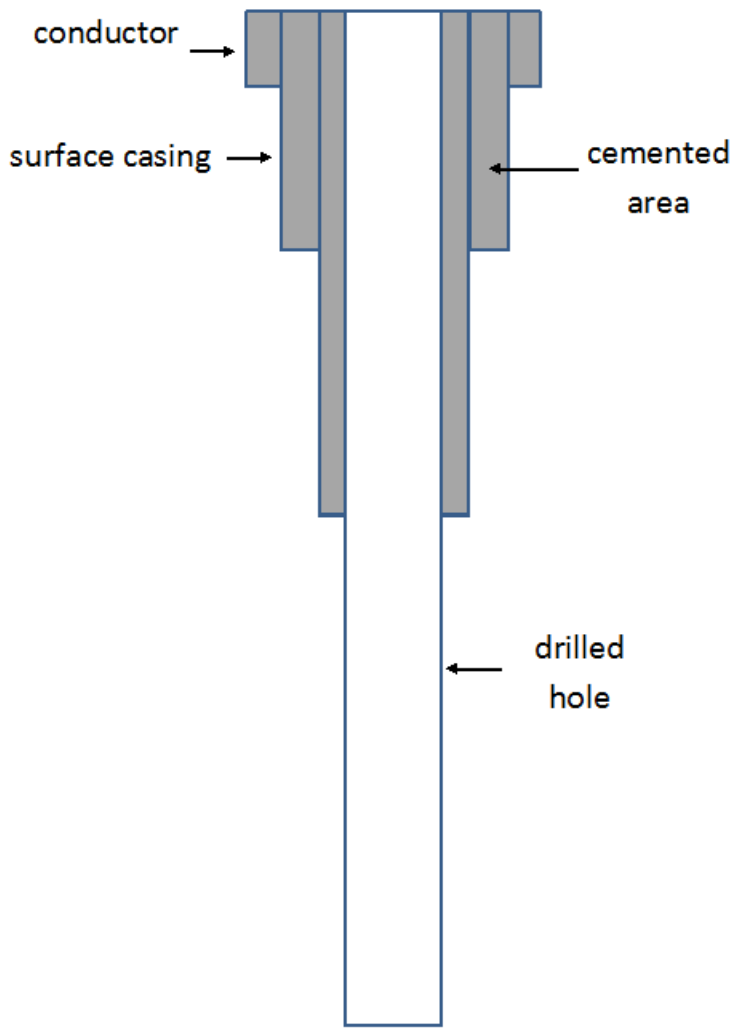

Figure 4. Drilling of a hole and the casing and cementing design

Figures 5 to 7 show the input data for the mud circulation module of GHGfrack. Figure 8 shows how the results are tabulated. The length and inclination of the well are among the

input parameters which should be set for the drilling module (see Figure 1). In the following we explain the hydraulic model formulation in detail. This helps with better understanding of the all input variables.

Mud Circulation: Input Data

	User	Example	
Mud Characteristics:			
Fluid type:	2	2	
(1) Newtonian			
(2) Bingham plastic			
(3) Power law			
Mud viscosity:			
Dynamic viscosity (Newtonian fluid)		1	cp
Plasic viscosity	25	25	cp
Consistency index K (Power law fluid)	0.066	0.066	equivalent cp
Power law index n	0.29	0.29	
Yield stress	15	15	lbs/100 ft^2
Mud density	12	12	lbs/gal

Figure 5. Mud circulation module-Input parameters related to mud characteristics

Drill cuttings characteristics:

Drill cuttings sieve diameter	0.5	0.5	in
Drill cuttings density	25.04	25.04	lbs/gal

Geometry:

Length of drill collar	700	700	ft
Hole diameter	24	12.25	inch
Drill pipe OD	6.63	6.63	inch
Drill pipe ID	5.97	5.97	inch
Drill collar OD	18.48	9.50	inch
Drill collar ID	8.69	4.43	inch
Number of segments of the drilling section	100	100	
Drill pipe roughness	0.00008	0.00008	inch

Figure 6. Mud circulation module-Input parameters related to the drill cuttings and well geometry.

Pump:			
Mud pump efficiency	65	65	%
Drill bit:			
Number of nozzles	5	3	
Size of nozzles	0.50	0.34	in
nozzle discharge coefficient Cd	0.95	0.95	
Is downhole motor in place?	Yes	Yes	Yes/No
	1		
Mud flow rate & downhole motor:			
Pressure drop across downhole motor	700	500	psi
Downhole motor rpm	100	100	rpm
Mud flow rate	NA	500	gpm
Other sources of pressure drop	0	0	psi
Modified cuttings transport ratio	2.21	2.21	

Figure 7. Mud circulation module inputs related to pump, drill bit, and mud flow rate.

Mud Circulation: Results	Mud Pump	
Average velocity in annulus (hole - drill pipe)	2.3	ft/s
Average velocity in annulus (hole - collar)	5.3	ft/s
Average velocity in drill pipe	35.1	ft/s
Average velocity in drill collar	16.6	ft/s
Mud flow rate	3057.2	gpm
Re in pipe	55557	
Re in collar	20686	
Re hole - pipe annulus	639	
Re hole - collar annulus	2603	
Pressure drop in drill pipe	0.3364	psi/ft
Pressure drop in drill collar	0.0587	psi/ft
Pressure drop in annulus (hole - drill pipe)	0.0045	psi/ft
Pressure drop in annulus (hole - drill collar)	0.0168	psi/ft
Pressure drop across the downhole motor	700	psi
Pressure drop across the bit nozzles	10712	psi
Pressure drop due to friction (max)	4	psi
Total pressure drop (max)	11416	psi
Mud pump BHP (max)	31327	hp
Drilling time	3.8	h
Energy consumption by mud pump	301.9	MMBtu

Figure 8. The results of mud circulation calculation

2.2.1. Mechanical energy of the mud pump

The mud circulation module calculates the energy consumption of the mud pump. The brake horse power of the pump is calculated using equation 3:[1]

$$BHP = \frac{\Delta P \times Q}{1714 \times \eta} \tag{3}$$

where:

BHP = brake horse power [hp]

ΔP = Differential pressure between the suction and discharge of the pump [psi]. If we assume the suction is at zero psig then this quantity is the pump discharge pressure [psig].

Q = flow rate of mud in US gallon per minute [gpm], and

η = mud pump efficiency.

The mechanical energy balance can be written for the mud flow between point A and B (see Figure S3):

$$\frac{\rho g h_A}{g_c} + \frac{\rho {V_A}^2}{2g_c} + P_A + W_p - W_f = \frac{\rho g h_B}{g_c} + \frac{\rho {V_B}^2}{2g_c} + P_B \quad (4)$$

in which

ρ is density of mud [lb_m/ft^3];

g is gravitational acceleration [ft/s^2];

V is velocity [ft/s];

P is pressure [lb_f/ft^2];

h is height [ft];

W_p is the work done by pump on the unit volume of the fluid $\left[\frac{ft.lbf}{ft^3} \equiv \frac{lbf}{ft^2}\right]$;

W_f is the friction energy loss per unit volume of the fluid $\left[\frac{ft.lbf}{ft^3} \equiv \frac{lbf}{ft^2}\right]$.

g_c is a coefficient for conversion of lb_m to lb_f:

$$F = \frac{ma}{g_c} \quad (5)$$

in which m is mass [lb_m];

a is acceleration in [ft/s^2];

and g_c = 32.174049 [lb_m-ft/lb_f-s^2].

if we define:

$$\gamma_{mud} = \frac{\rho g}{g_c} \quad \left[\frac{lb_f}{ft^3}\right]$$

then equation S4 can be written as:[1]

$$\gamma_{mud} h_A + \frac{\gamma_{mud} {V_A}^2}{2g} + P_A + W_p - W_f = \gamma_{mud} h_B + \frac{\gamma_{mud} {V_B}^2}{2g} + P_B \quad (6)$$

All the terms in equation 4 and 6 have the dimension of work per unit of liquid volume, which is equivalent to the pressure unit. Thus, equation 6 can be written in as a pressure balance equation:[1]

$$\Delta P_p = \Delta P_d + \Delta P_f - \Delta P_h + \Delta P_{other} \quad (7)$$

in which

ΔP_p is the pressure drop across the pump

ΔP_d is the change in dynamic pressure

ΔP_f is the pressure loss due friction

ΔP_h is the hydrostatic pressure due to the difference in elevation

ΔP_{other} is the pressure loss due other sources like pressure drop through the fittings

Referring to the diagram in Figure 3, $h_A - h_B$ is the difference between the level of the mud pump and the injection point on the rig, which is close to zero compared with the depth of an oil well, and is not significant compared with the pressure drop due to the other terms in equation 7. If desired, the pressure drop due this difference can be calculated and be entered as the "pressure drop from other sources" (see Figure 7). The pressure drop due the friction losses through the fittings at the well head can be added to this value.

The only significant dynamic pressure change is that across the jets of the bit.[1] The friction loss is due to the pipe friction and the pressure drop across the downhole motor. Thus, equation 7 can be rewritten as:

$$\Delta P_P = \Delta P_b + \Delta P_{dm} + \Delta P_{fdp} + \Delta P_{fdc} + \Delta P_{fadp} + \Delta P_{fadc} \quad (8)$$

in which ΔP_b is pressure drop across the jets of the bit [psi];

ΔP_{dm} is the pressure drop across the downhole motor [psi];

ΔP_{fdp} is the pressure drop across the drill pipe [psi];

ΔP_{fdc} is the pressure drop across the drill collar [psi];

ΔP_{fadp} is the pressure drop across the pipe – hole annulus [psi];

ΔP_{fadc} is the pressure drop across the drill collar-hole annulus [psi].

ΔP_{dm} should be entered by the user (see Figure 7). The other pressure drop terms of equation 7 are calculated as explained below.

1.2.2. The pressure drop across the jets of the bit

The pressure drop across the jets of the bit ΔP_b [psi] is calculated using equation 9:[1]

$$\Delta P_b = \frac{8.3\times10^{-5}\gamma_{mud}Q^2}{{C_d}^2{A_t}^2} \tag{9}$$

In which:

Q is gallon per minute [gpm];

γ_{mud} is mud density [lb_f/gal];

A_t is area of the jets open to the flow [in^2];

C_d is the nozzle discharge coefficient [dimensionless].

2.2.2 Friction pressure losses in the rotary rig circulating system

GHGfrack calculates friction pressure drop for Newtonian fluids and non-Newtonian fluids, which are modeled using either a Bingham plastic fluid or power law fluid approximations. Adding complexity, the flow of fluids can be in either the laminar or turbulent regime.

2.2.2.1 Mud rheology

Rheology is the study of the deformation of fluids.[1] For a Newtonian fluid like water the relationship between the shear stress and the shear rate is given by equations 10:

$$\tau = \mu\gamma \tag{10}$$

$$\gamma = \frac{dV}{dr} \tag{11}$$

in which:

τ is the shear stress [dyne/cm^2];

μ is viscosity [poise= $\frac{dyne \times s}{cm^2}$];

V is velocity of flow parallel to the pipe axis [cm/s];

r is radial distance in pipe [cm];

γ is the shear rate [1/s] (not to be confused with γ_{mud} which is mud density in lb_f/gal or lb_f/ft^3).

The field unit for viscosity and shear stress are centipoise and $lb_f/100ft^2$ respectively. GHGfrack uses field units. Shear stress and shear rate are covered further in introductory texts on physics of fluid flow or fluid mechanics.

The relationship between the shear stress and shear rate for non-Newtonian is different from equation 10. Drilling mud is typically understood to be a non-Newtonian fluid. Its rheology is mostly described by either Bingham plastic or power law model in the literature. Equation 12 and 13 show the relationship between shear rate and sheer stress in these two models:

Bingham plastic

$$\tau = \tau_y + \mu_p\gamma \tag{12}$$

Power law

$$\tau = k\gamma^n \quad (13)$$

where

τ_y is the yield stress or yield point $[\frac{lb_f}{100ft^2}]$

μ_p is the Bingham plastic viscosity [centipoise]

k is the consistency index [equivalent centipoise]

n is the power law index

The parameters of the equations 12 and 13 are input parameters of the mud circulation model, if the user chooses a non-Newtonian fluid model (Figure 5). GHGfrack let the user chooses Newtonian, Bingham plastic, or Power law model.

2.2.2.2 Reynolds number

The Reynolds number is a non-dimensional criterion to determine the flow regime. For a Newtonian fluid like water:

$$Re = \frac{928\gamma VD}{\mu} \quad (14)$$

in which:

γ is density [lb_f/gal];

V is the velocity [ft/s].

D is the internal diameter (ID) of the pipe or the equivalent diameter of the annulus [in];

μ is the viscosity of the Newtonian fluid [cp].

A flow with Reynolds number higher than 2100 is considered turbulent.[1] To calculate Reynolds number for annular flow, an equivalent diameter should be defined. We used the following definition:[1]

$$D_{eq} = 0.816\left(D_{hole} - D_{pipe\ OD}\right) \quad (15)$$

In which D_{eq} is the equivalent diameter for the annular flow [in];

D_{hole} is the diameter of the hole [in];

$D_{pipe\ OD}$ is the outside diameter of the pipe (OD) [in].

For a non-Newtonian fluid equation, 14 can be used if an equivalent Newtonian viscosity is used instead[1,2]. The equivalent viscosities for Bingham plastic and power law fluids depends on the geometry of the flow, that is, if the flow is occurring in the pipe or annulus.

For a Bingham fluid flowing in a pipe:

$$\mu_{eBp} = \mu_p + \frac{20 D_{ip} \tau_y}{3V} \tag{16}$$

μ_{eBp} is the equivalent viscosity for a Bingham fluid in pipe flow [cp].

For a Bingham fluid flowing in an annulus:

$$\mu_{eBa} = \mu_p + \frac{5\left(D_{hole} - D_{op}\right)\tau_y}{V} \tag{17}$$

μ_{eBa} is the equivalent viscosity for a Bingham fluid in annular flow [cp].

For a power law fluid flowing in a pipe:

$$\mu_{epp} = \frac{kV^{n-1}}{96 D_{ip}^{n-1}} \left[\frac{3 + \frac{1}{n}}{0.0416}\right]^n \tag{18}$$

For a power law fluid flowing in an annulus:

$$\mu_{epp} = \frac{kV^{n-1}}{144\left(D_{hole} - D_{ip}\right)^{n-1}} \left[\frac{2 + \frac{1}{n}}{0.0208}\right]^n \tag{19}$$

2.2.2.3 Friction pressure loss in Newtonian Laminar Pipe Flow (NLPF)

The Newtonian laminar pipe flow (NLPF) module is a module in GHGfrack that calculates the pressure drop for laminar flow regime using equation S20.[1]

$$\Delta P_{fp} = \frac{\mu V}{1500 D_{ip}^2} \tag{20}$$

ΔP_{fp} is pressure drop in pipe [psi/ft];

μ is viscosity of mud [cp];

V is the average velocity in pipe [ft/s];

D_{ip} is the internal diameter of the pipe [in].

2.2.2.4 Friction pressure losses in Newtonian Laminar Annulus Flow (NLAF)

The Newtonian laminar annulus flow (NLAF) module is a module in GHGfrack that calculates the pressure drop for such laminar flow using equation 21:[1]

$$\Delta P_{fa} = \left(\frac{\mu V}{1500}\right)\left(D_{hole}^2 + D_{op}^2 - \frac{D_{hole}^2 - D_{op}^2}{ln\left(\frac{D_{hole}}{D_{op}}\right)}\right)^{-1} \tag{21}$$

ΔP_{fa} is pressure drop in annulus [psi/ft];

μ is viscosity [cp];

V is the average velocity in the annulus [ft/s];

D_{hole} the hole diameter [in];

D_{op} the pipe outside diameter [in].

2.2.2.5 Friction pressure loss in Bingham Laminar Pipe Flow (BLPF)

The Bingham laminar pipe flow (BLPF) module is a module in GHGfrack that calculates the pressure drop for such flow regime using equation 22:[1]

$$\Delta P_{fp} = \frac{\mu_p V}{1500 D_{ip}^2} + \frac{\tau_y}{255 D_{ip}} \tag{22}$$

ΔP_{fp} is pressure drop in pipe [psi/ft];

μ_p is plastic viscosity [cp]. This is a parameter of the Bingham plastic model (see equation 12).

τ_y is the yield point or yield stress [$\frac{lb_f}{100ft^2}$], this is a parameter of the Bingham plastic model (see equation 12).

V is the average velocity in the pipe [ft/s];

D_{ip} is the internal diameter of the pipe [in].

2.2.2.6 Friction pressure loss in Bingham Laminar Slot Flow (BLSF)

The exact mathematical derivation of the equation for friction pressure loss in annular flow for non-Newtonian fluids with a yield value is quite complex [1]. Therefore, Azar and Samuel suggest an approximation of the annular flow by slot flow (flow between two flat plates). It can be shown that the annular flow can be accurately approximated by a slot flow when the ratio of the diameter of the pipe to hole diameter is greater than 0.3. This condition is generally met in drilling applications[1]. For more information about slot flow model, see Azar and Samuel.[1] The Bingham laminar slot flow (BLSF) module is a module in GHGfrack that approximates the pressure drop for laminar annular flow of a Bingam plastic fluid using equation 23:[1]

$$\Delta P_{fa} = \frac{\mu_p V}{1000\left(D_{hole} - D_{op}\right)^2} + \frac{\tau_y}{255\left(D_{hole} - D_{op}\right)} \tag{23}$$

ΔP_{fa} is pressure drop in the annulus [psi/ft];

μ_p is plastic viscosity [cp]. This is a parameter of the Bingham plastic model (see equation 12).

τ_y is the yield point or yield stress in [$\frac{lb_f}{100ft^2}$], this is a parameter of the Bingham plastic model (see equation 12).

V average velocity in pipe [ft/s];

D_{op} is the internal diameter of the pipe [in];

D_{hole} is the diameter of the hole [in].

2.2.2.7 Friction pressure loss in Power law Laminar Pipe Flow (PLPF)

The power law laminar pipe flow (PLPF) module is a module in GHGfrack that calculates the pressure drop for such flow regime using equation S24:[1]

$$\Delta P_{fp} = \frac{kV^n}{143700 D_{ip}^{n+1}} \left(\frac{3n+1}{0.0416}\right)^n \tag{24}$$

k is consistency index [equivalent cp];

n is the power law index;

V is the average velocity in pipe [ft/s].

2.2.2.8 Friction pressure loss in Power law Laminar Annular Flow (PLAF)

The power law laminar annular flow (PLAF) is a module in GHGfrack that calculates the pressure drop for such flow regime using equation S25:[1]

$$\Delta P_{fa} = \frac{kV^n}{143700 \left(D_{hole} - D_{op}\right)^{n+1}} \left(\frac{2n+1}{0.0208}\right)^n \tag{25}$$

The parameters are defined as in equations 23 and 24.

2.2.2.9 Friction pressure loss in Newtonian Turbulent Pipe Flow (NTPF)

The Newtonian turbulent pipe flow (NTPF) module is a module in GHGfrack that calculates the pressure drop for such flow regime using equation 26:

$$\Delta P_{fp} = \frac{f_p \gamma_{mud} V^2}{25.8 D_{ip}} \tag{26}$$

ΔP_{fp} is pressure drop in pipe in [psi/ft];

f_p is Fanning friction factor [dimensionless].

The Fanning friction factor for a Newtonian turbulent flow is calculated by Colebrook equation:[1]

$$\frac{1}{\sqrt{f}} = 3.48 - 4\log\left(\frac{2\varepsilon}{D_{ip}} + \frac{9.35}{Re\sqrt{f}}\right) \tag{27}$$

in which *f* is Fanning friction factor;

ε is pipe roughness with the same dimension as D_{ip}.

This equation is implicit in *f*. In contrast, Azar and Samuel introduce equation 28 equation for this purpose which is explicit in *f*. GHGfrack uses this equation which avoids an iterative solution for calculation of *f* [1].

$$\frac{1}{\sqrt{f}} = 2.28 - 4\log\left(\frac{\varepsilon}{D_{ip}} + \frac{21.25}{Re^{0.9}}\right) \tag{28}$$

The parameters in equation 28 are defined similar to equation 27.

2.2.2.10 Friction pressure loss in Newtonian Turbulent Annular Flow (NTAF)

The Newtonian turbulent annular flow (NTAF) module uses the same equations that are used by NTPF, however, in all related equations instead of the internal diameter of pipe, the equivalent diameter of the annulus is used. This equivalent diameter is calculated by equation 15.

2.2.2.11 Friction pressure loss in Bingham Turbulent Pipe Flow (BTPF)

The Bingham turbulent pipe flow (BTPF) module uses the equations proposed by Petroleum Engineering Handbook.[6] It should be noted that the following equations are based on metric units of measurement.

$$f = A(Re)^{-B} \tag{29}$$

In an exception from other equations, in the BTPF set of equations, the Reynolds number is based on the plastic viscosity not the equivalent Newtonian viscosity as defined in equations 16 and 17.

$$Re = \frac{\rho\, D_{ip}\, V}{\mu_p} \tag{30}$$

$$He = \frac{\tau_y \rho D_{ip}^2}{\mu_p^2} \tag{31}$$

$For\ He <= 0.75 \times 10^5, A = 0.20656, and\ B = 0.3780.$

$For\ 0.75 \times 10^5 < He <= 1.575 \times 10^5, A = 0.26365, and\ B = 0.38931.$

$For\ He > 1.575 \times 10^5, A = 0.20521, B = 0.35579$

$$\Delta P_{fp} = \frac{2 f \rho V^2}{D_{ip}} \tag{32}$$

in which:

He is Hedstrom number;

V is velocity [m/s];

ΔP_{fp} is pressure drop in pipe in [Pa/m];

μ_p plastic viscosity [cp];

ρ is mud density [kg/m^3];

τ_y yield stress (or yield point) [Pa];

f is Fanning friction factor [dimensionless];

D_{ip} is the internal diameter of pipe [m].

2.2.2.12 Friction pressure loss in Bingham Turbulent Annular Flow (BTAF)

The Bingham turbulent annular flow (BTAF) module uses the equations proposed by [insert author names] Petroleum Engineering Hanbook.[6] These equations are based on metric units of measurement. Fanning friction factor is calculated by the same equation that is used in BTPF module (equation S29). However, the parameters of the equation have been modified to be adjusted for the annular geometry.

$$Re = \frac{\rho\left(D_{hole} - D_{op}\right)V}{\mu_p} \tag{33}$$

$$He = \frac{\tau_y \rho\left(D_{hole}^2 - D_{op}^2\right)}{\mu_p^2} \tag{34}$$

$For\ He <= 0.75 \times 10^5, A = 0.20656, and\ B = 0.3780.$

$For\ 0.75 \times 10^5 < He <= 1.575 \times 10^5, A = 0.26365, and\ B = 0.38931.$

$For\ He > 1.575 \times 10^5, A = 0.20521, B = 0.35579$

$$\Delta P_{fa} = \frac{2f\rho V^2}{\left(D_{hole} - D_{op}\right)} \tag{35}$$

D_{hole} is the diameter of the hole [m];

D_{op} is the outside diameter of the pipe [m];

The rest of the parameters are defined as in the BTPF module.

The equation that Azar and Samuel suggested to calculate the Fanning friction factor for Bingham plastic fluids is implicit in *f*. Based on the literature, they also suggested use of existing relationships developed for Newtonian fluids in rough pipes can also be considered and gives examples of such calculations. GHGfrack allows the user to choose use of the Newtonian modules, NTPF/NTAF, instead of BTPF/BTAF if they decide that this is sufficient. The user can switch between the modules in the program settings worksheet (see Figure 9).

2.2.2.13 Friction pressure loss in power law fluid turbulent pipe and annular flow

For power law fluid turbulent pipe flow (PTPF) and power law fluid turbulent annular flow (PTAF), both Azar and Samuel and Handbook of Petroleum Engineering suggest the following equations for calculation of Fanning friction factor which are implicit in *f*:

$$\frac{1}{\sqrt{f}} = \frac{4.0}{n^{0.75}}\left(\log Re \times f^{1-\frac{n}{2}}\right) - \frac{0.4}{n^{1.2}} \tag{36}$$

in which Re (Reynolds number) is defined by:

$$Re = \frac{\rho V^{2-n} D_{ip}^{n}}{k\left[\frac{3n+1}{4n}\right]^{n} \times 8^{n-1}} \tag{37}$$

All the parameters have the same definition as mentioned earlier but the units of equations 36 and 37 which are taken from [insert author name] are all metric.

Azar and Samuel also suggests that existing equations which are developed for Newtonian turbulent flow in rough pipe can also be used in this case. In this version of GHGfrack we use NTPF and NTAF modules for the case of power law turbulent flow. The equivalent Newtonian viscosities which are given in equations 18, 19 are used to calculated the Reynolds number for this purpose.[1,2]

2.2.2.14 Approximation of the size of the drill string and drill collar

The length of the drill collar is an input parameter in GHGfrack. The length of the drill pipe equals to the length of the entire drill string minus the length of the drill collar. In GHGfrack we assume that the bottom hole assembly length (including the drill collar) and its ID and OD are equal to the drill collar. Azar and Samuel give numerous examples of drilling wells in which the sizes of the drill pipe and drill collar are given.[1] Based on the statistics of these examples, GHGfrack estimates the ID and OD of the drill pipe and collar as a function of the hole diameter. Note that is included as a helpful default value when the user does not have any idea of these parameters. Ideally, the user can provide this information directly from reported data. This module also lets the users manually set these

values or use their own approximation following the same format of the correlation that we used (see Figure 10).

2.2.3 Approximation of the mud flow rate

One function of the drilling mud is to efficiently remove the drill cuttings. To achieve this goal, the mud velocity should reach a critical velocity.[1] We use this critical velocity to approximate the mud flow rate in drilling. GHGfrack lets the user choose between setting the mud flow rate manually or to use the automatic mode to estimate the required mud flow rate (see Figure 9).

Program settings								
						user	default	
Bingham plastic turbulent annular flow						2	1	
Approximation with Newtonian turbulent flow					1			
Empirical equation					2			
Bingham plastic turbulent pipe flow						2	1	
Approximation with Newtonian turbulent flow					1			
Empirical equation					2			
Mud flow rate :						1	1	
Auto	1							
Manual	2							

Figure 9. Program Settings

Drill collar OD = a x hole size				
Drill collar ID = b x collar OD				
Drill pipe OD = c x collar OD				
Drill pipe ID = d x pipe OD				
	a	**b**	**c**	**d**
default	0.77	0.47	0.67	0.82
user	0.77	0.47	0.67	0.82
Automatic		1	1 for Automatic 0 for Manual	

Figure 10. Pipe settings

2.2.3.1 Drill cuttings slip velocity

As the drilling fluid moves up through the annulus to return to the surface, drill cuttings can fall through the fluid medium at a velocity called the *slip velocity* [1]. For the fluid to be able to lift the cuttings to the surface, the fluid *average annular velocity*, V_a, must be in excess of the cuttings average slip velocity, V_s.[1] The relative velocity between V_a and V_s is called the *average cuttings transport* (or *rise*) velocity, V_r:

$$V_r = V_a - V_s \tag{38}$$

The cuttings transport ratio, R_t, is defined by [1]:

$$R_t = \frac{V_r}{V_a} = 1 - \frac{V_s}{V_a} \tag{39}$$

The implication of eq. 39 is that if we can calculate the slip velocity of the drill cuttings and know the recommended value of R_t, then we can calculate V_a, and from there we can calculate the mud flow rate.

2.2.3.2 Transport of cutting in vertical wells

The recommended value for R_t in eq. 39 for vertical wells is 0.5 to 0.55. In GHGfrack we define R_t^* , a mathematical equivalent of R_t, that we call modified cuttings transport ratio:

$$V_a = R_t^* \times V_s \tag{40}$$

Comparing equations S39 and S40:

$$R_t^* = \frac{1}{1 - R_t} \tag{41}$$

Thus, the recommended values for R_t^* for vertical wells is between 2.0 to 2.2, corresponding to the recommended range for R_t. As we increase the modified transport ratio, we increase the mud flow rate. As seen in Figure 7, R_t^* is an input variable that the user can change.

A variety of models and correlations are suggested to calculate the slip velocity in drilling of the vertical wells [1]. GHGfrack uses eq. 42:[7]

$$V_s = 86.5 \sqrt{d_{cuttings}\left(\frac{\rho_{cuttings}}{\rho_{mud}} - 1\right)} \tag{42}$$

in which:

V_s is the slip velocity [ft/min];

$d_{cuttings}$ is the diameter of the drill cuttings [in];

$\rho_{cuttings}$ is the specific weight of the cuttings [lb_m/gal];

ρ_{mud} is the specific weight of the drilling mud [lb/gal].

The required annular velocity, $V_{a,required}$, is calculated by

$$V_{a,required} = R_t^* \times \frac{V_s}{60} \tag{43}$$

in which $V_{a,required}$ has units of [ft/s].

2.2.3.3 Empirical correlations for cuttings transport in high-angle wells

Empirical correlations for transport of cuttings are based on full scale laboratory data[1] for wells with inclination angle of greater than 50° from the vertical and for hole size of 5 inch and drill pipe of 2 3/8 inch. Scaling up to larger hole sizes may result in significant errors.[1]

The average annular velocity is calculated by

$$V_a = V_r + V_s \tag{44}$$

in which V_a is the average annular velocity [ft/s];

V_r is the average cuttings rise velocity [ft/s];

V_s is the average cuttings slip velocity [ft.s].

The average cuttings rise velocity is calculated by:

$$V_r = \frac{1}{\left[1 - \left(\frac{D_{op}}{D_{hole}}\right)^2 \left[0.64 + \left(\frac{18.16}{ROP}\right)\right]\right]} \tag{45}$$

in which:

D_{op} is drill pipe diameter [in];

$D_{hole}$is hole diameter [in];

ROP is rate of penetration of the bit in rock [ft/h].

It should be noted that ROP as an input variable should be set in the drilling input section of GHGfrack in [ft/min] (Figure 2). GHGfrack converts this to [ft/h].

$$V_s = V_s^* \times C_{angle} \times C_{Size} \times C_{mwt} \tag{46}$$

in which C_{angle} , C_{Size}, and C_{mwt} are correction factors for the hole angle, cuttings size, and mud weight respectively:

$$V_s^* = \begin{Bmatrix} 0.00516\mu_a + 3.006 \;\; for\ \mu_a \leq 53 \\ 0.02554\mu_a + 3.280 \;\; for\ \mu_a > 53 \end{Bmatrix} \tag{47}$$

$$\mu_a = \begin{Bmatrix} \mu_p + 1.12\mu_p\left(D_{hole} - D_{op}\right) for\ \mu_p \leq 20\ cp\ and\ \tau_p\ \leq 20\ \dfrac{lb_f}{100ft^2} \\ \mu_p + 0.9\mu_p\left(D_{hole} - D_{op}\right) for\ \mu_p > 20\ cp\ and\ \tau_p\ > 20\ \dfrac{lb_f}{100ft^2} \end{Bmatrix} \tag{48}$$

$$C_{angle} = 0.0342\theta - 0.000233\theta^2 - 0.213 \tag{49}$$

$$C_{size} = -1.04D_{cuttings} + 1.286 \tag{50}$$

$$C_{mwt} = 1 - 0.0333(\gamma_{mud} - 8.7) \tag{51}$$

in which:

$D_{cuttings}$ is the average diameter of the drill cuttings [in];

γ_{mud} is mud density [lb/gal].

2.2.3.4. Cuttings transport in low-angle wells

The current version of GHGfrack does not have an empirical equation for low-angle wells where the inclination from vertical is less than 50°. The automatic mode still uses equations 42 and 43 to calculate the mud flow rate. This facilitates a user who has field data to calibrate the model using the modified transport ratio R_t^*. This may be found useful specially when running GHGfrack for large number of wells and the uncertainty of the data leaves space for make simplifying assumptions. For mild inclination angle, one may assume this correlation is still valid when appropriate value of R_t^* is used. Nevertheless, we recommend that the user either use the manual mode with accurate case-specific data.

The automatic mode is not designed to substitute use of the field data. GHGfrack is an open-source code. This allows the user to enhance this automatic mode with their preferred correlations which determine the required mud flow rate more accurately for a given geometry.

2.3 Hydraulic fracturing

During hydraulic fracturing, water at high pressure is injected through the well to fracture the formation around a vertical or horizontal section of the wellbore that intersects the target formation. Fracturing water is mixed with sand and other chemicals such as friction reducers, biocides, and viscosity-adjusting agents. After fracturing occurs, the injected sand "proppants" prop the fractures open. Water can be injected for fracturing in several stages or in a single stage that covers the entire perforated area in the horizontal section (See Figure 11 and 12).

In a single stage fracturing, if the horizontal section is quite long, the flow rate of water will decline as it flows from the heel of the well to the toe at the end of the horizontal well, by flowing radially into the developing fractures. GHGfrack considers this decline in the flow rate of water in the axial direction. In multistage fracturing, the number of stages is often large and hence the length of the perforated area at each stage is much smaller compared with the total measured length of the flow path from the surface to the perforated area.[8-10] Therefore, GHGfrack assumes that the flow rate of water is constant value in the case of multistage fracturing.

Figures 13 and 14 show the worksheets for input variables and results for the hydraulic fracturing module in GHGfrack. After setting parameters the user can choose to run analysis using a single stage or a multistage method.

In the case of single stage fracturing, the user should set the number of *pipe segments*. These pipe segments are not physical segments and should not be confused with well (or casing) sections. These pipe segments are a mathematical discretization of the modeling problem by which the pipe is divided into smaller elements to calculate the pressure drop based on local flow velocity. The results across segments are then

integrated. The user can select the number of segments, with high segment counts resulting in more precise results but longer computation time. For multistage fracturing, the user sets the length of the perforated area for each stage of fracturing. Because GHGfrack assumes a constant flow rate of water everywhere, the above-described mathematical segmentation is not required.

Each section can have different inclination angle and diameter. The inclination angle is measured from vertical. Thus, a vertical section of the well has an inclination angle of 0 degree and a horizontal well has an inclination angle of 90°.

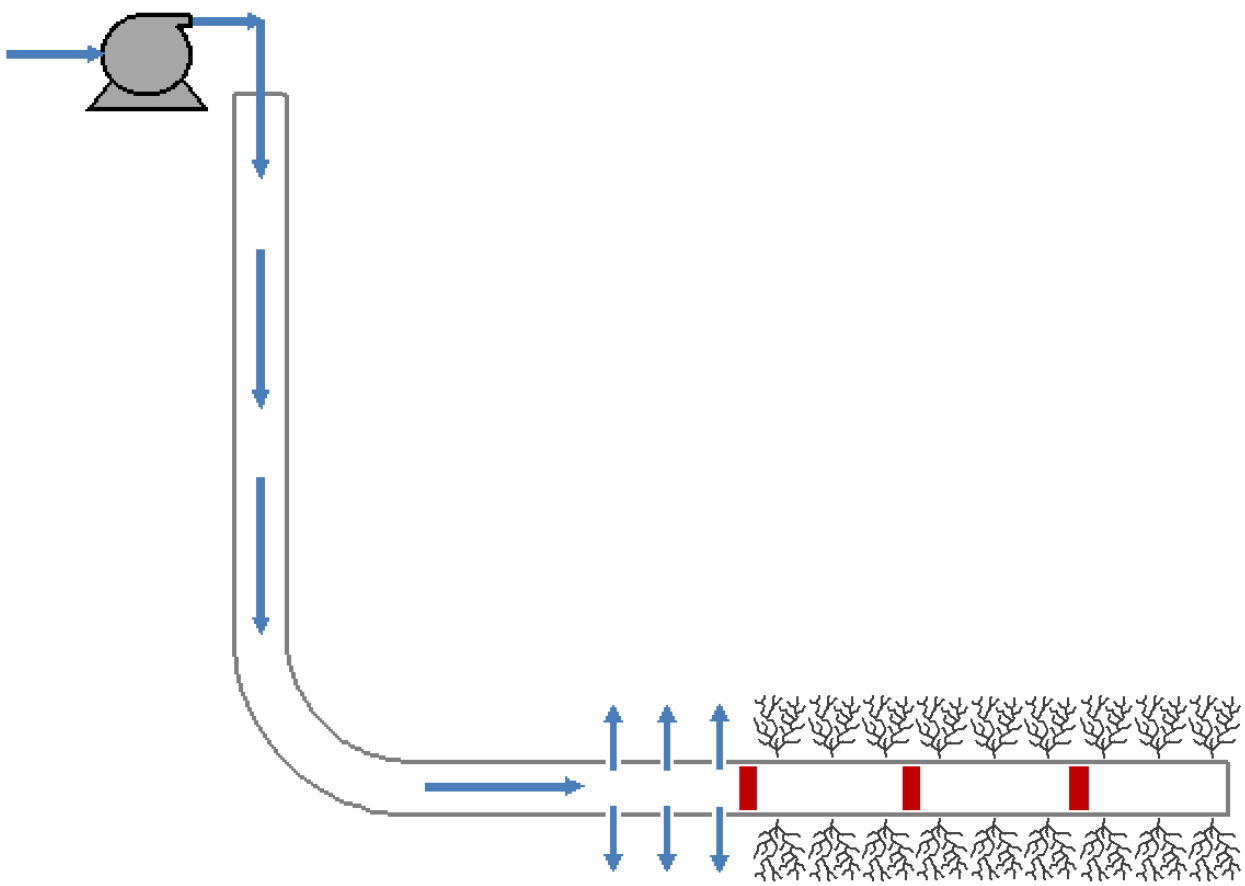

Figure 11. Multistage fracturing. The fractured section at each stage is plugged before fracturing of the next section is started.

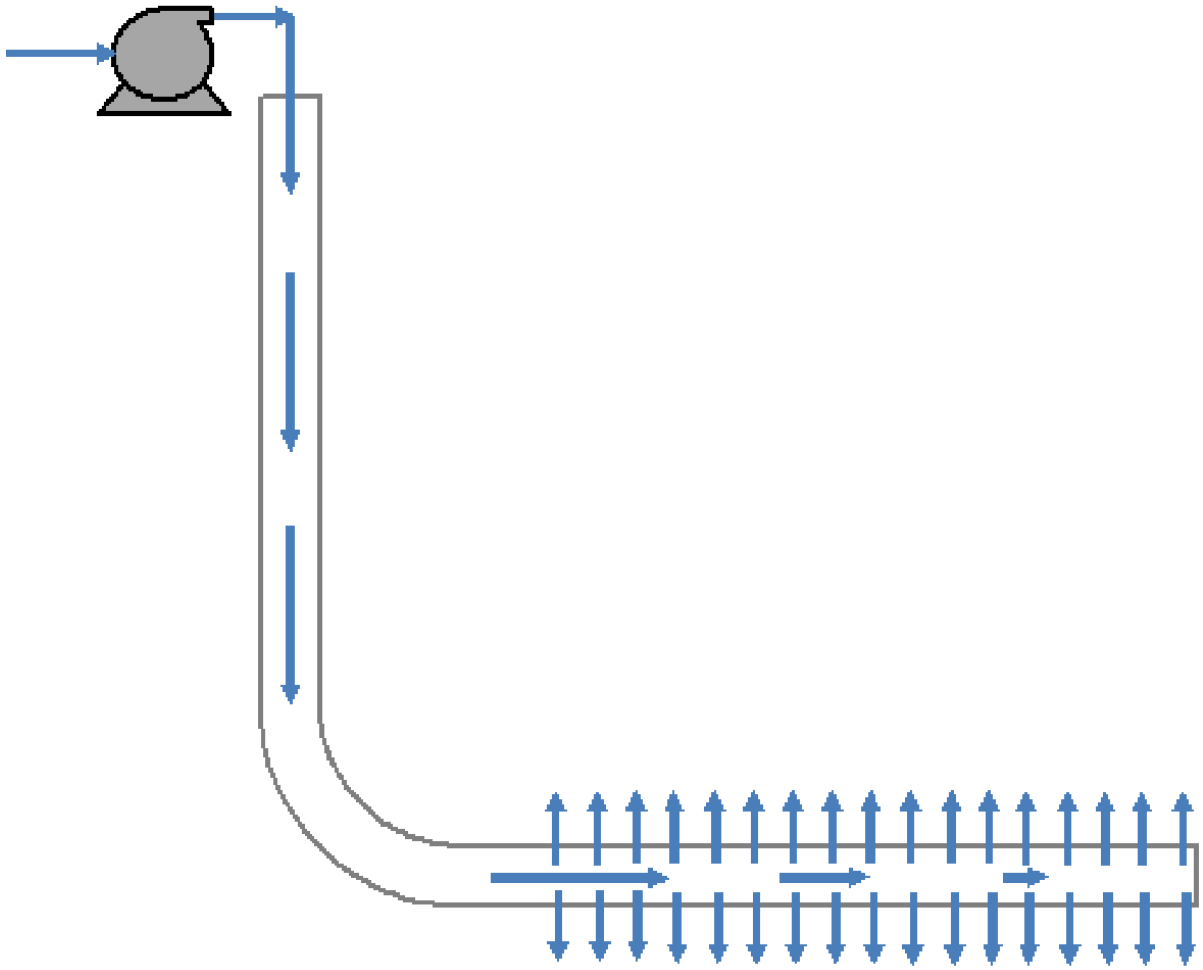

Figure 12. Single stage fracturing. In single stage fracturing the declining flow rate of water in the horizontal section is considered in the model.

Fracking Inputs	Single-Stage Hydraulic Fracturing		Multi-Stage Hydraulic Fracturing
	user	default	unit
Fluid density	9.0	9.0	lbm/gal
Viscosity	1	1	cp
Fracture gradient	0.9	0.9	psi/ft
Pipe roughness	0.00008	0.00008	in
g (gravitational acceleration)	32.17	32.17	ft/s2
Length of the fracking stage	300	300	ft
Number of segments	100	100	NA
Pump efficiency	65	65	%
Volume fluid injected	4871501	4871501	gal
Injection time	48	48	hr
Number of sections	3		Last section is the horizontal section
Table 1. Geometry			

Section No.	Net length(ft)	Inclination angle (degree)	pipe ID (in)
1	8500	0	5
2	2355	45	5
3	3645	90	5
4			
5			
6			
7			
8			
9			
10			

Figure 13. Input data worksheet of hydraulic fracturing module

Fracking Results

flow rate	1691	gpm
Pressure drop due friction in non-horizontal section	1706	psi
Pressure drop due friction in horizontal section	573	psi
Hydrostatic pressure	4772	psi
Pressure drop due hydraulic fracturing	9149	psi
Pump discharge pressure	6656	psi
Pump BHP	9712	hp
Pump energy consumption	1186	MMBtu
Fuel efficiency	6192	Btu LHV Diesel/hp.hr
Fuel consumption	22470	gal diesel
Emissions	228	ton CO2

Table 1: Non-horizontal section

Section No.	Net vertical distance (ft)	Pipe cs area (ft2)	Velocity (ft/s)	Re	Press drop (psi/ft)
1	8500	0.1363	27.7	1159508	0.1572
2	1666	0.1363	27.7	1159508	0.1572
3					
4					
5					
6					
7					
8					
9					
10					

Table 2: Horizontal Section

Fracking stage or segments	horizontal section flow length(ft)	velocity (ft/s)	Re	press drop (psi/ft)	BHP
1	3645	27.6529	1159508	0.15716	10105.2
2	3345	27.6529	1159508	0.15716	10033.7
3	3045	27.6529	1159508	0.15716	9962.07
4	2745	27.6529	1159508	0.15716	9890.49
5	2445	27.6529	1159508	0.15716	9818.91
6	2145	27.6529	1159508	0.15716	9747.33
7	1845	27.6529	1159508	0.15716	9675.74
8	1545	27.6529	1159508	0.15716	9604.16
9	1245	27.6529	1159508	0.15716	9532.58
10	945	27.6529	1159508	0.15716	9460.99
11	645	27.6529	1159508	0.15716	9389.41
12	345	27.6529	1159508	0.15716	9317.83

Figure 14. Results worksheet of hydraulic fracturing module

In Figure 13, Table 1, the length of each section is the measured distance from the top of that certain section to the bottom of that section. The section in which fracturing occurs must be placed at the last row in this table. The fracturing section is assumed to be horizontal. If part of the horizontal section before the fracturing section is meant not to be fractured, it should be placed above the last row.

GHGfrack uses the Newtonian fluid flow modules for hydraulic fracturing. These flow modules were described in the mud circulation section above. However, in the case of hydraulic fracturing the effect of the hydrostatic head of water should be considered in formulating the energy (or pressure) balance on the fluid flow. The hydraulic head of fluid in the wellbore can significantly reduce the required discharge pressure of the water injection pumps. There is no drill bit nozzles or downhole motor as sources of pressure drops. Therefore, we can rewrite equation S7 for hydraulic fracturing:

$$\Delta P_p = \Delta P_f + P_{fracturing} - \Delta P_h \tag{51}$$

in which

ΔP_p pump discharge pressure [psig];

ΔP_h is the static head [psi];

ΔP_f is pressure drop due friction [psi];

$P_{fracturing}$ is fracturing pressure [psi].

The fracturing pressure is calculated by the following equation:

$$P_{fracturing} = \lambda_{fracturing} \times TVD \tag{52}$$

$\lambda_{fracturing}$ is fracturing gradient [psi/ft];

TVD is true vertical depth [ft].

When all the data are added to the inputs data worksheet. GHGfrack calculates the TVD based on the data in Table 1 in Figure 13, assuming that the last row is the horizontal section that is to be fractured. Fracturing water is mixed with sand, so the fluid density is the density of the mixture not pure water (Figure 13).

Figure 14 shows the results worksheet. Some of the parameters that GHGfrack calculates in addition to main results are given in Table 1 and 2 in this worksheet. Table 2 is for the horizontal section where fracturing happens and Table 1 is for all other sections above it.

3. Model organization

The model is coded using Microsoft Excel 2013 VBA (Visual Basic for Application). This VBA code works in conjunction with the Excel worksheets that are used for model inputs and outputs (results). In describing the theoretical foundation, we separated drilling the rock from mud circulation. However, when we talk in general about drilling an oil and gas well, it always implicitly contains the circulation of drilling fluid unless it is emphasized otherwise. In the organization of the worksheets and the VBA model, the drilling tabs or

modules contain code and materials related to both physical drilling of the rock and mud circulation.

3.1 Excel worksheets

Most of these worksheets are described and depicted earlier, when we explained the theoretical foundation of GHGfrack:

- *Settings* (Figure 9): User can select between the Newtonian approximation or use of empirical equations for Bingham plastic fluids. In addition, user can decide on automatic estimation of the mud flow rate or to set it manually.
- *Pipe Spec* (Figure 10): User can choose between automatic approximation of the drill collar and drill pipe IDs and ODs or to set them manually. In addition, the users can modify the parameters of the correlations which are suggested between IDs and ODs and the hole diameter. This let the users calibrate the correlations using their own data.
- *Drilling Power* (Figures 1 and 2 and 6 to 8): This worksheet contains both drilling (top-drive) and mud circulation (the name is compressed to appear on a worksheet tab). The model inputs for estimation of drilling and mud circulation energy are set in this worksheet and the results appear at the same worksheet.
- *Bulk Data Drilling* (Figures 15 to 17): This is similar to *Drilling Power* worksheet, but it is expanded to include all sections of a well. This is more suitable for running of GHGfrack for large number of wells, which each have several sections. Figures S15 and S16 show the tables are drawn for up to 6 well sections. GHGfrack, however, does not limit the number of the well sections mathematically. User can extend the tables in the worksheet to any desired number of sections following the same order. User has to set the number of well sections at the top left corner in Figure 15. Number of a well sections are limited from the structural design perspective. However, this feature let the user to a physical section of the well, for example a curve, to several mathematical sections with different length and inclination angle from vertical to horizontal with different torque value to rotate the

drill string. Similarly, a long vertical or horizontal section can be split to several smaller mathematical sections with different applied torque, rotational speed, and ROP.

3.2. VBA code

In addition to the worksheets described above, the actual computations in GHGfrack occur in VBA modules. These modules are described below.

- *Drilling*: This VBA module contains the main subroutine for calculating the energy consumption of the top-drive drilling, which is named *Rotary_Table*. All subroutines of the hydraulic model including the subroutines for calculating pressure drop of Newtonian and non-Newtonian fluids are located in this VBA module

- *Mud_circulation*: This module is devoted to calculation of the energy consumption of the mud pump and uses hydraulic subroutines located in the *Drilling* module.

Rotation Energy via Rotary Table : Input Data		Run drill & mud circulation						
Number of sections	**5**	default	1	2	3	4	5	6
Is rotary table active	Yes/No	Yes	Yes	Yes	Yes	Yes	Yes	
User defined torque value	Yes/No	Yes	Yes	Yes	Yes	Yes	Yes	
Length of drill string at top of the section	ft	0	50	4250	8500	10855	0	
Length of drill string at bottom of the section	ft	10000	4250	8500	10855	14500	50	
Drilling rate (ROP)	ft/min	1	2.5	2.5	1.25	1.25	0.22	
Rotation rpm	rpm	60	60	60	60	60	20	
Inclination angle	degree	0	0	0	45	90	0	
Engine Efficiency	%	45	45	45	45	45	45	
Torque factor :		1.625	1.625	1.625	1.625	1.625	1.625	
		1.875	1.875	1.875	1.875	1.875	1.875	
		2.125	2.125	2.125	2.125	2.125	2.125	
		2.625	2.625	2.625	2.625	2.625	2.625	
Torque value :								
vertical	ft-lbs	9000	13000	13000	9000	9000	38500	
horizontal	ft-lbs	11000	15000	15000	15000	15000	15000	
inclined	ft-lbs	11000	15000	15000	15000	15000	15000	
Rotaion Energy via Rotary Table : Results								
			1	2	3	4	5	
Drilling time	h	28.0	28.0	28.3	31.4	48.6	3.8	
Drilling power segment 1	hp	329.9	329.9	329.9	380.6	380.6	325.6	
Drilling power segment 2	hp	NA	NA	NA	NA	NA	NA	
Drilling power segment 3	hp	NA	NA	NA	NA	NA	NA	
Drilling energy required	MMBtu	23.5	23.5	23.8	30.4	47.1	3.1	
Drilling power max	hp	329.9	329.9	329.9	380.6	380.6	325.6	
Fuel efficiency	Btu/hp.h	7093.6	7093.6	7093.6	7071.8	7071.8	7095.4	
Diesel fuel used	gallon	510.1	510.1	516.1	658.0	1018.4	68.1	
GHG emissions	ton CO2	5.2	5.2	5.2	6.7	10.3	0.7	

Figure 15. Bulk assessment of data for drilling energy consumption.

- *Fuel efficiency*: This module estimates the fuel efficiency of the diesel engine, based on the OPGEE method as explained earlier.
- *Pipe_Spec*: This module estimates the ID and OD of the drill pipe and drill collar.
- *Bulk*: This module contains subroutine *Bulk_Drilling* that calculates energy requirement of the top-drive drilling and mud circulation pump. This VBA code is activated via *Bulk Data Drilling* worksheet and uses the *Drilling* and *Mud_circulation* modules.
- *Facking*: This module calculates the energy consumption of water injection pump in hydraulic fracturing operations. It contains subroutines FrackPump_multiple and

FrackPump_single which calculate the energy consumption in multistage and single-stage hydraulic fracturing, respectively.

Mud Circulation : Input Data								
		default	1	2	3	4	5	6
Mud Characteristics :								
Fluid type :		2	2	2	2	2	2	
(1) Newtonian								
(2) Bingham plastic								
(3) Power law							.	
Mud viscosity :								
Dynamic viscosity (Newtonian fluid)	cp	3						
Plasic viscosity	cp	25	25	25	25	25	25	
Consistency index K (power law fluid)		0.95	0.066	0.066	0.066	0.066	0.066	
Power law index n		0.29	0.29	0.29	0.29	0.29	0.29	
Yield stress (Yield point)	lbs/100 ft^2	15	15	15	15	15	15	
Mud density	lbs/gal	12	12	12	12	12	12	
Drill cuttings characteristics :								
Drill cuttings sieve diameter	in	1.0	0.5	0.5	0.5	0.5	0.5	
Drill cuttings density	lbs/gal	25.0	25.0	25.0	25.0	25.0	25.0	
Geometry :								
Length of drill collar	ft	1000	700	700	700	700	700	
Hole diameter	inch	8 7/8	12 1/4	8 3/4	8 3/4	8 3/4	24	
Drill pipe OD		6 5/8	6 5/8	5	5	5	6 5/8	
Drill pipe ID		6	6	4	4	4	6	
Drill collar OD		9 1/2	9 1/2	6 3/4	6 3/4	6 3/4	18 1/2	
Drill collar ID		4 3/7	4 3/7	3 1/4	3 1/4	3 1/4	8 2/3	
Number of segments of the drilling section		100	100	100	100	100	100	
Drill pipe roughness	inch	0.00008	0.00008	8E-05	8E-05	8E-05	8E-05	
Pump:								
Mud pump efficiency	%	65	65	65	65	65	65	
Drill bit :								
Number of nozzles		5	5	5	5	5	5	
Size of nozzles	in	0.50	0.50	0.50	0.50	0.50	0.50	
nozzle discharge coefficient Cd		0.95	0.95	0.95	0.95	0.95	0.95	
WOB (including BHA)	lbf	88000						
Is downhole motor active		No	Yes	Yes	Yes	Yes	Yes	
Downhole motor type :		1	1	1	1	1	1	
(1) Turbine								
(2) Positive displacement								
(3) Electrical								
Is pressure drop across downhole motor known?		No	Yes	Yes	Yes	Yes	Yes	
Pressure drop across downhole motor	psi	500	500	500	700	700	700	
Downhole motor rpm	rpm	100	100	100	100	100	100	
Mud flow rate	gpm		NA	NA	NA	NA	NA	
Pressure drop across wellhead fittings	psi	0	0	0	0	0	0	
Modified cuttings transport ratio		2.21	2.21	2.21	2.21	2.21	2.21	

Figure 16. Bulk assessment of data for mud circulation energy consumption. Model inputs.

Mud Circulation : Results								
			1	2	3	4	5	6
Average velocity in annulus (hole - drill pipe)	ft/s		2.3	2.3	2.3	5.0	2.3	2.3
Average velocity in annulus (hole - collar)	ft/s		4.2	3.9	3.9	8.3	5.3	5.3
Average velocity in drill pipe	ft/s		7.0	7.6	7.6	16.1	35.1	35.1
Average velocity in drill collar	ft/s		12.7	11.5	11.5	24.3	16.6	16.6
Mud flow rate	gpm		610.0	296.2	296.2	628.8	3057.2	3057.2
Re in pipe			4226	4329	4329	14337	55557	55557
Re in collar			10446	7776	7776	22956	20686	20686
Re hole - pipe			586.5	552.7	552.7	2085.6	639.3	639.3
Re hole - collar			1398.4	1119.5	1119.5	3496.1	2602.6	2602.6
Pressure drop in drill pipe	psi/ft		0.0238	0.0464	0.0464	0.1598	0.3364	0.3364
Pressure drop in drill collar	psi/ft		0.0943	0.1128	0.1128	0.3792	0.0587	0.0587
Pressure drop in annulus (hole - drill pipe)	psi/ft		0.0152	0.0242	0.0242	0.0289	0.0045	0.0045
Pressure drop in annulus (hole - drill collar)	psi/ft		0.0166	0.0269	0.0269	0.1379	0.0168	0.0168
Pressure drop across the downhole motor	psi		500.0	500.0	700.0	700.0	700.0	500.0
Pressure drop across the bit nozzles	psi		426	101	101	453	10712	10712
Pressure drop due to friction (max)	psi		215.9	648.0	814.2	2965.6	3.8	3.8
Total pressure drop (max)	psi		1142	1249	1615	4119	11416	11216
Mud pump BHP (max)	hp		626	332	429	2325	31327	30778
Drilling time	h		28.0	28.3	31.4	48.6	3.8	3.8
Energy consumption by mud pump	MMBtu		41.3	21.1	32.6	263.7	301.9	296.6
Fuel efficiency	Btu/hp.h		6966.5	7092.7	7050.8	6236.1	6113.1	6132.8
Diesel fuel used	gallon		879.7	457.7	702.4	5031.4	5646.4	5565.3
GHG emissions	ton CO2		8.9	4.6	7.1	51.0	57.2	56.4

Figure 17. Bulk assessment of data for mud circulation energy consumption. Model results.

4. Model verification and calibration

The accuracy GHGfrack results is determined by three main factors. One is the accuracy in transcription of the mathematical formulae to the computer code and correct implementation of the algorithms. To verify the correctness of GHGfrack from this aspect, we solved several case studies related to each module (cases defined from standard drilling texts) and compared hand results with code outlet. These checks showed the accuracy of the code. Because GHGfrack is open-source, users can run tests as well, and change code as needed for their cases.

A second source of inaccuracy is inherent limitations of the empirical equations and simplifications in modelling the physics of the problem. For example, the empirical equation for determining the critical velocity for removal of drill cuttings from the horizontal well is limited as it is explained in section 2.3. We do not evaluate the accuracy of the

correlations and empirical equations from the cited literature as they are widely used and further work in this direction is out of the scope of the first phase of GHGfrack development. A third source of inaccuracy is completeness and accuracy of model inputs for a particular case study. Lack of access to field data can impair accuracy of results.

We compared GHGfrack model results against the field data and a commercial software. We demonstrated GHGfrack capabilities to evaluate emissions from oil fields with several thousands of wells in two case studies and investigated the sensitivity of the model to change of each model input. Please see reference 11 for more information about the verification of the model and the case studies.

5.Nomenclature

With few exceptions which are mentioned in the text, common oil field units (Imperial) has been used.

A_t = area of the jets open to the flow [in^2]

C_d = the nozzle discharge coefficient [dimensionless]

f = friction factor [dimensionless]

F = torque factor [ft-lbf/rpm]

g = gravitational acceleration [ft/s^2]

gc is a coefficient for conversion of lbm to lbf [$lbm\text{-}ft/lb_f\text{-}s^2$]

h= height [ft]

H_{rp} = rotary power [hp]

He = Hedstrom number [dimensionless]

ID = internal diameter [in]

k is the consistency index [equivalent centipoise]

n is the power law index [dimensionless]

N = rotary table speed [rpm]

OD = outside diameter [in]

P = pressure [psi]

Q = flow rate of in US gallon per minute [gpm]

Re = Reynolds number [dimensionless]

R_t = cuttings transport ratio [dimensionless]

R_t^* = modified cuttings transport ration [dimensionless]

T = torque [ft-lbf]

V = velocity [ft/s]

W_p is the work done by pump on the unit volume of the fluid $\left[\frac{ft.lbf}{ft^3} \equiv \frac{lbf}{ft^2}\right]$

W_f is the friction energy loss per unit volume of the fluid $\left[\frac{ft.lbf}{ft^3} \equiv \frac{lbf}{ft^2}\right]$

γ is the shear rate [1/s] (not to be confused with γ_{mud} which is mud density in lbf/gal or lb_f/ft^3)

$\gamma_{mud} = mud\ density\ \left[\frac{lb_f}{gal}\right]$

ΔP = differential pressure [psi]

η = mud pump efficiency [dimensionless]

μ = viscosity [cp]

μ_p = plastic viscosity [cp]

τ is the shear stress [lb_f/100 ft^2]

τ_y is the yield stress or yield point $[\frac{lb_f}{100ft^2}]$

6.Glossary

This is a brief glossary of petroleum engineering terminology which we used and is taken partially from Schlumberger oil field glossary.[12]

BHA- Bottom hole assembly. The BHA consists of the drill bit, drill collar, mud motor (or downhole motor), measurement-while-drilling (MWD), and other tools.

BHP- Break horse power is the power at output shaft of an engine.

Drillpipe- Drill pipe connects the rig surface equipment with the bottom hole assembly and the drill bit. Drill pipe is used to pump drilling fluid to the bit and to raise, lower and rotate the bottom hole assembly and drill bit.[12]

Drill collar- It is a component of drillstring that provides weight on bit for drilling. Drill collars are thick-walled tubular pieces machined from solid bars of steel. The bars of steel are drilled from end to end to provide a passage to pumping drilling fluids through the collars.[28] Drill collar is a part of bottom hole assembly.

GHG- Greenhouse gas.

MD – length of wellbore along path.[12]

MWD- measurement-while-drilling

OPGEE- Oil production greenhouse gas emission estimator.

ROP- Rate of penetration. Rate of penetration of drill bit in rock in ft/h or ft/min.

TVD- Total vertical depth independent of the path.[12]

TMD- Total measured depth.In GHGfrack, total measured depth is MD from the surface to the end of the well along its path and is equal to the total drilled depth.

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