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A SUSTAINABLE DRILLING TECHNIQUE

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ABSTRACT

Drilling is a necessary step for petroleum exploration and production. The conventional rotary drilling technique falls short since it is costly and contaminating surrounding rock and water due to the use of toxic drilling fluids. Conventional rotary drilling has been the main technique used for drilling in the oil and gas industry. However, this method has showed its limits regarding the depth of the wells drilled in addition to the use of toxic drilling fluids. To overcome the limitations of conventional rotary drilling technique, waterjet drilling may be the best solution. Due to this reason, waterjet drilling is becoming a popular technique. This paper introduces the waterjet drilling as an alternative to this conventional technique. This drilling technique is environment friendly, fast, and feasible. Based on laboratory experiments, empirical models have been developed to describe the jet-rock interaction simulated by using paraffin wax and beeswax samples. However, it is necessary to compare the characteristics of different laboratory samples for getting a real reservoir rock feature. This paper establishes the different behaviors of paraffin wax and beeswax with the aid of same parameters. The parameters such as depth of penetration (DOP), rate of penetration (ROP), thermal exposure time, length between jet-tip and sample top surface (paraffin wax, beeswax) have been considered. The resourceful and conclusive results show that DOP and ROP increase with thermal exposure for paraffin wax and increases and then decreases for beeswax. The results also show that beeswax is closer to the real rock matrix in the formation. Finally, the sustainability of waterjet technology is analyzed and it is shown that the waterjet technique is sustainable than conventional drilling techniques.

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NOMENCLATURE

DOP_B	= depth of penetration for beeswax, mm, $[L]$
DOP_P	= depth of penetration for paraffin wax, mm, $[L]$
ROP_B	= rate of penetration for beeswax, mm/h, $[L/t]$
ROP_P	= rate of penetration for paraffin wax, mm/h, $[L/t]$
t_T	= thermal exposure time, min, $[t]$
t	= drilling time, min, $[t]$

INTRODUCTION

Drilling is the most important and one of the oldest technologies in the earth. A parameter of principal importance in any drilling process is the “weight on bit”. This is the axial force acting on the bit during the cutting process. Normally this force is relatively larger and may be generated by proper anchoring of the drill machine to the drilled surface. Alternatively, weight on bit may be provided by the self-weight of the drill unit structure. Waterjet drilling does not require any weight on bit. The waterjet systems have little loss of pressure or power throughout its drill pipes. The bit power is essentially equal to the power available at the surface. The energy loss is nominal which is quite remarkable. These are the prime advantages of waterjet drilling. High pressure waterjet drilling (HPWD) need not require any torque or thrust during jet erosion. For this reason, HPWD supplies an exclusive capability for drilling a constant radius directional hole without any steering corrections. Moreover, pure waterjet drilling is less sensitive to formation changes than rotary drilling because cutting is controlled by the bit orientation. Chemical additives are used in rotary drilling system. HPWD present higher ROP because the power available at the bit is extremely high. Rotary drilling provides slightly higher drilling rates. However, this approach generates torque loads and these loads can cause the hole trajectory to spiral. HPWD is capable of rapidly drilling small-diameter holes in a wide range of erosion-resistant rock types. Finally, a HPWD system could be made very lightweight because the thrust and torque requirements are nominal. However, normal waterjet drilling is used as an accessory activity in many industries including the oil and gas industry. The technique is normally used to remove cuttings, rock chips, mud cake and to clean the formation of the reservoir as well as the surface.

Existing rotary drilling systems are capable of drilling shallow directional holes. The equipment is heavy, drilling rates are low and costs are high. For any drilling system, the factors such as type of formation, depth of drilling and depth of desired screen setting should be considered when selecting an appropriate drilling method. At present, drilling technology has modernized well profiles and directions. HPWD technique is now used for horizontal drilling. Horizontal wells are being drilled across the reservoir for exposing a relatively large reservoir area which is used as drainage or injection. Most of the new wells are completed without cementing or liner. Due to the long opening, acidization is used to remove mud cake. Since, this process is very costly, the HPWD process is increasingly used. HPWD is a cost effective and simple to handle process in drilling technology.

Normally, high strength, high permeability rock types such as Berea sandstone has a low specific energy and threshold pressure. Medium strength, low permeability rocks such as limestones and sandstones have intermediate specific energy. Finally, High-strength, low permeability rocks such as granite, quartzite and basalt have high specific energy and threshold pressures. So, it is necessary to compare the laboratory samples behavior to simulate the real formation rocks based on experimental results. Based on the batter benefits comparing with other rotary drilling system, this technology has been the topic of many researchers due to its variety usages in the industry. As a result, recently, researchers are very interested on this tropic.

Maurer et al. (1969) did a series of experiments by waterjet on different rock samples. They concluded that water jets can successfully drill sedimentary rocks. They used a high pressure pump up to 13,500 psi, which can give 200 to 300 ft/h penetration rate. They have also concluded that water jet is economical for drilling oil wells. They found that the hydraulic jet drilling rate is influenced by nozzle size, nozzle pressure, and rock strength. Fenn (1989) investigated the use of waterjet for use in conjunction with free-rolling cutters. He conducted a series of laboratory tests with disc and button cutters to determine the effect of variations in the jet and cutting parameters on the cutter performance. His results indicate that no additional improvement in cutting performance is gained by an increase in jet pressure above 40 MPa. Ho-Cheng (1990) studied waterjet drilling to model an optimal waterjet pressure which is a function of hole depth and material parameters. He found good agreement with data obtained from waterjet drilling of graphite epoxy laminate. He concluded that the predicted optimal waterjet pressure can be applied in a control scheme for maximizing the productivity of waterjet drilling of composite laminates. Hood et al. (1990) studied high-pressure waterjet for developing a better understanding of the erosion mechanisms to cut the rock materials. They developed an empirical model to describe the different parameters involved with the system. This model is described the rock erosion by a high-pressure water jet.

Yasuda and Hoshina, (1993) studied the fundamentals of the application of the ultra high pressure waterjet for rock drilling. They have developed an ultra high waterjet boring system using ultrahigh pressure waterjet. Aslam et al. (2000) have discussed the theoretical aspects of the HPWJ technology, case histories and well performance data. They have also pointed out that HPWJ can be used for steel cutting or to make holes by using abrasive materials such as sand and beads. It has been reported in the literature that the efficiency of the process depends on four factors such as (i) stand-off distance, (ii) fluid velocity, (iii) jet stream profile and (iv) rotation. Buset et al. (2001) described the penetration effects on formation zone due to water jet technology. Lia et al. (2001) pointed out that the combined cutting effect of waterjet and polycrystalline diamond compact (PDC) is very effective in very hard rocks. They did experiments on waterjet and PDC for ROP in hard rocks. Arangath et al. (2002) discussed the high hydraulic horsepower jetting tool which is used for scale removal. They have also shown waterjetting in horizontal well drilling. Dunn-Norman et al. (2002) discussed processes for sustainable recovery of heavy oil from ultra-shallow reservoirs, using low cost, innovative horizontal drilling and completion methods. They have argued the use of waterjet drilling over 15,000 ft (5,000 m) which is more competitive with the conventional rotary drilling system. They also concluded that waterjet drilling methods appear most favorable for drilling horizontal wells in ultra-shallow reservoirs.

Recently, Hossain et al. (2009, 2010, 2011) have briefly described the contributions of different researchers on waterjet drilling and the importance of this technology. They have developed some empirical relations using waterjet drilling on ROP, DOP and gap length between jet-tip and sample top surface based on paraffin wax and beeswax as a sample (Hossain et al., 2009, 2010 and 2011). They also have found out the variation of DOP, ROP, temperature, flow rate and pressure with time. The variations of DOP and ROP with temperature, side effect and thermal exposure time have also been studied. They also studied the effects of gap variation between drill bit tip and sample top surface (Hossain et al., 2009, 2011). They compared some of the influential drilling parameters using paraffin wax and beeswax samples (Hossain et al., 2011). However, these papers did not study the variation of the sample affects in waterjet drilling. They did not develop any empirical correlation for thermal exposure time and compare the effects based on thermal action. The present study has considered these unsolved questions to get a comprehensive idea about the sample characteristics.

To study the waterjet drilling system in more detail, paraffin wax and beeswax samples have been used instead of real reservoir rock sample. A series of laboratory tests were run to know the effect of DOP, ROP on thermal exposure time and length between jet nozzle and wax sample surface. To study the waterjet drilling as a sustainable technique, a flow chart analysis and compositional analysis of different chemicals are studied. Finally, it is outlined how waterjet becomes a sustainable technique for a drilling operation.

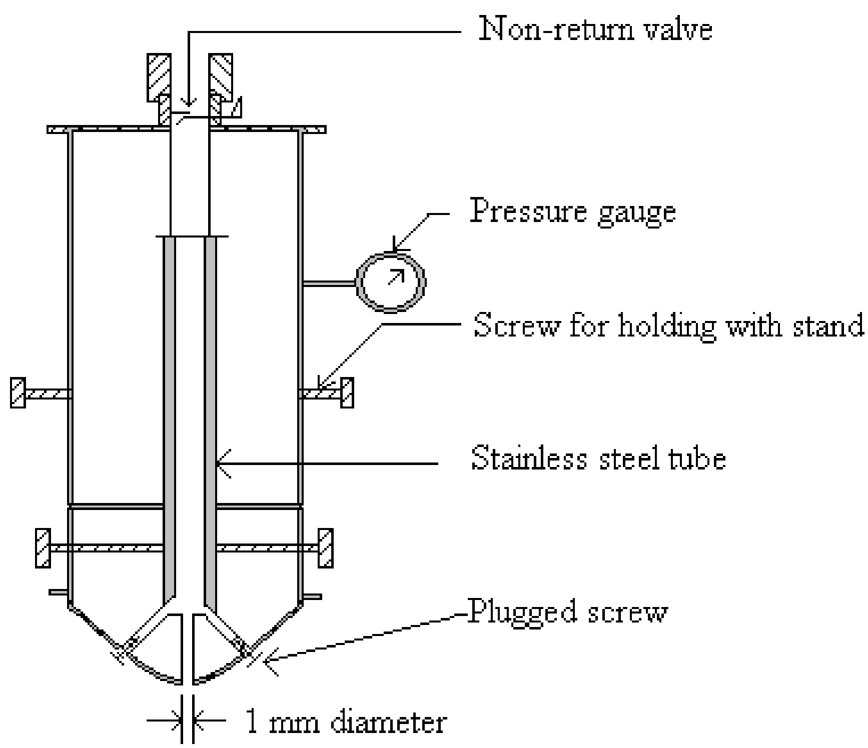

Figure 1. Stainless steel drill bit (redrawn from Hossain et al., 2010).

Figure 2. Paraffin wax for experimental (redrawn from Hossain et al., 2010).

EXPERIMENTAL SET-UP

Figure 1 shows a laboratory experimental drill bit for water jet drilling technique. Here normal tap water is used with a maximum of 72 psig pressure to create a waterjet through a 1 mm diameter hole at the tip of drill bit. A non-return valve has been used for protecting back flow and pressure. Two grooved screws are attached with the drill bit for holding it with a stand. A pressure gauge has been set with the bit for measuring the inside pressure of the bit. Figure 2 and 3 show the paraffin wax and beeswax samples used as a rock sample in the experiment. Figure 4 shows a schematic view of the experimental set-up used in the laboratory test for both paraffin wax and beeswax respectively. A garden hose was connected with the tap and drill bit top to get the continuous water flow. Here, it should be mentioned that beeswax is heterogeneous such as real reservoir rock and paraffin wax is homogeneous such as steel in core structure.

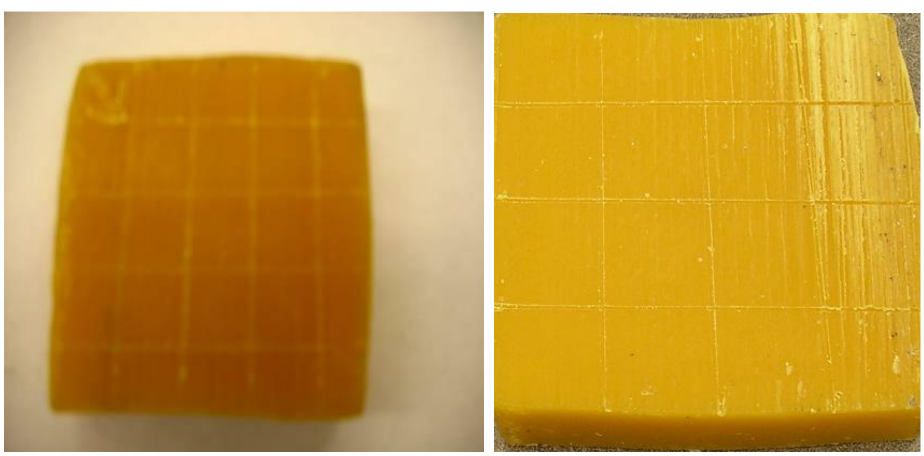

Figure 3. Beeswax sample for experiment (redrawn from Hossain et al., 2009).

Figure 4. Experimental set-ups at the laboratory (redrawn from Hossain et al., 2009 & 2010).

RESULTS AND DISCUSSION

Dependence on Thermal Exposure Time

Thermal exposure time of the paraffin wax sample is investigated since the same wax sample was drilled at high temperatures and for many holes consecutively (Figure 5). As thermal exposure time increases, DOP and ROP increase linearly with time. It is obvious that there is a thermal effect during any hot water action. To soften the rock matrix, thermal action is helpful during waterjet drilling. Equations (1) and (2) present the linear empirical correlations developed by using best fit regression analysis for both DOP and ROP.

$$DOP_P = 0.201\, t_T + 1.740 \text{ and } R^2 = 0.876 \qquad (1)$$

$$ROP_P = 0.558\, t_T + 8.542 \text{ and } R^2 = 0.820 \qquad (2)$$

Thermal exposure time of the beeswax sample is investigated since the same wax sample was drilled at high temperatures and for many holes consecutively (Figure 6). Experimental results show a nonlinear increasing and then decreasing pattern of DOP and ROP with thermal exposure time. It is obvious that there is a thermal effect during any hot water action. However, initially the influence is much more. The temperature is more sensitive in both DOP and ROP. When the beeswax sample temperature reaches the drilling fluid temperature, it becomes steady. This indicates that thermal effects on the sample are limited by its drilling fluid temperature. If the temperature of the drilling fluid increases, thermal exposure time increases. The longer the thermal exposures time the more DOP and ROP. Therefore, to soften the rock matrix, thermal action is helpful during waterjet drilling. As long as time progresses, thermal action plays a role in the rock matrix system shown in this figure. The best fit regression analysis gives nonlinear relationship of DOP and ROP for beeswax sample. These correlations are expressed in equations (3) and (4).

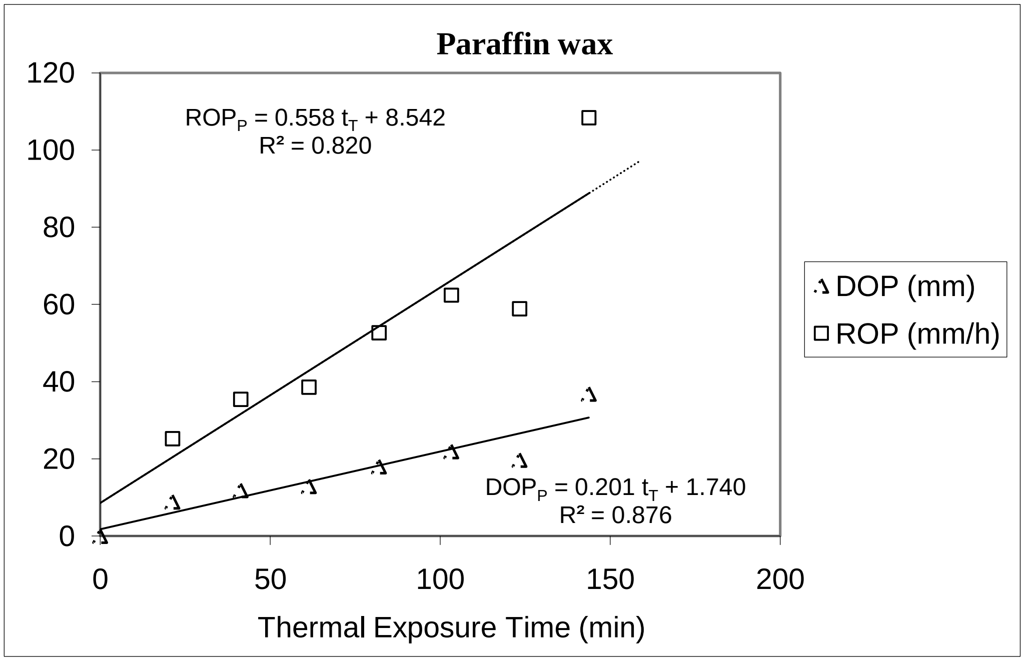

Figure 5. Variation of DOP and ROP with thermal exposure time.

$$DOP_B = -0.002\, t_T^2 + 0.361\, t_T + 0.189 \text{ and } R^2 = 0.986 \quad (3)$$

$$ROP_B = -\,0.006\, t_T^2 + 0.984\, t_T + 3.24 \text{ and } R^2 = 0.941 \quad (4)$$

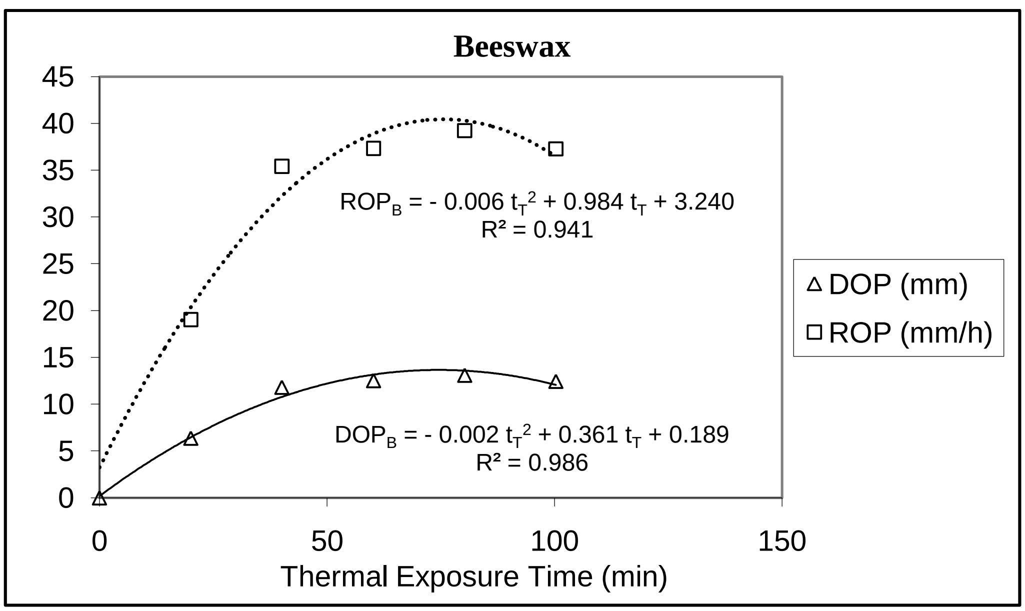

Figure 6. Variation of DOP and ROP with thermal exposure time.

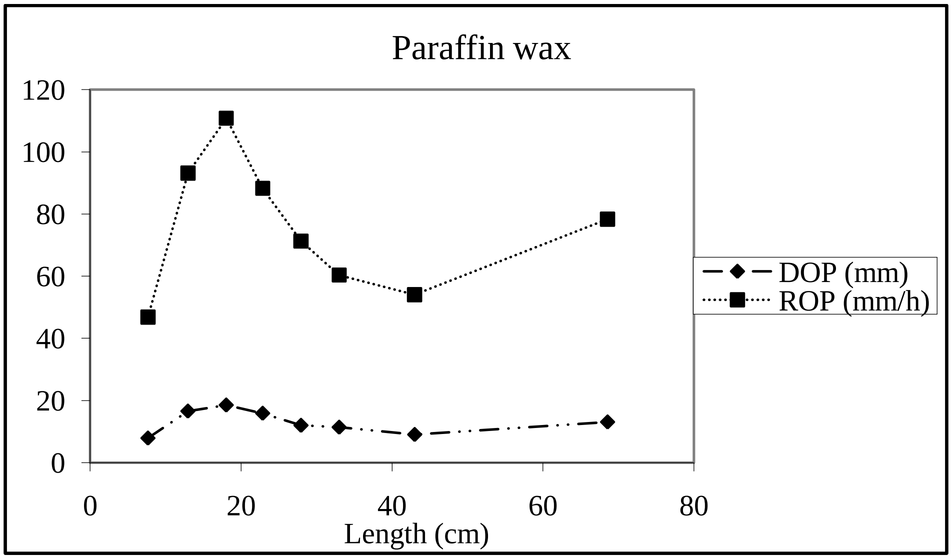

Figure 7. Dependence of DOP and ROP on length between jet nozzle and paraffin wax surface.

Dependence on DOP and ROP with Length between Jet Nozzle and wax Sample Surface

Figure 7 shows the affects of most influential parameters such as DOP, ROP, with length between jet nozzle and paraffin wax surface. It is shown separately due to its important observation in this experiment. DOP increases with gap between drill bit tip and top surface of paraffin wax sample (see Figure 7). This trend continues up to 18.5 mm for the length of 18.0 cm (7.1”). After this, the trend is decreasing with the length which goes up little bit beyond the gap length 43.0 cm. From this analysis, it can be concluded that the effective gap length is 18.0 cm. Hossain et al. (2011) describes a detail dependence of DOP and ROP for paraffin wax sample. In the same figure, ROP increases sharply with gap length up to 111.0 mm/h for the length of 18.0 cm (7.1”). After this, the trend is decreasing with the gap length up to 43.0 cm and then increases with gap length which is 78.5 mm/h. From this analysis, it can be concluded that the effective gap length is 18.0 cm for better ROP as well.

Figure 8 shows the affects of important parameters – DOP, and ROP with length between jet nozzle and beeswax surface. The trend is more clearly visible in this figure. Initially, DOP decreases with gap between drill bit tip and top surface of beeswax sample (see Figure 8). This trend continues up to 4.0 mm for the length of 18.0 cm. After this, the trend is bit increasing with the length which goes up little bit beyond the gap length 34.0 cm. The existing experimental setup gives the maximum depth of 8.0 mm, when the gap length is maintained at a length of 8.6 cm on beeswax. ROP decreases sharply with gap length from 47.0 mm/h to 20.0 mm/h for the length of 8.6 cm (3.4”) to 18.8 cm (7.4”) respectively. After this point, the trend is increasing little bit up to the gap length of 34.0 cm where ROP is 27.0 mm/h. Beyond this point, the trend of ROP is decreasing with gap length. From this analysis, it can be concluded that the effective gap length is 8.6 cm for better ROP.

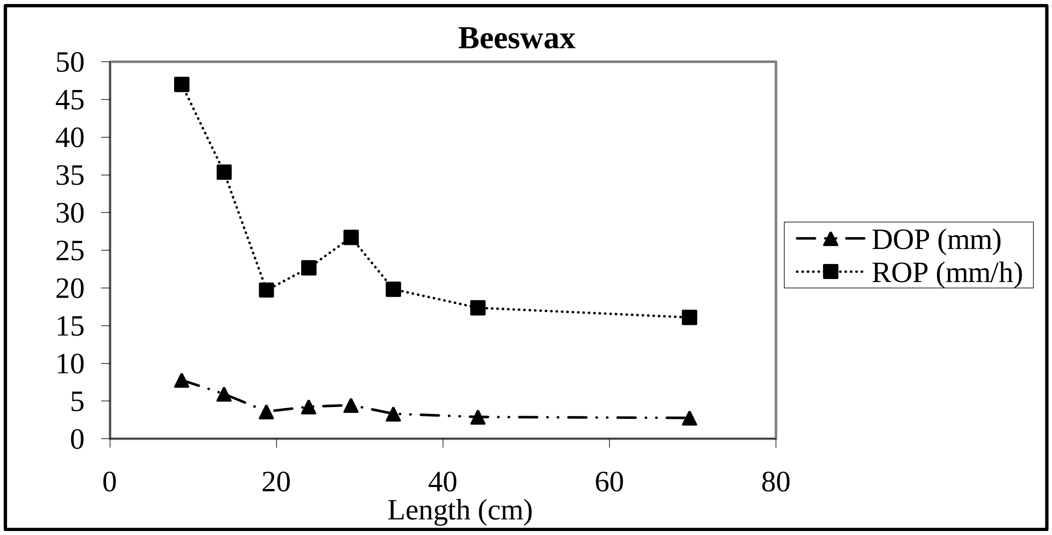

Figure 8. Dependence of DOP and ROP on length between jet nozzle and beeswax surface.

SUSTAINABILITY OF WATERJET DRILLING

The success of a high risk hydrocarbon exploration and production depends on the use of appropriate technologies. In this study, waterjet is proposed for the drilling operations. Generally, a technology is selected based on criteria, such as technical feasibility, cost effectiveness, regulatory requirements and environmental impacts. Recently, Khan and Islam (2006a) introduced a new approach in technology evaluation based on the novel sustainability criterion. In their study, they not only considered the environmental, economics and regulatory criteria, but investigate over sustainability of a technologies (Khan et al., 2005; Khan and Islam, 2005; Khan 2006a and 2006b). 'Sustainability' or 'sustainable technology' has been using in many publications, company brochures, research reports and government documents which do not necessarily gives a clear direction (Khan, 2006a; Appleton, 2006). Sometimes, these conventional approach/definition mislead to achieve true sustainability. Figure 9 shows the directions of true sustainability in technology devolvement. It shows the direction of nature-based, inherently sustainable technology, as contrasted with an unsustainable technology. The path of sustainable technology is its long-term durability and environmentally wholesome impact, while unsustainable technology is marked by Δt approaching 0. Presently, the most commonly used theme in technology development is to select technologies that are good for t='right now', or $\Delta t = 0$. In reality, such models are devoid of any real basis (termed "aphenomenal" by Khan et al., 2005) and should not be applied in technology development if we seek sustainability for economic, social and environmental purposes.

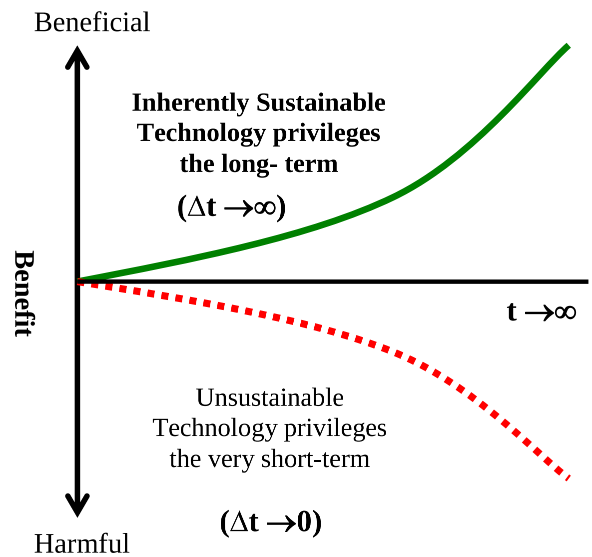

Figure 9. Direction of sustainable and unsustainable technology (Khan and Islam, 2006a).

In addition to technological details of the waterjet (which are discussed through out previous sections), the sustainability of this technology is evaluated based on the model proposed by Khan and Islam. (2006a). Figure 37 shows the detailed steps for its evaluation. The first step of this method is to evaluated the proposed waterjet technology based on time criterion (Figure 10). If the technology passes this stage than it will be evaluated about environmental, economical and social variants. According to Khan and Islam's (2006a and 2006b) method any technology is considered sustainable if it fulfills the environmental, economical and social conditions $(C_n + C_e + C_s) \geq$ constant for any time, t, provided that, $dCn_t/dt \geq 0$, $dCe_t/dt \geq 0$, $dCs_t/dt \geq 0$.

To evaluate the environmental sustainability the waterjet drilling technique was compared with the conventional drilling. The current drilling technologies are considered as most environmentally concerning activities in whole petroleum operations (Patin, 1998; Khan and Islam, 2003a; 2003b). The current practices produce numerous gaseous, liquid, and solid wastes and pollutants (Khan and Islam, 2003b; Holdway, 2002; Veil, 2002; EPA, 2000), none of which has been completely remedied. Therefore, it is believed that conventional drilling have negative impacts on habitat, wildlife, fisheries, and biodiversity (Wenger et al., 2004; Holdway, 2002; Khan and Islam, 2003a; Currie and Isaacs, 2004; Schroeder and Love, 2004).

For analyzing the environmental consequences of drilling conventional drilling practices have been analyzed in this section. In the conventional drilling different types of rigs used, but the drilling operations are similar. The main task of a drill rig is performed by the hosting, circulating and rotation system, backed-up by the pressure-control equipment. A drill bit is attached at the end portion of a drill pipe. Motorized equipment rotates the drill pipe to make it cut into rocks. During drilling, many pumps and prime movers circulate drilling fluids from tanks through a standpipe into the drill pipe and drill collar to the bit. The muds flow out of the annulus above the blowout preventer over the shale shaker (a screen to remove formation cutting), and back into the mud tanks.

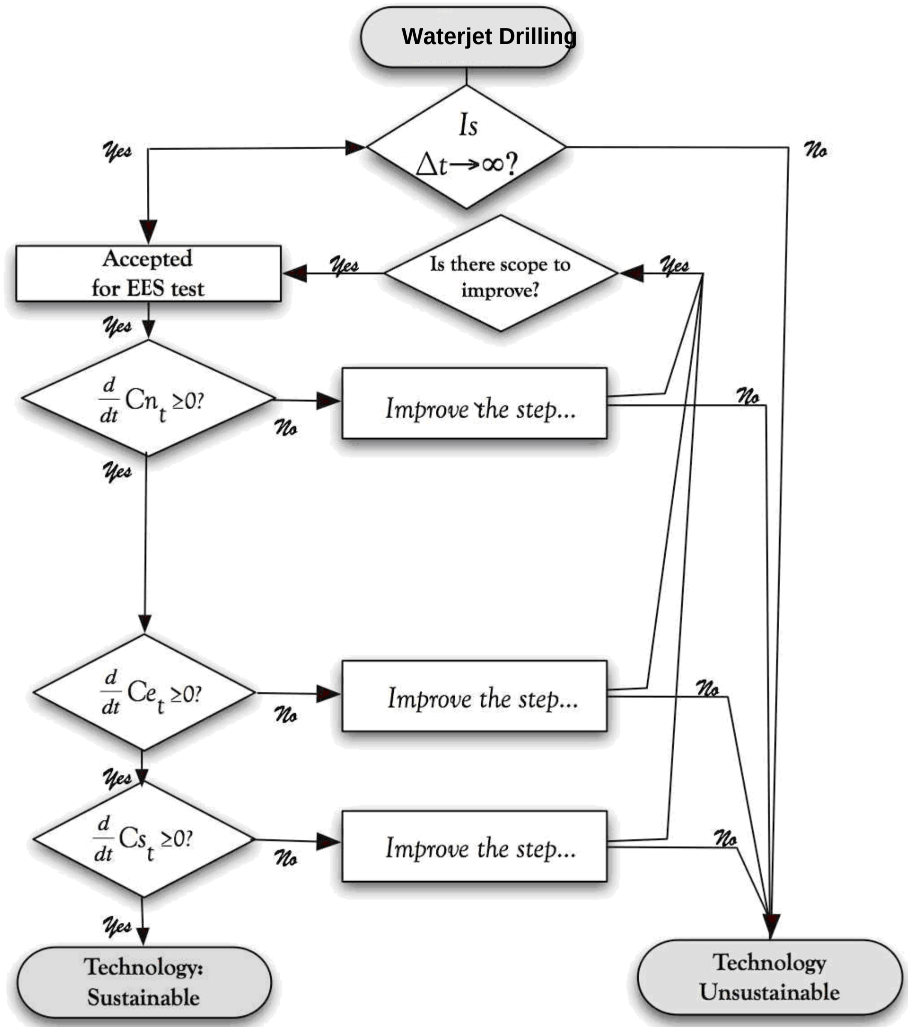

Figure 10. Flowchart of sustainability analysis of proposed waterjet drilling technology (redrawn from Khan and Islam, 2006b).

Drilling muds are composed of numerous toxic chemicals, which are highly toxic for the environment and its flora and fauna. The composition of drilling muds is shown in Table 1 (data source: Zwicker et al., (1983); Patin (1999) and Wenger et al., 2004). Using the proposed waterjet drilling is environmentally friendlier than conventional drilling, because waterjet does not need any drilling mud. In the conventional drilling, different types of muds, such as water-based, oil-based and synthetic-based muds are used in exploration and production drilling (Wenger et al., 2004; Khan and Islam, 2003a). The composition is ranged from a simple clay-water mixture to a complex blend of minerals chemically suspended in water and oil. Water-based mud is composed of water and betonies, and heavy minerals are also added for weight. Chemical additives are mixed in to stabilize the drilling fluids during use, and to reduce corrosion and bacterial activity (Table 1). Figure 11 shows the composition of oil-based and water-based drilling muds in percentage weight, excluding density control.

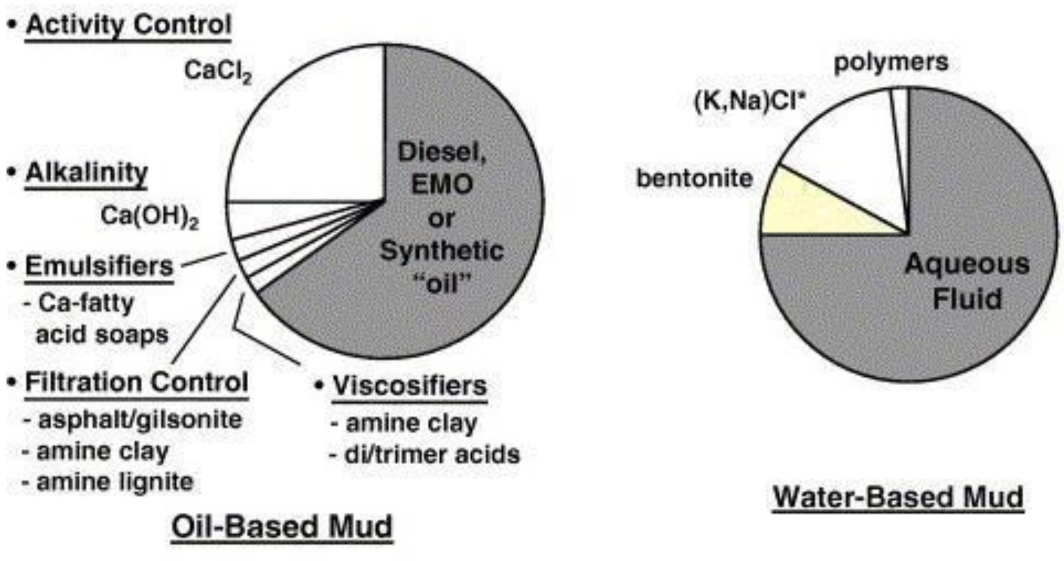

Figure 11. Composition of oil-based and water-based drilling muds (in weight %, excluding weighting agents) used in offshore oil and gas operations (redrawn from Wenger et al., 2004).

Table 1. Composition of drilling muds which are used in oil and gas exploration

Product	Composition	Concentration
Base fluid	Water, Bentonite clay (Sodium montmorillonite), Caustic soda (sodium hydroxide)	As needed
Additives	Lignosulfonate, Phosphates (sodium acid pyrophosphate and tetrasodiumpyrophosphate), Plant tains (predominant usage of quebracho), Lignite	1-2.7 kg/bbl
Density control	Barite (natural barium sulfate ore), Ferrophosphate ore, Calcite, Siderite, Hematite, and heavy metals.	0 – 317.5 kg/bbl
Fluid-loss control	Starch (corn and potato), Polyanionic cellulose polymer, Xanthum gum, Sodium carboxymethyle-cellulose, lignite.	<0.45-4.5 kg/bbl
Lost Circulation	Ground nut shells, Micas, Ground cellophane, Diatomacheous earth, Cottonseed hulls, Ground or shredded paper	0.9-13.6 kg/bbl
Corrosion and scale control	Sodium sulfite, Zinch chromate, Tall oil, Amines, Sodium hydroxide, Phosphates, Bactericides	0.11-2.7 kg/bbl
Solvents	Isoprophanol, Glycerol, Isobutanol, Ester alcohols, Diesel oil	----
Lubricant	Asphalts, Diesel oil, Fatty soaps, gilsonite, Glass beads, Rosin soap; Enhanced mineral oil; Synthetic oil (no aromatic content)	.09-2.7 kg/bbl

Source: Zwicker et al., (1983); Patin (1999) and Wenger et al., 2004; Khan, 2006.

Table 2. Estimated major wastes components of shallow and deep water development and exploratory drilling wells

Waste Component	Shallow Well (kgs)		Deep Wells (kgs)	
	Development	Exploratory	Development	Exploratory
SBF	30,381	63,666	45,975	102,221
Water	12,928	27,092	19,564	43,498
Barite	21,332	44,702	32,280	71,772
D-Cuttings	233,215	488,719	352,918	784,674
A-Cuttings	297,856	624,178	450,737	1,002,165
W-SBF	64,641	135,460	97,819	217,491
F-fluid	94	196	142	316

Source: Khan et al., 2006.

Table 3. Estimated priority pollutants from shallow-water and deepwater drilling wells

Priority Pollutant Organics	**Shallow Well (kgs)**		**Deep Well (kgs)**	
	Development	Exploratory	Development	Exploratory
Cadmium	2.34599178	4.91621664	3.5501159	7.8933036
Mercury	0.21327198	0.44692879	0.3227378	0.7175731
Antimony	12.1565029	25.4749407	18.396055	40.901664
Arsenic	15.1423106	31.7319437	22.914385	50.947687
Beryllium	1.49290386	3.1285015	2.2591647	5.0230114
Chromium	511.852752	1072.62908	774.57074	1722.1753
Copper	39.8818603	83.5756828	60.35197	134.18616
Lead	74.858465	156.872004	113.28097	251.86814
Nickel	28.7917173	60.335386	43.569604	96.872362
Selenium	2.34599178	4.91621664	3.5501159	7.8933036
Silver	1.49290386	3.1285015	2.2591647	5.0230114
Thallium	2.55926376	5.36314542	3.8728537	8.6108766
Zinc	427.61032	896.092214	647.08931	1438.734
Non-Conventional Metals (kgs)				
Aluminum	19343.5553	40535.9939	29271.997	65083.158
Barium	1254039.24	2627941.26	1897698.3	4219329.5
Iron	32725.0924	68578.0936	49521.858	110106.56
Tin	31.1377091	65.2516026	47.11972	104.76567
Titanium	186.612983	391.062687	282.39558	627.87642

Source: Khan et al., 2006.

The oil-based muds are composed of mineral oils, barite and chemical additives (Table 1). Oil-based muds are used for deeper well sections and in cases where the well is drilled at an angle. In case of synthetic-based mud, mineral oil is replaced by oil like substances. This makes it more environmentally acceptable. Requirements as to appropriate drilling mud depend on well depth and the geological conditions of the drilling area. In conventional drilling, water-base, oil-base, and synthetic-base mud/fluids are used in drilling. The detailed compositions of different types of drilling mud are shown in Figure 11. Due to considerations of toxicity and environmental degradation, synthetic-based mud types are recommended in Europe, USA, and Canada (EPA, 2000; CNSOPB, 2000, and Wenger et al., 2004). Due to its high toxic levels, OBM is not recommended for use. In case of waste estimation, SBM is favored because it has been widely used (EPA, 2000; Khan and Islam, 2006c). The oil retention level of the mud was considered as only 10.2%, which corresponds to conventional uses (EPA, 2000).

Table 2 shows the comparative wastes released from a typical drilling well come from drilling mud, cuttings, barite, formation fluid (F-fluid). For all types of wells, exploratory drilling in deeper wells (which is more than 1000 m) generates the maximum amount of wastes. The major wastes components are drilling cuttings, SBS, formation oil, water, and barite. The solid wastes, including dry-cuttings, wet-cuttings, and barite that are generated from deepwater exploratory drilling are 71,772, 784,674, and 1,002,165 kgs respectively. The estimated amount for the other three types of wells is presented in Table 2. Barite is another solid waste which is generated in the highest volume from the same well. However, using waterjet drilling the SBF, Barite and W-SBF can be completely avoided (Table 2) and other wastes will also be minimized.

In the present practice of drilling many toxic heavy metals are used drilling fluids. Table 3 shows the types and amounts of organic pollutants used in the drilling process. Using waterjet technology instead of conventional drilling these chemicals can be avoided, because in the proposed waterjet drilling does not required any drilling fluid. As a whole the waterjet drilling is simpler and less environmental impacts. Based on these above discussion, the waterjet technology fulfills the environmental criteria ($dCn_t/dt \geq 0$) and brings a major change to environmental condition. The waterjet technology is less expensive, because it does not use any expensive muds and save the cost of thousands barrels of drilling muds in a single oil site. As result, waterjet technology fulfills the economic criterion ($dCe_t/dt \geq 0$) as the total change of economic benefit is positive. However, the waterjet technology does not have any direct social benefit and social criterion ($dCs_t/dt \geq 0$) can not be fulfilled as all fossil fuel based technologies are developed based on top down corporate approach and users have no 'say' for their sake. However, waterjet technology is fulfills the environmental and economic condition of sustainability.

CONCLUSIONS

The conventional practice in the oil industry is to use different drilling techniques where huge capital is involved. The technology is also more complicated to handle. In this regard, waterjet drilling is simpler and needs less capital involvement. Both DOP and ROP increase with thermal exposure time in the case of paraffin wax. However, DOP and ROP have the nonlinear relationship with thermal exposure time for beeswax. Therefore, there is a side effect during the experiment which needs to be investigated. Empirical correlations for DOP, ROP with thermal exposure time are developed for both paraffin wax and beeswax.

The variation of DOP and ROP on length between jet nozzle and wax sample surfaces are also studied and shown. From this analysis, it can be concluded that the effective gap length is 18.0 cm for paraffin wax and the effective gap length should be low for beeswax. The existing experimental setup gives the maximum depth of 8.0 mm, when the gap length is maintained at a length of 8.6 cm on beeswax. Maximum ROP (111.0 mm/h) can be reached with gap length of 18.0 cm for paraffin wax. The existing experimental setup gives the maximum ROP of 47.00 mm/h, when the gap length is maintained at a length of 8.6 cm for beeswax.

A sustainability analysis of waterjet is completed in this study. It is found that waterjet is more effective and sustainable than conventional rotary drilling.

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