Experimental study of effective cuttings transport in drilling highly inclined geothermal wells*

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Abstract: Japan is estimated to have the third-largest amount of geothermal resources in the world. However, developments have been restricted for several decades because approximately 80% of the country’s geothermal resources are located in its national parks. Recently, the government has announced plans to approve the development of geothermal energy if access is made outside the national parks using directional drilling technology.

The author experimentally studied effective cuttings transport for highly inclined geothermal wells in which drilling fluids with low to moderate viscosity and low density are generally used for the inhibition of drilling fluid gelation due to high temperature, the prevention of lost circulation, and the reduction of cost. Optimum drilling fluid properties and operating conditions determined on the basis of the experimental results were discussed in this study.

Keywords: geothermal well, highly inclined well, cuttings transport, equivalent circulating density, flow experiment

1. Introduction

Following the United States of America and Indonesia, Japan is estimated to have the third-largest amount of geothermal resources in the world (Stefansson, 2005; Muraoka, 2012). Because approximately 80% of geothermal resources are located in the national parks in Japan, the government has restricted the development of geothermal energy for several decades for environmental conservation. Since the Japan Earthquake and the following accident at Fukushima nuclear power plant on March 11, 2011, debates have continued on whether the dependence on nuclear power should be reduced. Reflecting such a situation, the Ministry of the Environment plans to ease regulations and to approve the development of geothermal energy if access is made outside the national parks using directional drilling technology.

For effective hole cleaning in highly inclined wells, previous laboratory and field studies have indicated a preference for drilling fluid properties and operating conditions that enhance turbulent flow. However, the application of these parameters generally obtained for oil and gas wells has not been sufficiently confirmed in geothermal wells because limited information is available on the field experiences of highly inclined well drilling for geothermal development. In this study, numerous experiments were conducted using a large-scale flow loop apparatus with the ability to simulate two-phase flow of drilling fluid and cuttings in an inclined hole annulus. Cuttings concentration and frictional pressure loss in the annulus were measured for commonly used types of drilling fluids in geothermal wells under a variety of drilling conditions to determine optimum drilling fluid properties and operating conditions that are discussed in this study.

2. Characteristics of Drilling Fluids for Geothermal Wells

Geothermal wells differ from oil and gas wells. The formation temperature of the former is extremely high relative to well depth. In addition, most of the formations to be drilled are under subnormal formation pressure, and their numerous fractures tend to induce large-scale lost circulation. For these
reasons, compared to drilling fluids for oil and gas wells, those for geothermal wells generally include fewer viscosifiers to prevent degradation or gelation in drilling fluids due to high temperature and have lower density. For example, sepiolite-based drilling fluids widely used in geothermal well typically have properties as shown in Table 1 (Telnite Co., Ltd., 2013). Use of fewer additives in geothermal drilling fluids is also effective for cost reduction. In some cases, fresh water or air is used for geothermal well drilling.

After the mid-1980s, many comprehensive studies of cuttings transport in highly inclined and horizontal wells have been conducted experimentally and theoretically (Kelessidis et al., 2011). As a result of these studies, guidelines for efficient hole cleaning in horizontal wells have been demonstrated and are summarized as follows (Pilehvari et al., 1999; Mitchell and Ravi, 2006):

- Maximize fluid velocity by increasing pump power or using large-diameter drill pipes and drill collars.
- Design the drilling fluid rheology so that it enhances turbulence in inclined/horizontal sections.
- In large-diameter horizontal wellbores, where turbulent flow is not practical, use drilling fluids with high suspension properties and those with high V-G meter dial readings at low shear rates.

However, in practice, drilling fluids with considerably high viscosity are often used for oil and gas wells for borehole stability, shale inhibition, and other reasons, though low-viscosity fluids are suitable for enhancing turbulent flow. In addition, high V-G meter dial readings at 6 rpm are maintained for hole cleaning in these applications. Example properties of drilling fluids actually used in highly inclined oil and gas wells are shown in Table 2 (Naganawa et al., 2011).

On the other hand, from the above guidelines, less-viscosified geothermal drilling fluids appear to be suitable for effective hole cleaning in relatively small-diameter inclined/horizontal section. However, high-viscosity drilling fluids have also been used in the field for good hole cleaning in the drilling of large-diameter geothermal well with approximately 60° inclined hole sections (Jotaki, 2000), although it remains unclear whether this usage originates through misconception or anxiety in using low-viscosity drilling fluids.

As previously stated, hesitation in using low-viscosity drilling fluids for most highly inclined wells may stem from lack of certainty in the effect of low-viscosity fluids on hole cleaning. Therefore, comprehensive studies of the effectiveness of low-viscosity fluids should be conducted and accumulation of more data is needed.

### 3. Experiments

#### 3.1 Experimental apparatus

The experimental apparatus used was a large-scale flow loop apparatus known as the Cuttings Transport Flow Loop

### Table 1 Properties of typical sepiolite-based drilling fluid widely used in geothermal well drilling

<table>
<thead>
<tr>
<th>Fluid Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid Density</td>
<td>1.03 – 1.13 SG</td>
</tr>
<tr>
<td>Funnel Viscosity</td>
<td>38 – 42 s</td>
</tr>
<tr>
<td>PV</td>
<td>5 – 10 cp</td>
</tr>
<tr>
<td>YP</td>
<td>5 – 10 lb/100ft²</td>
</tr>
<tr>
<td>Gel Strength</td>
<td>5 – 10 lb/100ft²</td>
</tr>
</tbody>
</table>

### Table 2 Example properties of drilling fluids actually used in highly inclined oil and gas wells

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Hole I.D. (inch)</th>
<th>Density (SG)</th>
<th>PV (cp)</th>
<th>YP (lb/100ft²)</th>
<th>Initial Gel (lb/100ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>990</td>
<td>12-1/4</td>
<td>1.08</td>
<td>67</td>
<td>135</td>
<td>33</td>
</tr>
<tr>
<td>1,727</td>
<td>12-1/4</td>
<td>1.14</td>
<td>51</td>
<td>61</td>
<td>10</td>
</tr>
<tr>
<td>2,182</td>
<td>8-1/2</td>
<td>1.30</td>
<td>33</td>
<td>39</td>
<td>5</td>
</tr>
</tbody>
</table>

![Flow diagram of the Cuttings Transport Flow Loop System](image)
System (CTFLS) that has a 9-m long test section simulating a borehole annulus (Naganawa et al., 2002; Naganawa et al., 2006). A flow diagram and photograph of the apparatus are shown in Figs. 1 and 2, respectively. The test section consists of a 5-inch I.D. outer pipe (borehole/casing) and a 2.063-inch O.D. inner pipe (drill pipe). The middle section of the 7-m long outer pipe is composed of transparent acrylic resin to enable visual observation of flow behavior in the annulus. The inclination angle of the test section can be arbitrarily set between vertical (0°) and horizontal (90°) in 15° steps. The inner pipe can be set at a concentric or eccentric position to the outer pipe and can be rotated in a similar manner as the actual drill pipe.

This apparatus is known as a once-through type of flow loop that means drilling conditions with arbitrary penetration rates from 5 to 50 m/h can be reproduced by controlling the feed rate of cuttings into the test section. Cuttings are fed and mixed into the fluid flow line at the bottomhole side or inlet of the test section by a screw feeder at a given rate. Cuttings discharged from the surface side or outlet of the test section are separated from drilling fluid at the shaker screen and are conveyed to the reservoir hopper by a bucket conveyer. The drilling fluid is returned to the return tank, and then, it is pumped again into the flow loop. Weights of both the cuttings feed hopper and reservoir hopper are continuously measured by respective load cells from which the cuttings weight in the test section annulus can be calculated.

Data from sensors such as hopper weight, differential pressure, and temperature were digitized and stored in a computer at 1-s intervals and can be simultaneously monitored online.

### 3.2 Experimental method

In the experiments, cuttings concentration and frictional pressure loss in the annulus were finally obtained at the steady-state flow condition attained after drilling fluid and cuttings were circulated for about 5 min at constant rates.

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**Fig. 2** Photograph of the Cuttings Transport Flow Loop System

**Fig. 3** Time plot (upper) and its correction (lower) for a typical experimental result

**Fig. 4** Time plot (upper) and its correction (lower) for an experimental result with drill pipe rotation
The cuttings concentrations were obtained from the continuously measured weight data of the cuttings feed hopper and reservoir hopper in the following manner. First, we assume that drilling fluid and cuttings flow in the annulus in steady-state conditions at constant rates. If the fluid flow rate decreases from the steady-state flow condition, an unsteady situation appears temporarily such that amount of cuttings in the annulus increase gradually. After a short time, this increase ceases, and a steady-state flow condition is again attained. By subtracting the cumulative weight of discharged cuttings from that of fed cuttings, the weight of cuttings accumulated in the annulus can be obtained at any given time.

In practice, fluid flow rates were changed in five steps as 70 m$^3$/h, 60 m$^3$/h, . . . , 30 m$^3$/h in one experiment to obtain time-series data of cumulative weights of fed, discharged, and accumulated cuttings in the annulus as shown in Fig. 3. Because weight data directly obtained from this apparatus are of the entire hopper content rather than that of the cuttings alone, a data correction process was needed to obtain the actual amount of cuttings. In addition, other corrections performed include those for the amount of fine cuttings crushed in the screw feeder and passed the shaker screen, water content of recovered cuttings, time lag of weight measurement of the reservoir hopper due to conveyance, and dead volume of flow line. From the data obtained in this manner, average cuttings concentration in the entire annulus in a steady-state flow condition was calculated for each flow rate. Typical plots of before (upper) and after (lower) these corrections are shown in Fig. 3.

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Experimental conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hole I.D.</td>
<td>5 inch (127.0 mm)</td>
</tr>
<tr>
<td>Drill Pipe O.D.</td>
<td>2.063 inch (52.4 mm)</td>
</tr>
<tr>
<td>Drill Pipe Eccentricity</td>
<td>0.8</td>
</tr>
<tr>
<td>Hole Inclination</td>
<td>60°</td>
</tr>
<tr>
<td>Drill Pipe Rotation</td>
<td>0 rpm, 180 rpm</td>
</tr>
<tr>
<td>Drilling Fluid</td>
<td>Water</td>
</tr>
<tr>
<td>Fluid Flowrate (Annular Velocity)</td>
<td>30–70 m$^3$/h (0.79–1.85 m/s)</td>
</tr>
<tr>
<td>Fluid Temperature</td>
<td>30°C</td>
</tr>
<tr>
<td>Cuttings Diameter</td>
<td>3.2 mm (+1/8 inch)</td>
</tr>
<tr>
<td>Cuttings Density</td>
<td>2.4 SG</td>
</tr>
<tr>
<td>Penetration Rate (Feed Rate)</td>
<td>10 m/h (0.13 m$^3$/h), 20 m/h (0.25 m$^3$/h)</td>
</tr>
</tbody>
</table>

Table 4  Average properties of drilling fluids used in the experiments

<table>
<thead>
<tr>
<th>Density (SG)</th>
<th>PV (cp)</th>
<th>YP (lbf/100ft$^2$)</th>
<th>Initial Gel (lbf/100ft$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mud 1</td>
<td>1.00</td>
<td>5.9</td>
<td>8.3</td>
</tr>
<tr>
<td>Mud 2</td>
<td>1.03</td>
<td>19.0</td>
<td>13.9</td>
</tr>
</tbody>
</table>

Fig. 4  Rheologies of drilling fluids used in the experiments tank and flow lines.

Penetration rate, drill pipe rotation speed, and types of drilling fluids were selected as experimental parameters. Two cases of moderate and high penetration rates, 10 and 20 m/h, respectively, were studied. The rotation speed of the drill pipe that affects cuttings transport efficiency was set to 0 and 180 rpm. The rotating drill pipe was restricted to whirl by braces installed in the test section. Water and two types of mud, Mud 1 and Mud 2, were used as drilling fluids. Water was ordinary fresh water, Mud 1 was a water-based mud with 0.15% partially hydrolyzed polyacrylamide (HPHA), and Mud 2 was a water-based mud with 5% bentonite and 0.1% PHPA. Average rheological properties of the drilling fluids measured before and after each experiment using the Fann Model 35 V-G meter are shown in Table 4, and the relationship between shear stress and shear rate for each drilling fluid is shown in Fig. 4.
4. Results and Discussion

4.1 Optimum fluid flow rate

Fig. 5 shows results of cuttings concentration and frictional pressure loss in the annulus for the experiments with Water and Mud 2, and Fig. 6 shows the behaviors of cuttings deposition in the annulus for these experiments. In both cases, cuttings concentration increased with a decrease in fluid flow rate, which proved that a certain flow rate is required for effective cuttings transport. Although the frictional pressure loss generally increased with fluid flow rate, it also increased with a decrease in the fluid flow rate region below 50 m³/h, particularly in the Water case. This result indicates that the fluid flow rate of 50 m³/h, at which frictional pressure loss was minimum and cuttings concentration was reasonably low, is optimum in the Water case. For the Mud 2 case, a minimum fluid flow rate at which the frictional pressure loss is minimum, similar to that in the Water case, was not observed. However, a fluid flow rate of 60 m³/h, at which cuttings concentration was low and frictional pressure loss was not so large, was determined as the optimum fluid flow rate.

From the aspect of hydraulics, the experiments demonstrated the optimum fluid flow rates to enable sufficient cuttings transport and minimal frictional pressure loss. These results indicate that in drilling highly inclined wells, excessive fluid flow rate is not preferable for preventing increase of...
4.2 Effect of penetration rate

Fig. 7 shows a comparison of cuttings concentration and frictional pressure loss in the annulus at various penetration rates for the Water case. In the region of low fluid flow rate with the formation of a cuttings deposit bed, penetration rate increase was related to a higher cuttings deposit bed, and therefore, a higher cuttings concentration. Although the cuttings feed rate in the case of a higher penetration rate was two times that of the lower rate, the difference in cuttings concentration between the two cases was less significant.

On the other hand, the frictional pressure loss increased with cuttings concentration because of a high penetration rate. Although the estimation or calculation method widely used in oil and gas well drilling fields for frictional pressure loss in the well annulus (Bourgoyne et al., 1991) does not consider the effect of cuttings deposition, it is generally known that frictional pressure loss increases with solid concentration in the field of solid-liquid two-phase flow in pipes (Wani, 1986). The experimental results agree with this principle. Therefore, the effect of cuttings concentration on frictional pressure loss cannot be ignored in drilling highly inclined wells.

On the basis of these results, the use of controlled drilling is recommended to restrict the penetration rate in cases of insufficient cuttings transport or if an undesirable increase in pump pressure is anticipated.

4.3 Effect of drill pipe rotation

The time record for the experiment with drill pipe rotation is shown in Fig. 8. In this experiment, the rate of increased amount of cuttings discharged from the test section and recovered into the reservoir hopper decreased with time, and ultimately, only 70% of the fed cuttings were able to be recovered. Visual observation revealed that the drill pipe was slightly whirled, resulting in crushed cuttings. The crushed fine cuttings passed the shaker screen and were not recovered to the hopper. Although the lower graph of the figure reflects corrections, these experimental results may contain a considerable amount of error because of the large amount of crushed cuttings to be corrected. Therefore, these results should be carefully interpreted.

A comparison of cuttings concentration and frictional pressure loss in the annulus with and without drill pipe rotation for the Water case is shown in Fig. 9. The cuttings concentration dramatically decreased with high-speed pipe rotation. Frictional pressure loss in the annulus simultaneously increased with drill pipe rotation, particularly at low fluid flow rates.

Although drill pipe rotation has an effect of mechanical agitation of cuttings in the annulus, which is very effective for cuttings transport, it is necessary to carefully monitor the undesirable increases in frictional pressure loss.

4.4 Optimum drilling fluid properties for highly inclined geothermal well drilling

A comparison of cuttings concentration and frictional pressure loss in the annulus among the three types of drilling fluids is shown in Fig. 10. Mud 2 with higher plastic viscosity (PV), yield point (YP), and gel strength showed slightly lower cuttings concentration than that observed in the low-viscosity Mud 1 case. However, no significant difference was observed in cuttings concentration between the Water and Mud 2 cases. Moreover, the frictional pressure loss for the Water case was maintained at a lower rate than that in other higher viscosity drilling fluids.

A previous work by numerical simulation reported that drilling fluids with high YP or high initial gel strength were favorable for the implementation of effective hole cleaning and those with small YP or initial gel strength were desirable to maintain low frictional pressure loss even if a certain degree of cuttings deposit bed was allowed to form (Naganawa et al., 2011). Our result showing that cuttings concentration for the Mud 2 case with higher YP and initial gel strength was smaller than that for the Mud 1 case agrees with this report.

In addition, the experimental result that Water may have cuttings transport ability comparable to that of Mud 2 appears to be consistent with the guidelines mentioned in preceding section. Such results occur because the flow of water under usual flow rate conditions in well drilling can enhance turbulence, therefore, cuttings rarely form a stationary bed when water is used as a drilling fluid. Although fresh water is not used as a drilling fluid in oil and gas wells except for...
particular circumstances, such fluid can be considered as an important option for drilling geothermal wells that contain high risks of lost circulation.

5. Conclusions

In this study, flow experiments that assumed drilling in highly inclined geothermal wells with an inclination angle of 60° were conducted using a large-scale flow loop apparatus with a test section simulating well annulus. Results are summarized as follows:

- It was confirmed that in drilling highly inclined wells, hydraulically optimum fluid flow rates were determined to enable effective cuttings transport and sufficiently suppressed frictional pressure loss.
- Because the cuttings concentration in the annulus increased, and accordingly, frictional pressure loss increased with penetration rate, it is desirable to employ controlled drilling to maintain a low penetration rate according to the circumstances.
- It was confirmed that drill pipe rotation had an effect of mechanical agitation of cuttings in the annulus, which proved effective for cuttings transport. However, careful monitoring is necessary to detect undesirable increases in frictional pressure loss due to drill pipe rotation.
- In drilling geothermal wells, low-viscosity drilling fluid such as fresh water may be an important option. Drilling with water suppresses frictional pressure loss and is expected to achieve a reasonable level of cuttings transport efficiency because of its turbulence.

Acknowledgments

This study was conducted as part of collaborative research project among Geothermal Energy Research & Development Co., Ltd., Teiseki Drilling Co., Ltd., SK Engineering Co., Ltd., and The University of Tokyo. This project was funded by the Ministry of the Environment, Japan, as a Low Carbon Technology Research and Development Program. The author would like to thank those concerned with the project. The author also would like to thank Japan Oil, Gas and Metals National Corporation (JOGMEC) for its support in the experimental work.

SI metric conversion factors

<table>
<thead>
<tr>
<th>Unit</th>
<th>Conversion Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>cp</td>
<td>$1.0^{-3}$ Pa·s</td>
</tr>
<tr>
<td>inch</td>
<td>$2.54^{-2}$ m</td>
</tr>
<tr>
<td>lbf/100 ft$^2$</td>
<td>$4.788 026^{-1}$ Pa</td>
</tr>
</tbody>
</table>

*Conversion factor is exact.

References


Experimental study of effective cuttings transport in drilling highly inclined geothermal wells


要 旨
高傾斜地熱坑井掘削時の効果的掘屑運搬に関する実験的研究
長 紳 成 実

日本は世界でも第 3 位の地熱資源保有国である。しかしながら、国内地熱資源の約 80%が自然公園内に存在するために、その開発は長らく制限されてきた。最近になって、政府は、自然公園外から傾斜掘削技術を用いて地熱資源にアクセスするのであれば、有望な再生可能エネルギーである地熱資源の開発を認める方針を示した。地熱坑井の高傾斜掘削技術の開発が喫緊の課題となっている。

著者は、高温による掘削流体のゲル化や逸泥の防止、掘削コストの低減のために比較的低粘性、低比重の掘削流体が用いられる地熱坑井における高傾斜掘削に対する効果的な掘屑運搬について実験的研究を行った。本研究では、実験結果に基づいて得られた最適な掘削流体性状および掘削条件について考察した。