Chapter 8

New Development of Air and Gas Drilling Technology

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Additional information is available at the end of the chapter

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Abstract

Gas drilling technology has been widely promoted and applied in recent years. Known for being capable of discovering and protecting reservoirs, improving the penetration rate and avoiding loss circulation, two key issues of gas drilling still need to be addressed. First, a more accurate way of determining the gas injection rate is needful. In this text, we present a modified mathematical model for predicting the optimum range of gas injection rate required to balance the borehole cleaning and well-integrity issues. The optimum gas injection rate should be sought between the minimum value required for hole cleaning and the maximum permissible value to avoid hole erosion. Good consistency between the model prediction and field problem-free nitrogen gas injection rate indicates the reliability of the proposed model. Second, the problem of environmental pollution and wasting of resources caused by direct discharging or combustion of the returned gas is to be solved. To address the latter issue, we introduce a new technology of gas recycling system (GRS). Our research group has carried out a comprehensive investigation, including integration design, technological process, cuttings transport analysis, separation and filter equipment selection, and control system design. The feasibility of GRS has been verified through an open-loop pilot test.

Keywords: air and gas drilling, optimum gas injection rate, gas recycling system, penetration rate, gas-recycling drilling

1. Introduction

Air and gas drilling technology is the utilization of mainly (>97% in volume) compressed air or other gases (e.g., nitrogen or natural gas) as a rotary drilling circulating fluid to carry the rock cuttings to the surface. When the gases are injected into the well with incompressible fluids such as fresh water, oil, or drilling mud, the operations are called aerated drilling or stable foam drilling if foaming agents are added to create a continuous foam circulating fluid. Due to the strong capability of cutting transportation of the aerated drilling and foam drilling, the gas injection rate calculation is less significant compared to that in air and gas drilling. Therefore, discussion of aerated and foam drilling is beyond the scope of this chapter.

Gas injection rate is one of the basic parameters during the design process of air and gas drilling. On the one hand, overestimated value of required gas injection rate may lead to high equipment investment, high cost, and ice balling of drill bit. On the other hand, underestimated value of required gas injection rate may cause cuttings transport and pipe-sticking problems. However, how to find the optimum gas injection rate accurately remains a question.

Several criteria and methods for determining the minimum gas volume requirement have been used in the gas drilling industry. They fall into two categories: (1) the minimum velocity criterion and (2) the minimum kinetic energy criterion. The minimum velocity criterion considers the interactions between solid particles, fluids, and the boundary of flow domain (borehole wall). The concept of terminal velocity is used to determine the minimum required gas velocity at the deepest large annulus. The terminal velocity of a solid particle can be influenced by many factors, including size, shape, and density of the particle; density and viscosity of the fluid and flow regime. Among many mathematical models proposed to account for the effects of these factors, Gray's model has been widely accepted for small-size hole drilling because it considers particle-wall interaction [1, 2].

The minimum kinetic energy criterion was established in 1950s based on Angel's pioneering work [3]. The mixture of gas and solid is treated as one homogeneous phase with mixture density and velocity, i.e., interactions between particles and fluids are not considered. Several models have been presented, for example, see [3–6]. Although McCray and Cole's model permits a constant-percentage slip velocity of solid particles, it uses the same particle lift criterion as Angel's model. The criterion for the minimum volume requirement is based on the experience gained from quarry drilling with air. The minimum annular velocity to effectively remove solid particles from the borehole is usually assumed to be 15 m/s, or 50 ft./sec (ft/s), under atmospheric conditions. This velocity was believed to be high enough to remove dust-like particles in air drilling. Although big cuttings not removed from the vicinity of the bit by the circulating air are reground by the bit teeth, it would be uneconomical to lift large cuttings without first trying to control their initial size at the bit. It is reported in [7] that the gas flow rate values obtained from Angel's method were at least 25% below the actual field's needs. This motivated numerous investigators to develop more accurate models to determine the minimum required gas injection rate for gas drilling, for example, see [8–17].

Guo et al. performed a comparison of results from the model calculation and the field experience [18]. The comparison shows that, among those existing models, only the result given by Angel's is mostly consistent with actual needs. Guo et al. found that the assumption of Weymouth friction-model is the reason for the underestimation. The Weymouth friction-model is suitable for smooth pipe walls, but not for the borehole walls which are rather rough. Then Guo et al. introduced Nikuradse's friction factor into Angel's model so that the modified model become more reasonable and practical. However, due to the difficulty in determining the friction factor, the application of Guo's model is limited to some extent. The latter motivates us to develop a new mathematical model to determine the gas injection rate. Li et al. [19]

investigated the optimum range of nitrogen injection rate in shale gas well drilling. Chen et al. [20] present a method for determining the minimum gas injection rate required for hole cleaning in horizontal gas drilling.

Recent developments in gas drilling include thermal failure of rock and gas temperature prediction. Zhang et al. [21] determined the effect of fluid temperature on rock failure in borehole drilling with gas. Li et al. [22] identified the complexity of thermal effect on rock failure in gas-drilling shale gas wells. Li et al. [23] developed a closed-form mathematical model for predicting gas temperature in gas-drilling unconventional tight reservoirs. Guo et al. [24] presented an analytical thermal-model for optimization of gas-drilling in unconventional tight-sand reservoirs. Guo et al. [25] published a mathematical modeling of heat transfer in counter-current multiphase flow found in gas-drilling systems with formation fluid influx. Other recent development in gas drilling includes distribution of the sizes of rock cuttings in gas drilling [26] and gas-lift drilling [27].

Another key issue of air and gas drilling to be solved is the environmental pollution and wasting of resources caused by direct discharging or combustion of the returned gas. To address this problem, our research group developed a new gas recycling system [28–30]. Unlike the conventional gas drilling process, the returned gas is re-injected into the wellbore after treatment by separators and fine filters, rather than being discharged or burned directly. The impurity content, humidity and other parameters of the treated gas can fully meet the requirements of the gas suction standard of a compressor. Therefore, the returned gas can be recycled through compressors, and consequently, the objectives of saving resources, lowering the cost, and environmental protection are achieved.

In the current work, a modified mathematical model for predicting the minimum gas injection rate is derived, taking into account Charles' theory of particle grinding energy. The maximum required value of gas injection rate is estimated using the sonic flow criterion at a bit. The proposed model allows calculating the optimum range of gas injection rate more precisely. Also, we present our work in developing the gas recycling system, including the corresponding equipment, operating procedure, and results of a pilot test. The test results indicate a promising prospect of GRS.

The structure of the text is as follows. Section 2 presents the modified mathematical model for predicting the optimum gas injection rate and the comparison between the model prediction and the field experience. Section 3 demonstrates the newly developed gas recycling system. Section 4 concludes this chapter.

2. Mathematical model for gas injection rate

2.1. The minimum required gas injection rate

It is shown in [18] that only the result given by Angel's minimum kinetic energy criterion has a trend that is consistent with field experience, although the minimum volumetric gas requirements are underestimated. We believe that this underestimation is partially because Angel's model does not consider the gas energy consumed on grinding cuttings from large size to small size in the borehole annular space. We propose the following equation to modify Angel's model (derivation is given in Appendix):

$$\frac{1}{2}\rho_g v_g^2 = \frac{1}{2}\rho_{g0}\left(v_{g0}\sqrt{1+n}\right)^2 \tag{1}$$

where

$$n = \frac{W_g}{\frac{1}{2}\rho_{g0}v_{g0}^2} \tag{2}$$

$$W_g = \frac{100 f_g D_h^2 W_i \rho_s h_{ROP}}{Q_{g0}}\left(\frac{1}{\sqrt{d}} - \frac{1}{\sqrt{D}}\right) \tag{3}$$

ρ_g and v_g in Eq. (1) are dependent on gas-flow-rate through bottom hole pressure; therefore, this equation has to be solved for Q_{g0} numerically.

2.2. The maximum permissible gas injection rate

The excessive gas flow rate through bit can cause several problems including borehole erosion, hole deviation, and ice-balling of drill bit [2]. These problems are usually associated with the sonic flow condition at bit. The temperature of gas at bit can be much lower than expected under sonic flow conditions. This low temperature is due to the Joule-Thomson cooling effect, i.e., a sudden gas expansion below the bit orifice causes a significant temperature drop. The temperature can easily drop to below ice point, resulting in ice-balling of the bit if water exists. Even though the temperature can still be above the ice point, it could be below the dew-point of water vapor, resulting in the formation of liquid water which promotes mud ring problems in the annulus. If natural gas is used as the drilling fluid, it can form gas hydrates with water around the bit, i.e., hydrate balling. The temperature at the bit orifice downstream may be predicted by assuming an isentropic process for an ideal gas flowing through bit orifices [2]. The bit upstream temperature may be lower than the geothermal temperature at the bit depth because the downstream gas cools the bit body, and the bit body, in turn, cools the upstream gas. The process can continue until a dynamic equilibrium with geothermal and gas temperatures is reached at the bottom of the hole. Ref. [31] presented an analytical method for predicting borehole enlargement due to low-pressure and low-temperature effects. In additional to the borehole erosion, hole deviation and ice-balling, the sonic flow condition can also cause pipe sticking problem [2].

The flow equation for subsonic flow is given by [2]:

$$Q_g = 5.6CA_n p_{up}\sqrt{\frac{k}{S_g(k-1)\left(\frac{9}{5}t_{up}+492\right)}\left[\left(\frac{p_{dn}}{p_{up}}\right)^{\frac{2}{k}} - \left(\frac{p_{dn}}{p_{up}}\right)^{\frac{k+1}{k}}\right]} \tag{4}$$

Eq. (4) relates the upstream pressure to the down-stream pressure only in subsonic flow conditions. This relation was first presented in [32]. The boundary between the sonic flow and subsonic flow is identified by the critical downstream to upstream pressure ratio $\frac{p_{dn}}{p_{up}} = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} = 0.53$ when k is 1.4 for air [32]. The choke flow coefficient C takes the maximum value of 1.2, according to [32]. Substituting $C = 1.2$, $k = 1.4$, and the critical pressure ratio of 0.53 into Eq. (4) gives an expression of the maximum gas flow rate without causing sonic flow as:

$$Q_{g\max} = \frac{3.25 A_n p_{up}}{\sqrt{S_g\left(\frac{9}{5} t_{up} + 492\right)}} \tag{5}$$

If the operating gas injection rate is higher than this value, larger orifice area A_n should be utilized to expand the maximum permissible flow rate. If changing the orifice area A_n is not an option, a flow diverging joint (FDJ) should be employed at the shoulder of the drill collar. Application procedure of FDJ is reported in the literature, for example, see [33].

2.3. Application examples

Shale sections of two wells in the Daqing Field, China, were drilled with nitrogen. Basic data are shown in **Table 1**. For the hole section in Well no. 1, Angel's model predicted the minimum required gas injection rate of 69 standard cubic meter per minute (Nm^3/min). For the hole section in Well no. 2, Angel's model gave the minimum required gas injection rate of 66 Nm^3/min.

The initial cuttings size was estimated on the basis of rate of penetration and rotary speed to be about 6 mm. The average cuttings size received at surface was observed to be about 1 mm. Assuming the major content of the shale is clay, its fragmentation energy is 6. 3 kWh/t. The n-value in Eq. (1) reflects the amount of fragmentation energy from the lowing gas. An empirical $n = 1/3$ is assumed based on the observations that the average size of returned drill cuttings is significantly larger when the drilling string is not rotating while the gas booster is turned on.

Site elevation (above mean sea level)	200 m
Ambient pressure	0.1 MP_a
Ambient temperature	20°C
Relative humidity	10%
Geothermal gradient	3C/100 m
Specific gravity of rock	2.7 water = 1
Hole section in Well no. 1	2840–3650 m
Hole section in Well no. 2	2550–3305 m
Bit diameter	215.9 mm
Drill pipe outer diameter	127 mm
Bit orifices	14.29 mm×3
Rate of penetration	18 m/h
Rotary speed	50 rpm

Table 1. Basic data for the nitrogen drilling cases in the Daqing Field, China.

Well no.	1	2
Hole section (m)	2840–3650	2550–3305
The minimum required gas injection rate (Nm^3/min)	—	—
Angel's model	69	66
The new model	85	82
The maximum permissible gas injection rate (Nm^3/min)	144	134
Field-applied gas injection rate (Nm^3/min)	120	95

Table 2. Comparison of model-calculated data and field observations.

On the one hand, the latter phenomenon is due to the weak ability of cuttings transportation of gas, i.e., the cuttings have to be fine enough so as to be returned from the bottom. On the other hand, the excessive gas injection rate is non-commercial and may lead to the ice-balling of drill bit induced by Joule Thompson effect as we have mentioned in the previous text. Moreover, field practice and theoretical analysis have shown that the returned debris in gas drilling is extremely fine, regardless of strata types [34]. Utilizing this value in the new model expressed by Eq. (1) gives the minimum required gas injection rate of 85 and 82 Nm^3/min for the two hole sections in Well no. 1 and Well no. 2, respectively. The maximum permissible gas injection rates were calculated by Eq. (5) to be 144 and 134 Nm^3/min for the two hole sections in Well no. 1 and Well no. 2, respectively.

Table 2 shows a comparison of model-calculated data and field-applied gas injection rates. Using the new model and a design factor of 1.15, The designed gas injection rate was 1.15×85, or 97.8 Nm^3/min. For the hole section in Well no. 1. The section was drilled with a fixed compressor capacity of 120 Nm^3/min, which is between the minimum required gas rate of 85 Nm^3/min and the maximum permissible gas rate of 144 Nm^3/min, with no problem of hole cleaning and hole enlargement. Using the new model and the same design factor of 1.15, the designed gas injection rate was 1.15×82, or 94.3 Nm^3/min for the hole section in Well no. 2. The section was drilled smoothly with a fixed compressor capacity of 95 Nm^3/min, which is between the minimum required gas rate of 82 Nm^3/min and the maximum permissible gas rate of 134 Nm^3/min. This comparison indicates a good consistency between the model-predicted optimum range of gas injection rates and the field-observed problem-free gas injection rates.

3. New technology of gas recycling drilling

The current gas drilling practice of handling gas returned from the borehole is to discharge it to the atmosphere directly. If the gas can be recycled in the same way as drilling mud, the energy consumption and drilling cost can be greatly reduced. The recycling system can also allow the produced gas from the reservoir to be compressed and transported to the gas gathering system in the field. The overall efficiency of gas drilling will be improved significantly.

The gas recycling system (GRS) has been investigated at the China University of Petroleum, Beijing (CUPB), for several years. A systematic research and development group at the CUPB

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carried out a comprehensive study including an integration design, technological process investigation, cuttings transport analysis, separation and filter equipment selection, and control system design.

3.1. System description

The general idea of the GRS is to separate gas effectively from the gas-liquid-solid mixtures returned from the well and re-inject the gas back into the well. At the same time, cuttings and fluids are discharged after the separation. During the natural gas drilling process, the separated gas can be released to the gas gathering system in the field. The integrated design of the process is illustrated in **Figure 1**.

When nitrogen is used as the drilling fluid, a low-capacity nitrogen generator is employed to supply nitrogen gas and inject it into the well. If the well is deep, compressors or boosters may be used to provide the required injection pressure. When the gas pressure and volume reach the required value for recycling, the gas drilling process can be initiated. Because the nitrogen gas is recycled, only a low-capacity nitrogen generator is required for supplying a small amount of nitrogen gas to make up the losses due to leakage and to meet the requirement of additional gas volume in the wellbore as depth increases.

The major equipments in the GRS are described as follows:

Compressors and boosters: The compressors and boosters used in the gas recycling system are the standard equipment used in conventional gas drilling operations. After filtration, the clean nitrogen gas is introduced into the system through parallel connections.

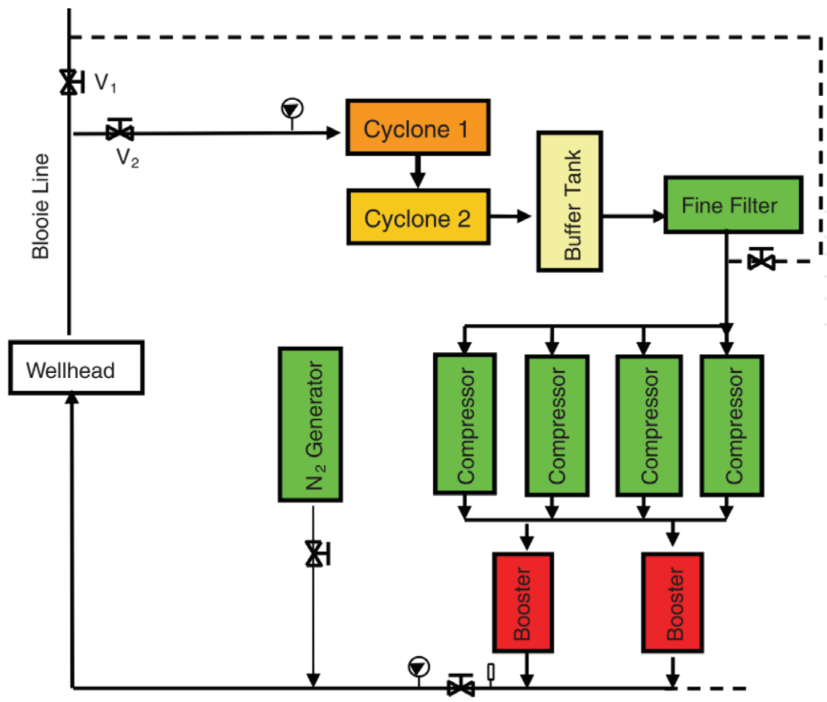

Figure 1. A sketch of the gas recycling system.

Primary separator: The primary separator separates drill cuttings of larger than 0.1 mm equivalent diameter by centrifugal force. Water is introduced into the separator to dilute the cuttings in the separator. The solid particles and liquid are discharged at the bottom of the separator. The separated gas exits the separator at the top and flows into a cyclone separator for further purification. The discharge system was designed to prevent gas loss and liquid overflow by automatically maintaining the dynamic liquid level during the solids and liquids discharge process in the pressurized separator. It is expected that any liquid hydrocarbon/condensate from the drilled formation will drain out of the system at the bottom of the separator.

Cyclone separation unit: Two cyclone separators are used to separate solid particles of a size larger than the 7 μm equivalent diameter. An air-lock and waste-discharge device is specially designed in the separator to guarantee the timely debris-discharging by using the recycled water and the gas tightness. Consequently, the separator can work continuously without deposition of debris. Use of the two cyclone separators in series guarantees that most, although not 100%, of the drill cuttings are removed from the gas phase. The gas phase with small particles (dust) is led to a fine filter for further purification.

Fine filter: The fine filter works on the principle of filtration and aggregation to remove the solid particles that are larger than the 3 μm equivalent diameter. The purity of the post-separation gas is superior to the atmospheric air in terms of particle concentration. The filtered gas is introduced to the compressors for injection into the well. Two fine filters are prepared for alternation. If the debris is overstocked in one of the fine filters, the other one is switched over duly. And the element of the overstocked filter is replaced.

3.2. Operating procedure

The procedure of operating the GRS is different from that of the conventional gas drilling system. The procedure is outlined as follows:

Air displacement: If the upper well section is drilled with mud, one can follow the conventional air drilling procedure to lift the liquid and dry the hole with compressed air in order to save the cost of nitrogen generation. When the air lift is completed, one can replace the air in the well with nitrogen gas to ensure safe drilling.

Preparation of nitrogen gas: The nitrogen generator is started first. The generated nitrogen gas is injected into the well by the compressors. Drilling operation is initiated when the gas pressure and gas flow rate reach the desired levels for the well condition.

Nitrogen supplement: The fluid mixture returned from the well is led to the separation system to remove solids and liquids. The separated gas from the gas-liquid-solid mixture is fed into the compressors and boosters and reinjected into the well. The nitrogen generator runs intermittently to make up for the gas loss in the system and the increased borehole volume as the well deepens.

Drill pipe connection operation: Pipe connection will cause some gas loss. The loss in the annulus can be controlled by closing the rotating head. To minimize the gas loss, one can use the check valves in the drill string to prevent backflow of nitrogen gas during pipe connections.

Treatment of drilling complications: In case of drilling complications such as borehole collapse and excessive formation liquid influx, the nitrogen gas flow rate should be increased immediately. The nitrogen generator should be turned on as soon as possible to provide additional nitrogen gas volume. For instance, if the normal gas circulation rate is 120 Nm^3/min and the capacity of the membrane nitrogen is 30 Nm^3/min, turning on the nitrogen generator will increase the gas rate to 150 Nm^3/min. Because the gas is still in recycling, gas shortage will not be a problem. Moreover, as time passes, the gas volumetric flow rate in the well will continue to increase to clean the borehole.

System control: The process in the GRS is more complicated than that in a conventional gas drilling system. The gas supplement rate adjustment, the valve activation during pipe connection, the timely turning on/off of the nitrogen generator, etc., cannot be achieved by manual operations. An automatic control system was implemented in the developed gas recycling system to ensure operational safety.

3.3. Pilot test

To verify the feasibility of the GRS and the performance of the related equipment, the development group at the CUPB conducted a special test of the system on the Dayi101 well in 2010. An open loop mode was adopted to ensure the safety of the drilling operation. The assembled system is shown in **Figure 2**.

The GRS was installed in the middle of the blooie line. This arrangement was based on two considerations. First, the setup location was not close to the drilling floor to prevent its direct influence on the drilling floor operations should complications occur. Second, the location was not close to the outlet of the blooie line, thereby avoiding the impact of the igniting device on the GRS. The safe distance is essential for preventing hazardous conditions when gas leaks from the separation system.

Figure 2. A gas recycling system installed in Sichuan province of China.

The first objective of the pilot test was to assess the performance of the separation and filtration equipment. This was achieved by evaluating the capacity of separation and filtration equipment, including separating performance of the first and second cyclone separators, stability of the separation system, and the purity of gas at the outlet of the fine filter. The second objective of the test was to assess the adaptability of separation and filtration equipment to the drilling conditions, including normal drilling condition and complication condition such as formation fluid influx. Three working conditions were created. The first condition was the closed-gas flow test to check the liability of the separation system. The second condition was the normal gas drilling test to examine the effectiveness of the separation system. The third condition was the formation fluid influx test to inspect the adaptability of the new system.

Gas tightness test: After the third openhole section of Dayi 101 had been drilled with water, a gas lift was conducted to blow off water and cuttings out of the hole. It took 8 hours to dry the hole completely. The gas circulation was normal. This was a favorable condition for the tightness test of the new system. During the tightness test, the gas injection pressure was 3.8 MPa and the gas injection rate was 90 Nm^3/min. A small leak was found at the outlet of the second cyclone separator. After an investigation, it was confirmed that a collision had occurred to the outlet of the separator during transportation, which damaged the gaskets and caused the leak. After the gaskets were replaced, no more leaks were found during a half-hour test, which indicated that the seal was effective. It provided a sound base for conducting the subsequent tests.

Separation test: Water zones were encountered during drilling in the fourth openhole section. The drilling operation was immediately stopped for discharging water. During this period, a separation system test was conducted. The injection gas pressure was about 4.6 MPa and injection gas rate was 90 Nm^3/min. Visible dust and water were seen at the outlet of the blooie line in the beginning, as shown in **Figure 3a** and **b**. After switching to the separation system, however, the gas at the outlet was seen to be clean and no water droplets were observed, as shown in **Figure 4a** and **b**. This indicated that the formation water and cuttings had been separated effectively by the system. The white mist was caused not by the solid dust, but by the high velocity of gas. However, there was no evidence of any remaining liquid hydrocarbon/condensate in the gas stream.

Because the formation water influx was little and the amount of dust was small in the hole drying process, the system worked effectively. The next step was to test the separation system in normal drilling conditions in which a large amount of dust exists in the system.

a)

b)

Figure 3. Water and dust was seen at the outlet of the blooie line before separation.

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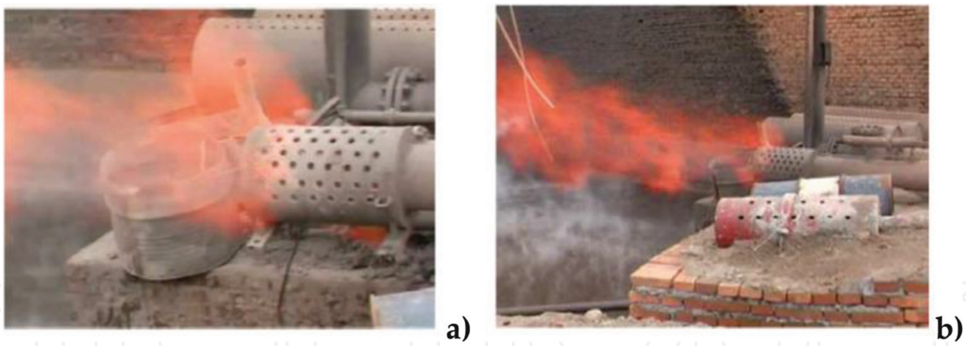

Figure 4. No water or dust was seen at the outlet of the blooie line after separation.

The drilling process started after the hole drying operation. To ensure operational safety, a driller was appointed to control the valve on the blooie line (V_1 in **Figure 1**). In case of an unforeseen situation, the V_1 should be immediately switched to the conventional work position.

The output at the exit of the blooie line was normal after the drilling operation began. Therefore, the inlet valve (V_2 in **Figure 1**) to the separation system was opened and the V_1 was closed. Then the full stream of the gas-liquid-solid mixture returned from the well entered the separation system. To better observe the effect, the water pump for dust removal was closed temporarily. Dust appeared at the exit of the blooie line before separation. After resuming the water injection with the pump to initiate separation, no visible dust was observed at the exit of the blooie line. The filtered gas was very clean. The test result showed that the separation was effective.

As the separated gas was prepared for recycling, its purity must meet the requirement of the compressor. Therefore, a dust concentration test was conducted for the separated gas. Before the test, the dust concentration of the air at the well site was measured to be 0.03–0.1 mg/m^3. The concentration monitoring instruments were installed at both the inlet and outlet of the filter. The quality parameters of the gas were recorded and analyzed automatically. The monitoring result showed that the dust concentration at the inlet of the filter was 50–80 mg/m^3 and that at the outlet was 0.05–0.08 mg/m^3. This means that the purity of the filtered gas reached the level of the

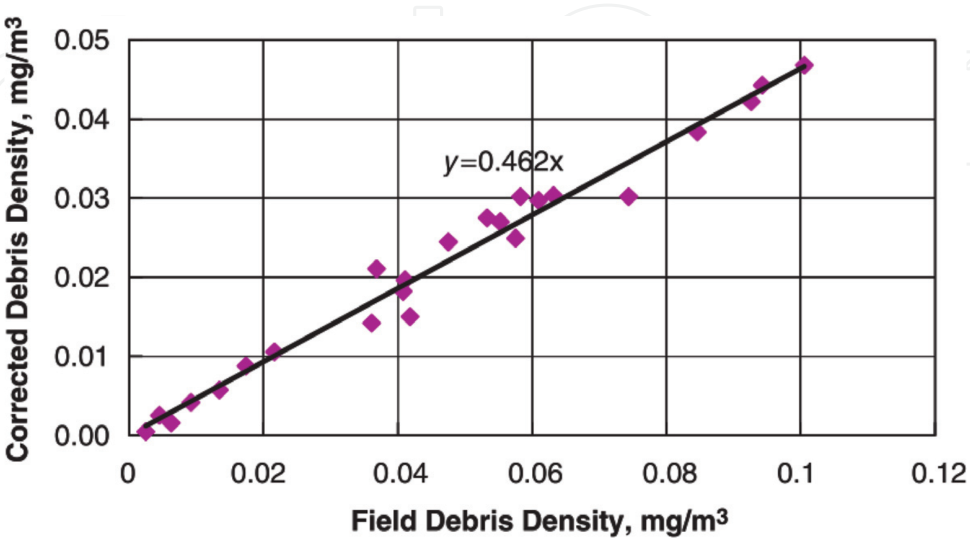

Figure 5. The contrast curve of TSI AM510 measurements and PALAS 3000 measurements.

atmospheric air. It is believed that the filter device completely blocked dust particles that are larger than 3 μm equivalent diameter and the purified gas met the requirement of the compressor.

In order to ensure the accuracy of the measurements, a calibration test for the on-site monitor TSI AM510 was further conducted. The calibration device PALAS 3000 is a more accurate instrument suitable for indoor test. A calibrated contrast curve is presented in **Figure 5**, which shows that the dust concentration was much lower than that of the field data. This again proves the reliability of the separation and filtration system.

It was known from the data collected by the mud logger that the stand pipe pressure increased by only 0.1 MPa because of the separation process. This is the total pressure drop in the separation system. Apparently, the separation system has negligible effect on the drilling pressure.

3.4. Problems and solutions

The first open-loop field test of the GRS was essentially successful. All the equipment was in working order and the separation efficiency was high. This work served as a solid base line for more closed-loop tests. The following problems were found during the test:

3.4.1. Continuous discharge design

According to the original plan, the separated cuttings should be discharged continuously by circulating water. However, the electrical motor for suction pump was not explosion-proof. It did not meet the field security requirement. Therefore, the gas discharge mode had to be adopted. All electrical equipment must be explosion-proof in the future design. In the discharge process, the working condition of the second cyclone separator was normal. However, the blooie line of the first separator was blocked for a moment. Larger size blooie line should be adopted in the future design.

3.4.2. The height of the equipment and skid mounted design

The current separation system is about 7 m high. Collision may occur easily during the transportation and installation process. This height is also inconvenient for monitoring and maintenance of the system. Therefore, the equipment's height should be reduced in the subsequent design without affecting separation efficiency. At this time, the design of a new horizontal separation system has been completed. After further improvements, a skid mounted system will be fabricated for easy transportation and equipment integration.

3.4.3. System measurement and control design

When a closed-circulation is achieved, the operating parameters such as pressure and gas flow rate should be monitored in real time for safety. Valve switching should be used with both manual and automatic modes. In addition, a real-time alarm system should be added for safe operation. Due to the constraints of time and field conditions, an onsite reading method was used in this test. The automatic measurements and control systems should be emphasized in subsequent development.

3.4.4. Compressor inlet design

The entrance of a conventional compressor is open to air. Because the separated gas needs to be introduced to the compressor through piping, a proper parallel gas distributing manifold should be designed to fit the compressor inlet. Currently, such a manifold has been conducted and tested with conventional compressors and the result is satisfactory.

3.5. Operational risks

Some operational risks still exist with the new technology. These risks include: (1) quick addition of gas volume into the borehole in an emergency, (2) oxygen rust corrosion, and (3) downhole fire/explosion.

Whenever the hole cleaning raises a concern because of drill cuttings accumulation, borehole collapse, excessive formation liquid influx, and/or gas leakage, it is imperative to automatically switch on the membrane nitrogen generator for increasing gas input volume to the system. This step will minimize drilling complications and ensure smooth drilling. Since nitrogen gas is highly compressible, which does not cause an immediate pressure drop in the borehole, it may be a good practice to select between 25 and 35% of the capacity of the membrane nitrogen generator using normal nitrogen drilling practice.

Rust corrosion due to oxygen in a wet system is a concern in any nitrogen gas drilling if the oxygen filters do not perform well, whether the system is an open or a closed one. Fortunately, most membrane nitrogen generators remove oxygen to much lower than percent level and no significant risk is expected. Because CO_2 and H_2S corrosion occurs in wet systems, they should be minimized with inhibitors whenever these gases are encountered during drilling.

Downhole fire/explosion can occur when drilling hydrocarbon-bearing zones in the presence of oxygen. For this to happen, the oxygen/hydrocarbon ratio has to be in a certain range. In systems containing natural gas and air only, the natural gas concentration needs to be between 5 and 15%, depending on pressure. Since air contains about 21% of oxygen while membrane-generated nitrogen contains less than 5% oxygen, it is uncommon to see a downhole fire/explosion in a nitrogen gas drilling operation.

4. Conclusions

Regarding the determination of the required gas injection rate and direct discharge of the returned gas in gas drilling, we derived a mathematical model for predicting the optimum range of gas injection rate, developed a new technology of gas recycling drilling, established a system of gas separation and filtration corresponding in the GRS, and performed a pilot test. This study allows for drawing the following conclusions:

1. Based on the modified energy criterion, the minimum required gas injection rate for hole cleaning is nearly proportional to the grinding energy contributed by the flowing gas.
2. The range of the optimum required nitrogen gas injection rate given by the newly developed mathematical model is consistent with field experience.
3. The first open-loop field test on the GRS was successful. The purity of the post-separation gas is superior to the atmospheric air in terms of particle concentration. The filtered gas met the requirement of gas compressor and circulation in the well. The success of the test has laid a good foundation for future development of the system. The GRS has been proven to be a viable and feasible innovation for reducing the cost of gas drilling. It has a huge potential to be applied to the gas drilling operations including nitrogen drilling and natural gas drilling. This technology is predicted to have a huge impact on reducing the cost of gas drilling and improving drilling performance.

A. The minimum energy criterion for hole cleaning considering cuttings grinding

According to Angel [3], the gas stream at bottom hole should be powerful enough to have at least a kinetic energy given by the following expression:

$$\frac{1}{2}\rho_g v_g^2 = \frac{1}{2}\rho_{g0} v_{g0}^2 \tag{A.1}$$

The right-hand-side of Eq. (A.1) is equal to 142 J/m^3.

Angel's energy criterion underestimates the gas flow rate requirement for hole cleaning possibly because it does not consider the gas energy consumed on grinding cuttings from large size to small size in the borehole annular space. We propose the hypothesis that gas stream should have at least the kinetic energy of.

$$\frac{1}{2}\rho_g v_g^2 = \frac{1}{2}\rho_{g0} v_{g0}^2 + W_g \tag{A.2}$$

where W_g is the gas energy spent on grinding cuttings, J/m^3.

Gas drilling produces drill cuttings of dust-like. The fine sizes of the solid particles are believed to be resulted from many times of collisions of drill cuttings to the borehole wall and drill string. If this is true, the energy spent on the collision must be from the flowing gas and the rotating drill bit and drill string. Consider the work done during the collision. Charles' equation for grinding energy has been widely used in the powder grinding industry [35]:

$$dW = -cx^{-a}dx \tag{A.3}$$

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where W is the energy requirement for crushing an individual particle, x is particle diameter, c is a proportionality coefficient, and a is a diameter index. When the particle is ground from its initial diameter D to its final diameter d, Eq. (A.3) can be integrated to obtain a relation:

$$W = k\left(\frac{1}{d^b} - \frac{1}{D^b}\right) \tag{A.4}$$

where $b = a - 1$ and $k = \frac{c}{a-1}$.

In gas drilling, the initial cuttings equivalent diameter is usually in the order of 10 mm. The final cuttings equivalent diameter is normally greater than 0.5 mm. This particle size range falls into the category of Bond Crack Propagation where $b \approx 0.5$. Eq. (A.4) then degenerates to.

$$W = W_i\left(\frac{10}{\sqrt{d}} - \frac{10}{\sqrt{D}}\right) \tag{A.5}$$

where W is the energy requirement for crushing an individual particle, kWh; $W_i = k/10$ represents the fragmentation energy determined in standard test [35], kWh/t.

If the energy requirement is expressed in Joule per particle, Eq. (A.5) becomes:

$$w = \frac{3.6 \times 10^6}{907} W_i\left[\rho_s\left(\frac{\pi}{6}D^3\right)\right] \times \left(\frac{1}{\sqrt{d}} - \frac{1}{\sqrt{D}}\right) \tag{A.6}$$

or

$$w = 3.97 \times 10^3 W_i \rho_s D^3\left(\frac{1}{\sqrt{d}} - \frac{1}{\sqrt{D}}\right) \tag{A.7}$$

where w is the energy requirement for crushing an individual particle, J; ρ_s is the density of solid particle, kg/m^3.

The number of drill cuttings (m) created by the drill bit in a unit volume of gas at standard condition can be estimated on the basis of rate of cuttings volume generation (Q_c), volume of individual cuttings (V_c), and gas injection rate (Q_{g0}):

$$m = \frac{\frac{Q_c}{V_c}}{Q_{g0}} \tag{A.8}$$

The rate of cuttings volume generation is expressed as:

$$Q_c = \frac{c\pi D_h^2 h_{ROP}}{4(60)} \tag{A.9}$$

where D_h is the hole diameter, m; h_{ROP} is the rate of penetration, m/hr.

Assuming cuttings sphericity 1.0, the volume of individual cuttings is.

$$V_c = \frac{4\pi}{3}\left(\frac{D}{2}\right)^3 \tag{A.10}$$

Substituting Eqs. (A.9) and (A.10) into Eq. (A.8) results in

$$m = \frac{D_h^2 h_{ROP}}{40 Q_{g0} D^3} \tag{A.11}$$

The energy requirement for grinding all particles in a unit volume of gas is then expressed as.

$$W = mw \tag{A.12}$$

It is understood that crushing energy should be from rotating drill bit, drill string, and the flowing gas. Assuming the fraction of the crushing energy from the flowing gas is f_g, we have

$$W_g = f_g mw \tag{A.13}$$

Substitution of Eqs. (A.7) and (A.11) into Eq. (A.13) yield:

$$W_g = \frac{100 f_g D_h^2 W_i \rho_s h_{ROP}}{Q_{g0}}\left(\frac{1}{\sqrt{d}} - \frac{1}{\sqrt{D}}\right) \tag{A.14}$$

Substituting Eq. (A.14) into Eq. (A.2) results in:

$$\frac{1}{2}\rho_g v_g^2 = \frac{1}{2}\rho_{g0} v_{g0}^2 + \frac{100 f_g D_h^2 W_i \rho_s h_{ROP}}{Q_{g0}}\left(\frac{1}{\sqrt{d}} - \frac{1}{\sqrt{D}}\right) \tag{A.15}$$

To make the model easy to be adopted in existing computer models, this equation can be rewritten in the same form of Angel's equation as:

$$\frac{1}{2}\rho_g v_g^2 = \frac{1}{2}\rho_{g0}\left(v_{g0}\sqrt{1+n}\right)^2 \tag{A.16}$$

where

$$n = \frac{W_g}{\frac{1}{2}\rho_{g0} v_{g0}^2} \tag{A.17}$$

Nomenclature

A_n	total nozzle area, mm^2
C	choke flow coefficient (≈1.2 according to Guo and Liu [2])

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d	final diameter, m
D	initial diameter, m
D_h	hole diameter, m
F_g	fraction of grinding energy contributed by the flowing gas, dimensionless
h_{ROP}	rate of penetration, m/h
k	heat capacity ratio of gas (≈ 1.4 according to Guo and Liu [2])
p_{dn}	downstream pressure, MPa absolute
p_{up}	upstream pressure, MPa absolute
Q_{g0}	the minimum required gas volumetric flow rate at standard condition, Nm^3/min
S_g	gas specific gravity, air = 1
t_{up}	upstream temperature, °C
W_g	the energy spent on grinding cuttings by the gas stream, J/m^3
W_i	fragmentation energy, 6.30 kWh/t for clay and 12.74 kWh/t for limestone

Greek symbols

ρ_g	gas density at bottom hole condition, kg/m^3
v_g	gas velocity at bottom hole condition, m/s
ρ_{g0}	gas density at standard condition (0. 1 MPa, 15°C), 1.22 kg/m^3
v_{g0}	Angel's gas velocity at standard condition for hole cleaning (0. 1 MPa, 15°C), 15 m/s
ρ_s	density of solid particle, kg/m^3

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