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Distribution of the Sizes of Rock Cuttings in Gas Drilling At Various Depths

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Abstract: In the process of gas drilling, the mechanism of transport of the cuttings up the annulus is significant, because it controls the minimum amount of volume of the required gas, the cost of cleaning the borehole, the stability of the borewell and the drill pipe erosion, etc. However, current studies in this area are only limited to theoretical discussions. The reason why drill cuttings are of very fine sizes , in air drilling, is believed to be due to the repeated crushing action of drill bit at the bottom of the hole, and the collision between cuttings themselves and the collision of the cuttings with the wellbore wall, and with the drill pipe , during the transport of the cuttings in the annulus. In this study, a mathematical model describing the crushing of the cuttings in gas drilling is developed by coupling the gas/solid two phase flow with rock failure mechanics. Using the presented model a numerical simulation was carried out on five particle sizes to study the particle distribution during the transport of the cuttings in the annulus. The simulation results clearly demonstrate the effect of the size of the cuttings on the distribution of the concentration of the cuttings along the annulus, and explains the fact why only small cuttings are observed at the wellhead. Samples of the cuttings were collected from the field in gas drilling, and sieve tests were conducted. The results prove that the presented mathematical model is valid. Consequently, this study helps understand the process of the transport of drill-cuttings in gas drilling, and contributes to an optimal design of separating/filtering equipment in recyclable gas drilling.

Keywords: gas drilling; cuttings lifting; solid transport by gas; crush; particle concentration; cuttings sieve test

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1 Introduction

Air drilling is widely used, because it allows for a high penetration rate. Li et al (2012) proposed a new theory for recyclable-gas drilling, and assessed its feasibility through field testing. The sizes of cutting particles play a critical role in the requirements of gas volume, and of gas reinjection, during the particle -separation and filtration processes. In studying the process of the lifting of the cuttings, most of the publications focus on the requirement of the minimum annular velocity of gas, and on the critical point selection. Very few publications deal with questions of the sizes of the cutting particles, and the distribution of their concentrations [Angel (1957),Chen et al (2006),Guo et al (1994),Guo et al (2006),Wolcott et al (1986),Yang et al (2012) and Zhu et al (2010)]. During gas drilling, the drill bit breaks the rock, and creates cuttings. These cuttings are entrained at the bottom of the hole, and carried out of the borehole by the injected gas. This continuous operation is known as the crush and transport of the cuttings. In this process, gas flow in the borehole is turbulent, and the gas velocity changes rapidly with the geometry of the path of flow. It is generally recognized that the particles of cuttings collected from the wellhead are very small, normally in the magnitude of a millimeter. However, the samples of cuttings obtained in mud drilling, and those received by the down hole collectors of cuttings in gas drilling, are much larger, usually of the magnitude of a centimeter. This implies that particles of cuttings are re-crushed during their transport in the annular space. The re-crush process should be influenced by a series of factors, including the gas velocity, the concentrations of cuttings, sizes of cutting particles, and the interactions between gas and gas, as well as solid and solid.

2 The Mechanism of Crushing and Transport of the Cuttings

2.1 Crushing & Transport at the Drill Bit

In operations of gas drilling, the fluid pressure acting on the surface of the rock formation is very low. The rock at the bottom of the hole is under the condition of released stress. This should make the drill bit crush the rock more easily, and thus generate larger particles of cuttings faster. As a result of the enhanced penetration rate, a larger amount of cuttings is expected to accumulate at the bottom of the hole. Solid particles which are small enough, can be carried to the surface by gas flow. Medium size particles should experience a complex movement in the space close to the drill bit, and the drill collar, depending on their sizes. Large solid particles which are not lifted up due to their heavy weight, should accumulate at the bottom of the hole. They tend to stay around the drill bit, and are subjected to re-crush repeatedly by the bit until they become small enough in size and are carried up the hole by the flowing gas. In continuous gas- drilling operations, the cuttings will go through a dynamic process of crushing and transport. On the one hand, the drill bit continuously crushes the new rock, thus generating cuttings of large sizes; on the other hand, large cuttings are subsequently crushed and become small ones, which are then carried away by the gas flow from the bottom of the hole. It is expected that the maximum concentration of the cuttings occurs at the drill bit, and the accumulated large cuttings would increase the gas pressure and affect the gas flow conditions at the bottom of the hole.

2.2 The Collision of Particles in the Annulus

As the particles of cuttings, of medium and smaller sizes are lifted up from the bottom of the hole, severe collisions occur between the cuttings themselves, between the cuttings and the wall of the borewell, and between the cuttings and drill-string. These processes re-crush the particles of cuttings. Some cuttings may still accumulate at the shoulder of the drill collar, where the sudden change of gas pressure and gas velocity occurs. The dominant effects on the medium and small cutting particles in the annulus, are collision and transport after leaving the bottom of the hole. As the gas flow rate increases, the collision and repeated crushing of the particles of cuttings become more intensive, which result in the generation of particles of finer sizes. The repeated crushing process reaches completion when the particles of cuttings become small enough, that they do not possess sufficiently high momenta for further sever collisions.

2.3 Transport of Crushed Cuttings

After the crushing process is completed, the kinetic energy of the gas would be consumed mainly in transporting the cuttings and in overcoming friction. At this stage, the effect of gravity on the movement of cuttings should be negligible. Smaller sized cuttings and the gas should form a homogeneous mixture, with an approximately the same flow velocity. In this condition, the mixture of the cuttings and the gas may be considered as a single phase, and their transport may be analyzed using the kinetic energy theory[Guo et al. (1994)], and not necessarily the theory of cuttings-slip.

3 Mathematical Modeling for the Distribution of Particle Sizes in the Annulus

In gas drilling, the transport of cuttings relies mostly on the high speed gas flow, while different intensities of repeated crushing between cuttings and the drill string, between the cuttings and the borewell wall, and between the cuttings and cuttings themselves, can occur at different depths. This is indeed a very complex process involving many factors, including the rock's physical properties, fluid properties, fluid velocity, pipe motion, and the string and borehole geometries. The particles of cuttings with different sizes behave differently during the crush-transport process. Thus, a time-dependent mathematical model which describes the distribution of particles of cuttings in the borehole, is needed to understand the mechanism of transport of the cuttings. To derive such a model, the following assumptions are made:

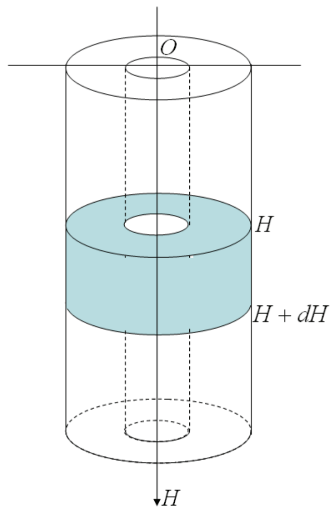

Figure 1: Geometrical sketch of a borehole element where cuttings crushing occurs.

1. As shown in Figure 1, in a small distance from H to H+dH, the cuttings and the gas mix evenly and instantly, after the crushing, while traveling a distance dH.

2. The process of the lifting of the particles consists of the superposition of crush and transport, controlled by the physical properties and sizes of the particles of cutting. The transport of the cuttings occurs only in the axial direction.

3. The system of particles can be divided into *n* particle groups, with different ranges of the sizes of particles. A particle concentration function for group *i* , denoted by *Ci* (H,t), can represent the characteristics of all particles in that group, as a function of location and time.

3.1 Concentration of the Particles of Cuttings[Lu et al (1998)]

By defining $Q_i(t)$ as the total mass of the particles of the size of level-i at time t, the change of mass over the time interval dt is $dQ_i(t)/dt$. This change of mass is equal to the mass of new particles falling into this group from the group with larger particles, minus the mass of particles leaving this group to the group with smaller sizes, during the time period dt. The latter term is expressed as $S_iQ_i(t)$, where S_i is the c probability of of crushing of the level-i particles per unit time, known as the selection function. The former term is $\sum_{j-1}^{i=1} S_jB_{ij}Q_j(t)$, where B_{ij} is the proportion of the level-j particles ($j<i$) becoming particles of level-i after being crushed. It is known as crushing function with expression of $B_{ij} = \left(1-e^{-i/j}\right)/\left(1-e^{-1}\right)$. Therefore, in the time interval dt, the mass increment of the level-i particles is:

$$\frac{dQ_i(t)}{dt} = -S_iQ_i(t) + \sum_{j-1}^{i=1} S_jB_{ij}Q_j(t) \quad i = 1, 2, \cdots, n \tag{1}$$

By substituting $Q_i(t) = C_i \cdot dH$ into Eq. (1), we obtain Eq. (2) which presents the mass change of level-i particles due to crushing:

$$\frac{\partial C_i}{\partial t} \cdot dH = -S_iC_idH + \sum_{j-1}^{i=1} S_jB_{ij}C_idH \quad i = 1, 2, \cdots, n \tag{2}$$

Dividing the both sides of Eq. (2) by dH gives the concentration (C_i) as a function of time.

$$\left.\frac{\partial C_i}{\partial t}\right|_{crush} = -S_iC_i + \sum_{j-1}^{i=1} S_jB_{ij}C_i \quad i = 1, 2, \cdots, n \tag{3}$$

3.2 The Transport of Particles of Cutting by Gas Flow

Particles, with various diameters, which are generated by the drill bit are carried by the gas flow to the wellhead. The mass transport of the level-i particles under steady-state conditions at well depth H is expressed as

$$J_i^H = V_i^H A_i \tag{4}$$

In Eq. (4), J_i^H is the amount of mass transported for level-i at well depth H ($kg/m^2 \cdot s$), V_i^H represents the coefficient of mass transport (m/s), which can be considered to be the velocity of level-i particles at well depth H, A_i stands for the concentration of level-i particles at well depth H (kg/m^3), which can be expressed as $A_i = C_i/S$ where, S is the cross-section area of annulus.

Without the consideration of the crushing effect, the mass change of level-i particles in a borehole interval of depth is only induced by the gas flow. The mass of level-i particles in the interval, entering from the cross-sectional plane at $H+dH$, from t to $t+dt$, is $J_i(H+dH)S\cdot dt$, and the mass leaving the interval at the cross-section plane H is $J_i(H)S\cdot dt$. Thus, the change of mass of the level-i particles , which is triggered by the transport is:

$$dM_i = [J_i(H+dH) - J_i(H)]S\cdot dt \tag{5}$$

And the change of mass of the level-$i$particles in the interval dt is:

$$dM_i' = [C_i(H,t+dt) - C_i(H,t)] \tag{6}$$

Since

$$dM_i = dM_i' \tag{7}$$

Eqs. (5) and (6) can be combined to yield:

$$\left.\frac{\partial C_i}{\partial t}\right|_{trasport} = \frac{\partial J_i(H)}{\partial H}S \tag{8}$$

Considering Eq. (4), we have:

$$\left.\frac{\partial C_i}{\partial t}\right|_{transport} = -V_i^H\frac{\partial C_i}{\partial H} \quad i = 1,2,\cdots,n \tag{9}$$

Eq. (9) is the equation for the concentration (C_i), solely due to the transport effect. The process of lifting of the cuttings should consider both the effects of supersession of crushing as well as of transport . The overall expression for the concentration distribution is the sum of Eq. (3) and Eq. (9), i.e.,

$$\frac{\partial C_i}{\partial t} = -S_iC_i + \sum_{j-1}^{i=1} S_jB_{ij}C_i - V_i^H\frac{\partial C_i}{\partial H} \quad i = 1,2,\cdots,n \tag{10}$$

which is the governing equation for the concentration of level-i particles, as a function of both the time and the location.

The controlling parameter in Eq. (9) is the mass transport coefficient V_i^H, which is the velocity of level-i particles at well depth H. This mass transport coefficient can be analyzed. In the borehole annulus, the gas velocity is higher than the slip velocity, in order to achieve a positive upward motion of particles. Based on the theory of gas-solid two phase flow, the particle velocity is theoretically equal to the difference between the gas velocity and the slip velocity:

$$V_i^H = V_g^H - V_{io} \tag{11}$$

where, V_g^H is the gas velocity at well depth H (m/s) and V_{io} is the slip velocity of level-i particles (m/s). The gas velocity in the annulus can be obtained based on gas vertical lifting model and the gas law for ideal gas [Gas Research Institute (1997)]:

$$V_g^H = \frac{T_H P_0 Q_g}{T_0 S} \cdot \frac{1}{\sqrt{\frac{Q_g^2 \cdot b}{a} \cdot (e^{aH} - 1) + P_0^2 \cdot e^{aH}}} \tag{12}$$

where $a = \frac{2g}{ZRT_H}$ and $b = \frac{16P_0^2}{\pi^2 D^5}$. The slip velocity for level-i particles is expressed as[12]

$$V_{io} = \sqrt{\frac{4gD_i\left(\rho_s - \rho_g^H\right)}{3\rho_g^H C_D}} \tag{13}$$

where, T_H and ρ_g^H are the average temperature (^{o}K) and the density (kg/m^3) at well depth H, respectively; T_0 and P_0 are the local temperature and pressure (Pa) in the well site; Z and R are compression factor and gas constant respectively; Q_g, D_i and C_D are the gas injection rate(Nm^3/min), particle diameter (m) and drug coefficient, respectively.

4 Computational Example

The distribution of the concentration of particles of cuttings, along the borehole, can be estimated by simulating the process of generating the cuttings with the developed mathematical model. Solving the concentration C_i in Eq. (10) for transient flow is difficult. However, in the normal drilling operation, the whole system is steadt-state, that is, the concentration C_i for every level of particles is independent of time ($\partial C_i/\partial t = 0$). The computational difficulty is then much reduced. The parameteric values used in the present simulation case are illustrated in Table 1.

Figure 2 shows the calculated slip velocity of particles of different diameters. It is seen that the slip velocity for cuttings of a larger size is more sensitive to the well depth than that for the smaller size cuttings. That is because the settling of larger particles is dominated more by gravity than by gas density; while the settling of small particles is resisted more by the dense gas, than by gravity at a greater depth.

The collision and crushing of the particles with the wellbore wall, with the drill string, and with the other particles are random, which means that some levels of

Table 1: Parametric values used in the present numerical simulation

Wellbore Geometries:		Formation Parameters:				
Well Depth (m)	2000	Surface Temperature (°)				22
Casing Depth (m)	300	Formation Temp. Gradient (°/m)				0.03
Drill Collar Length (m)	150	Drilling Parameters:				
Drill Bit Diameter (in)	8.5	Rate of Penetration (m/hr)				170
Casing ID (in)	9.625	Gas Injection Rate (Nm^3/min)				100
Drill Collar OD (in)	6.625	Wellhead Pressure (MPa)				0.1
Drill Collar ID (in)	2.8125	Characteristic Particle Diameter (mm) and the Initial Concentration (kg/m)				
Drill Pipe OD (in)	4.5	9	5.93	1.48	0.375	0.12
Drill Pipe ID (in)	3.826	1.096	0.548	0.548	0.274	0.274

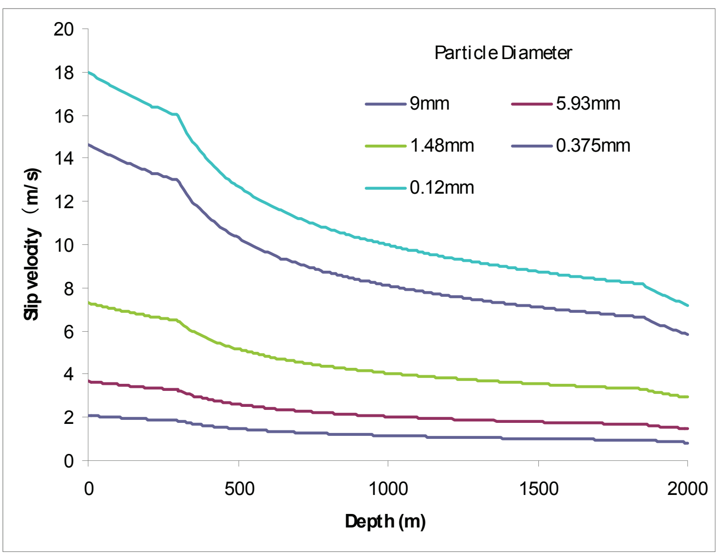

Figure 2: Calculated particle slip velocities for particles of different sizes sizes in a borewell

particles being crushed are more and some other levels are less. However, it is believed that large particles are more vulnerable to crushing than smaller particles, due to their low mobility. Most collisions occur between the cuttings, and those with the borewell wall/drill string are with certain angles, which dramatically reduces the probability of crush of small particles. The values selected for S_i are shown in Table 2. When the particles are crushed, the probability to form small particles varies. The probability for large particles to be crushed into mid-size particles is higher than than to be crushed into small-size particles. As a result, due to collision and crush of cutting particles, the concentration of smaller particles is always higher than that of particles that are larger than but close to their sizes at a given well depth H.

Table 2: Parametric values used in the computations of the crushing of cuttings

Characteristic Particle Diameter (mm)	Particle Crushing Function B_{ij}					Particle Crushing Probability S_i
9	0					0.05
5.93	0.763	0				0.045
1.48	0.240	0.349	0			0.0275
0.375	0.065	0.097	0.354	0		0.01
0.12	0.021	0.032	0.433	0.433	0	0.002

Using the data presented in Tables 1 and 2 and Figure 1, Eq. (10) was first solved for C_1 and then the values forC_2, C_3, C_4, C_5 were calculated sequentially. The results are plotted in Figure 3. As indicated in the figure, when the rock-formation is first crushed by the drill bit teeth, at bottom of the hole, the concentration of large cuttings particles (D_1= 9mm) is the highest. Because the crush probability for the largest cuttings is the highest, continuous collision occurs between the cuttings and the borewell wall/drill string, resulting in the rapid drop in the concentration of the largest particles. While particles are carried to shallower depths, due to the decrease of particle concentration and the increase of the vertical velocity, the probability of the collision between cuttings of size D_1 and the borewell wall/drill string decreases, so that the particle concentration tends to stabilize as they approaches the surface. The concentration of particles of size D_2 declines as the depth decreases. This is because the amount of particles changing from size D_1 to size D_2 is greater than the total amount of particles changing from size D_2 to sizes D_3 , D_4, and D_5 while travelling up the borehole. The concentration of particles of size D_3 remains constant, due to the fact that the total amount of particles changing from sizes D_1 and D_2 to size D_3 is equal to the total amount of particles changing from size D_3 to sizes D_4 and D_5while travelling up the borehole. The concentration of particles of size D_4 increases as the depth decreases. This is because the total amount of particles changing from sizes D_1, D_2, and D_3 to size D_4 is greater than the amount of particles changing from size D_4 to size D_5 in the transport process. The concentration of particles of size D_5 increases quickly as the depth decreases. This is because the total amount of particles changing from sizes D_1, D_2, D_3 and D_4 to size D_5 is positive and the amount of particles changing from size D_5 to smaller size is zero which a boundary condition set in the simulation.

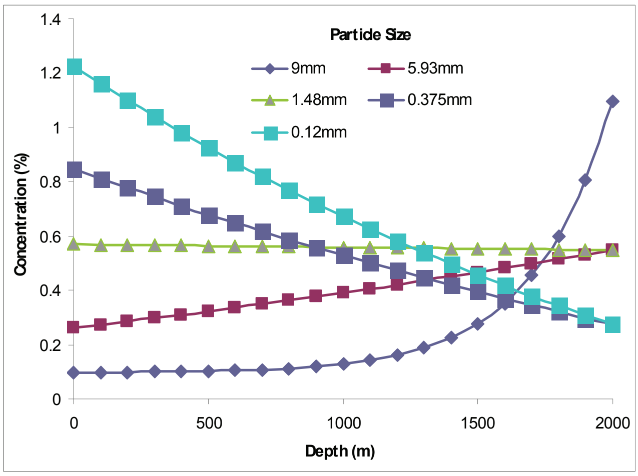

Figure 3: Computed particle concentration profiles for different levels of particle characteristic diameter

5 Field Data Analysis

It is desirable to conduct experimental tests for validating the presented mathematical model and the results from the crushing-transport theory. However, obtaining cuttings samples from various depths in the wellbore is not realistic. Therefore, cuttings sieve tests were run using the cuttings samples collected from 3 wells drilled with gas in north-western Sichuan, China. The particle diameters were determined based on the different sieve sizes. The following issues were considered in obtaining the samples of cuttings:

1. Quantity of sample: To ensure that the sample of cuttings will contain the full range of sizes that are representative of the reality in the borehole, the

quantity of each sample was controlled to be no less than 100g with a typical range from 100g to 200g.

2. Depth of samples: The samples collected should cover a certain depth range. The rock formations at different depths are under different stresses, and thus the cuttings formed in drilling are also different. Through collecting samples of cuttings from various well depths, the distribution of concentration of particles with the same lithology was analyzed.

3. Lithology consistency: When collecting samples of cuttings at a certain well depth, the lithology consistency should be ensured. A sample of cuttings from a given depth should be either sandstone or mudstone, for data quality control.

4. Lithology diversity: The lithology diversity is required to validate the theory, with cuttings from different types of rocks. In other words, samples need to cover multiple formation intervals, such as sandstone, mudstone, etc., so that the effect of lithology on the particle concentration distribution can be studied. Taking well No. 1 as an example, the cuttings carried out to the wellhead were generated by an air hammer that crushed the formation rock at a depth interval from 305m to 2000m. Mudstone dominated the overall lithology. Samples were collected every 50m with the weight about 100g per pack. Figure 4 shows dried cuttings samples from Well No. 1.

Figure 4: Cuttings in different samples collected from Well No. 1.

Cuttings with an equivalent diameter greater than 0.55mm were classified as large size cuttings, 0.55mm$\sim$0.05mm were referred to as medium size cuttings, and those less than 0.05mm were considered to be small size cuttings. Figure 5.a presents the concentration profile of small cuttings collected from Well No. 1. It shows that the concentration of small cuttings increased as the borehole was deepened. This is consistent with the theory of collision and crushing in the annulus because the deeper the borehole is, the more collision and crushing can occur in the long annulus that results in the formation of more smaller cuttings.

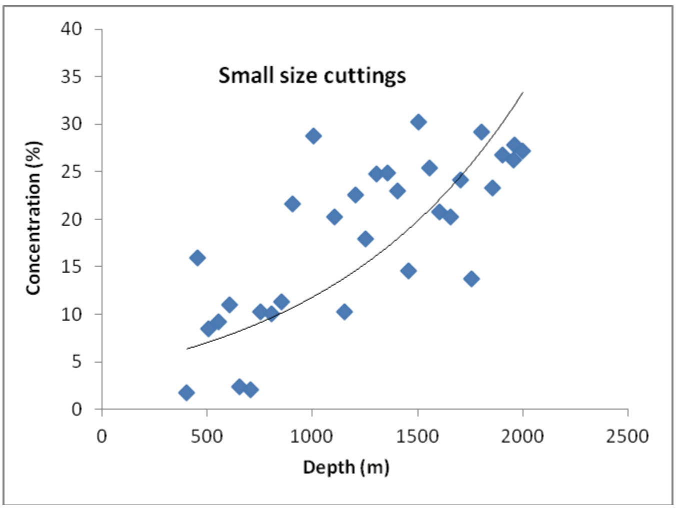

Figure 5.a: Concentration of small-sized cuttings increases with depth in Well No. 1

Figure 5.b demonstrates the concentration profile of middle size cuttings collected from Well No. 1. It indicates that the concentration of middle size cuttings remains almost constant as the borehole was deepened. This is consistent with the theory of collision and crushing in the annulus because the amount (weight) of large cuttings which change to the middle size cuttings is approximately equal to the amount (weight) of middle size cuttings which change to small-size cuttings at all depths.

Figure 5.c illustrates the concentration profile of large cuttings collected from Well No. 1. It indicates that the concentration of large cuttings decreased as the borehole was deepened. This is consistent with the theory of collision and crushing in the annulus because the deeper the borehole is, the more collision and crushing can occur in the long annulus that results in less amount of remaining large cuttings received at surface.

Figures 6 and 7 present concentration data for cuttings collected from Well No. 2 and Well No. 3. They show the same trends as observed from the data for Well No.

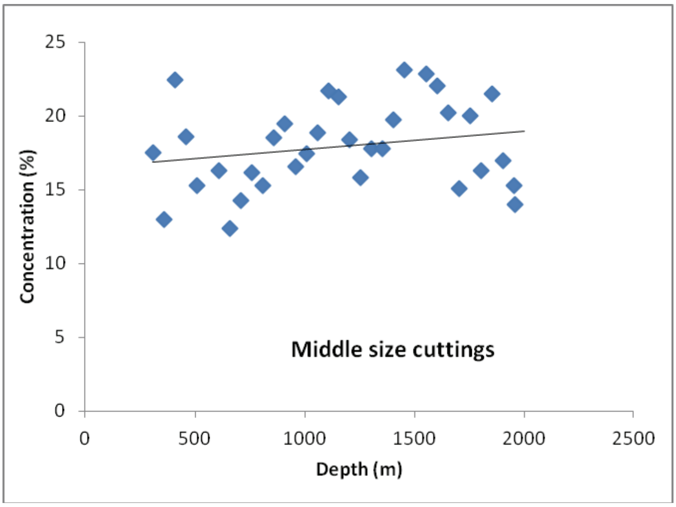

Figure 5.b: Concentration of mid-size cuttings does not change with depth in Well No. 1

1. The good consistency between the data from the 3 wells proves the validity of the method of analysis and the developed theory.

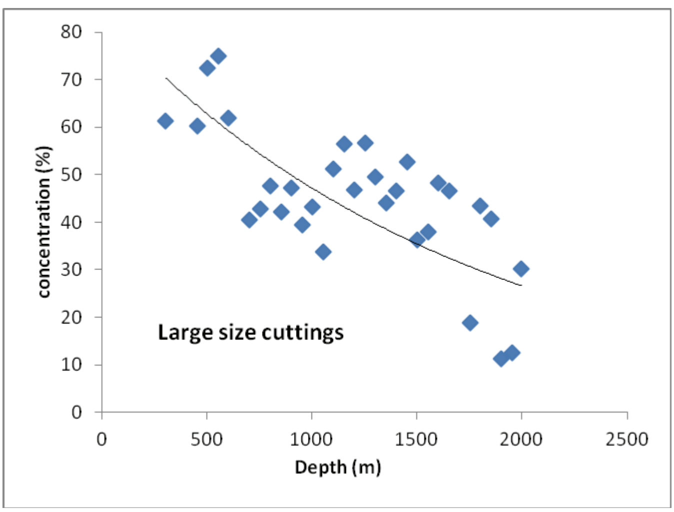

Figure 5.c: Concentration of large cuttings decreases with depth in Well No. 1

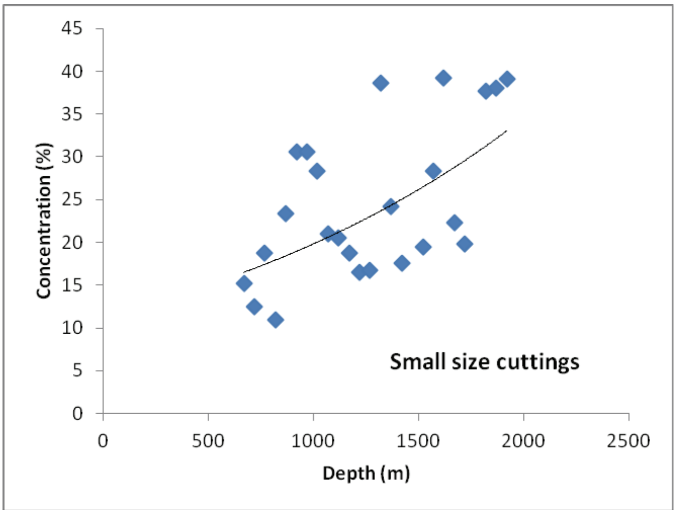

Figure 6.a: Concentration of small cuttings increases with depth in Well No. 2

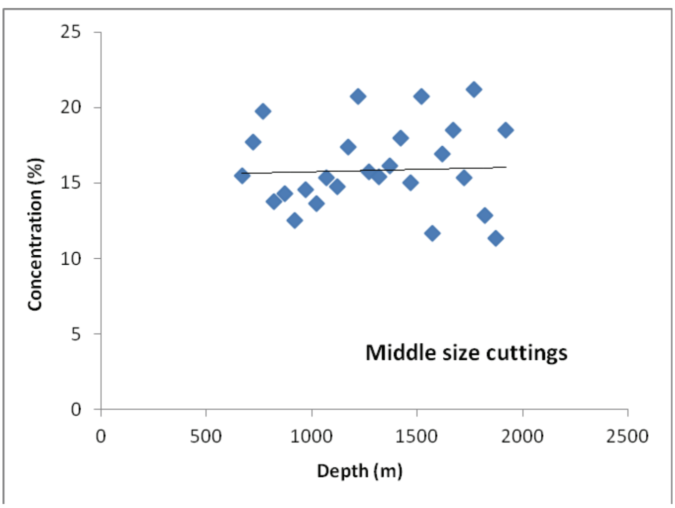

Figure 6.b: Concentration of mid-size cuttings does not change with depth in Well No. 2

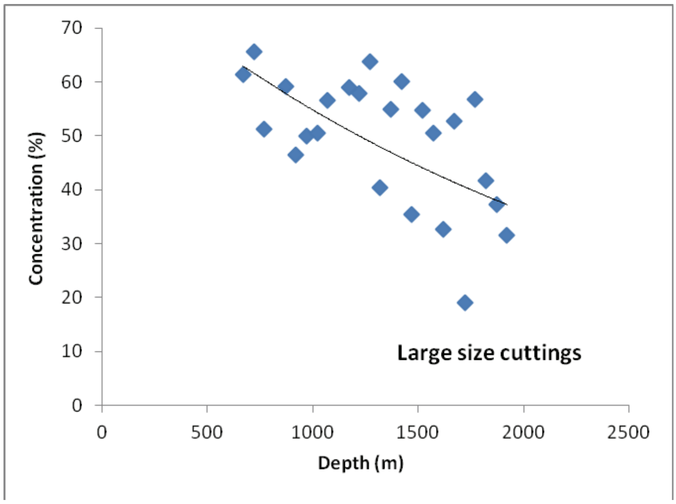

Figure 6.c: Concentration of large cuttings decreases with depth in Well No. 2

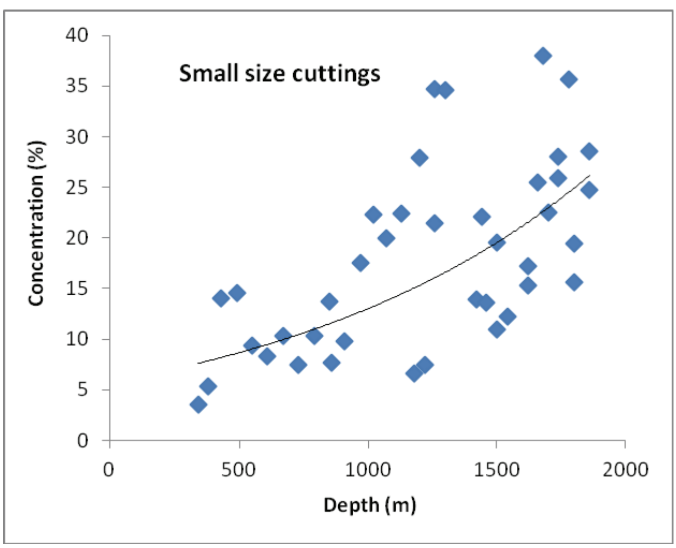

Figure 7.a: Concentration of small cuttings increases with depth in Well No. 3

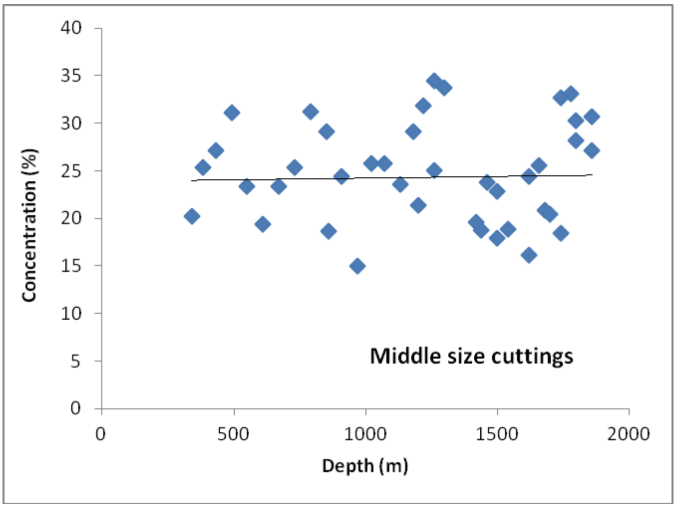

Figure 7.b: Concentration of mid-size cuttings does not change with depth in Well No. 3

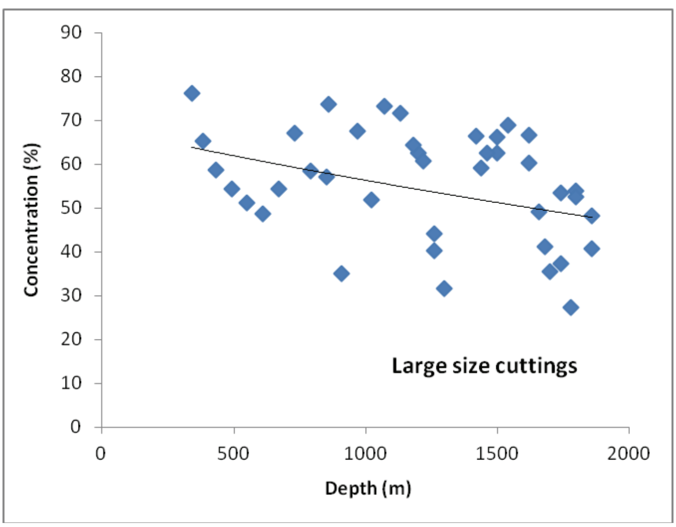

Figure 7.c: Concentration of large cuttings decreases with depth in Well No. 3

6 Conclusions

1. An analytical model was developed in this study to investigate the changes of sizes of rock-cuttings in gas drilling. The present model explains why the cuttings which are received at the surface of the borewell, in gas drilling are much smaller than those from mud drilling. An analysis of the data of cuttings, from 3 different wells drilled with gas, proves that the theory behind the analytical model is valid.

2. There exist three different phases of generation of cuttings, and their transport, in gas drilling: a) large cuttings are created by the drill bit, b) larger cuttings are re-crushed by the drill string, and the other cuttings themselves, into smaller cuttings while they are travelling upward in the annulus, and c) small cutting are carried to the surface of the borewell, by the flow of gas.

3. Both the transport and the collision affect the concentrations of cuttings of different sizes at a given depth under steady flow conditions. These effects can be coupled in a mathematical model.

4. Numerical simulation shows that, as the borehole deepens, the concentration of large cuttings decreases, and the concentration of small cuttings increases, due to re-crushing of the cuttings in the annulus.

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References

Angel, R. (1957): Volume Requirements for Air or Gas Drilling. *Trans. AIME*, Vol. 210, pp. 325-330.

Chen, G.; Chen, X. (2006): The Application of Air and Air/Foam Drilling Technology in Tabnak Gas Field, Southern Iran. *The IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition*, Bangkok.

Gas Research Institute. (1997): Underbalanced Drilling Manual, GRI Reference No. GRI-97/0236.

Guo, B.; Miska, S.; Lee, R. (1994): Volume Requirements for Directional Air Drilling. *The SPE/IADC Drilling Conferenc*, Texas.

Guo, B.; Ghalambor, A.; Xu, C. (2006): A Systematic Approach to Predicting Liquid Loading in Gas Wells, *SPE Production & Facilities Journal*, Vol. 21, PP.81-88.

Li, J.; Liu, G. H.; Guo, B, Y. (2012): Pilot Test Shows Promising Technology for Gas Drilling. *JPT*, Vol.7, pp. 32-37.

Lu, H. G. (1998): Introduction to Powder Technology, Tong-Ji University Press.

Wolcott, S.; Sharma, P. (1986): Analysis of Air Drilling Circulating Systems With Application to Air Volume Requirement Estimation. *The SPE Eastern Regional Meeting*, Ohio.

Yang, S. J.; Liu, G. H.; Li, J. (2012): The characteristics of recycling gas drilling technology. *Petroleum Science*, No.1, pp. 59-65.

Zhu, H.; Meng, Y. (2010): Influence of Relevant Parameters on Hole Cleaning and Pipe String Erosion in Air Drilling. *The SPE Oil and Gas India Conference & Exhibition,* Mumbai.