Enhancing cuttings removal with gas blasts while drilling on Mars

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[1] Future missions to Mars envision use of drills for subsurface exploration. Since the Martian atmosphere precludes the use of liquids for cuttings removal, proposed drilling machines utilize mechanical cuttings removal systems such as augers. However, an auger can substantially contribute to the total power requirements, and in the worst scenario it can choke. A number of experiments conducted under Martian pressures showed that intermittent blasts of gas at low differential pressures can effectively lift the cuttings out of the hole. A gas flushing system could be incorporated into the drill assembly for assistance in clearing the holes of rock cuttings or for redundancy in case of auger jamming. A number of variables such as the particle size distribution of the rock powder, the type of gas used, the bit and auger side clearances, the initial mass of cuttings, and the ambient pressure were investigated and found to affect the efficiency. In all tests the initial volume of gas was close to 1 L and the differential pressure was varied to achieve desired clearing efficiencies. Particles were being lifted out of the hole at a maximum speed of 6 m/s at a differential pressure of 25 torr and ambient pressure of 5 torr. Flushing tests lasted on average for 2 s. The power required to compress the thin Martian atmosphere to achieve a sufficient gas blast every minute or so at 10% efficiency was calculated to be of the order of a few watts.

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1. Introduction

[2] Conventional earth drilling uses liquid or air for flushing the rock cuttings from the hole bottom. The flushing medium has the dual purpose of removing the newly formed rock debris as well as cooling down the drill bit. Removing the rock cuttings in a timely manner in itself contributes to keeping the bit cool. This is because up to 70% of heat generated during the rock breaking process is trapped in the cuttings [*Uhlmann et al.*, 2003]. On Mars the atmospheric conditions, which are close to the triple point of water preclude the use of liquids. Continuous circulation of Martian air, according to *Blacic et al.* [2000], on the other hand, requires more compressor power than is likely to be available in currently planned Martian landers. This statement, however, needs to be investigated again as *Blacic et al.* [2000] assumed the rock debris to be larger than the actual rock cuttings produced by diamond drilling, the drilling method most likely to be used on Mars.

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[3] The majority of the proposed Martian drills utilize an auger for cuttings removal. The problem with augers is that they do not work well at low rotational speeds and for small diameter drills [*Mellor*, 1981]. Instead of relying on the centrifugal force and the friction against the casing or a bore hole wall for cuttings removal, the auger now has to rely on a volumetric displacement of rock powder and the reaction from the newly formed cuttings on the hole bottom. This in turn leads to excessive friction, which could consume too much power, or in an extreme case, cause the auger to choke.

[4] If the power required for cuttings removal exceeds the maximum power provided by the Martian lander, the drill will jam and the mission fails. Therefore another system for cuttings removal must be incorporated for assisting in cuttings removal or for redundancy in case of auger choking. Since the rate of penetration during coring under simulated Martian conditions was found by the authors to be strongly dependent on the efficiency of the cuttings removal system, it would be more effective to use an additional method for cuttings removal in parallel with the auger. One of the possible methods of removing cuttings

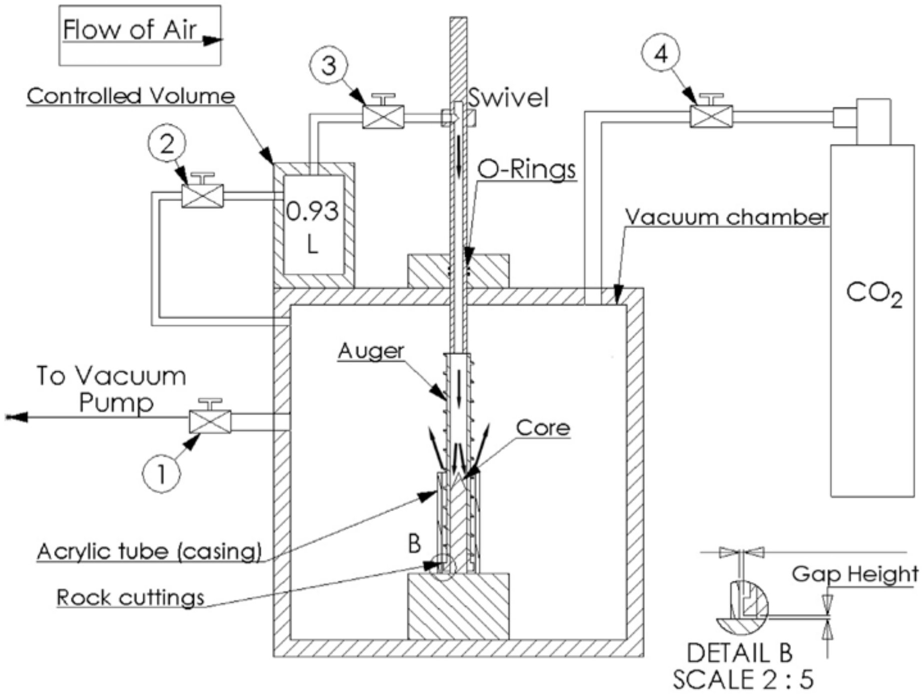

Figure 1. Experimental arrangement.

from the hole bottom is by intermittent gas blasts, which has proven effective [see *Zacny et al.*, 2004]. The gas can be provided either from pressurized gas canisters brought from Earth or by an in situ compressor. The power required to compress the Martian atmosphere to a useful pressures between the consecutive gas blasts (every minute or more) was found to be of the order of few watts, which is well within the power budgets of the current or proposed Mars missions.

[5] The current work addresses issues related to the gas blasts. In all tests, 0.93 L of gas at various pressures was used to clear the cuttings from the hole bottom. The parameters that were investigated included the particle size, the differential pressure, the ambient pressure, the initial amount of rock powder, the gap distance between the drill and the hole bottom, the annular clearance, as well as different gases. In addition, extra tests were performed to establish the precision of the data and to determine whether tests can be reproducible. A set of tests was also filmed to investigate the flow regime and to determine the velocity of the cuttings leaving the bore hole and the duration of the gas blasts.

2. Experimental Details

[6] Figure 1 shows the experimental arrangement used for the tests. In order to simulate the gas blasting experiments, a few modifications were made to an existing vacuum chamber that was constructed for drilling under simulated Mars like environment. In particular, the air swivel was added to the drill string assembly, acrylic tubes of different lengths and diameters were attached to the base to simulate the borehole or a casing and a metal rod was attached to the center of the base to simulate the rock core (see also Figures 2 and 14).

Figure 2. Actual experimental arrangement showing the bit with the auger, aluminum core, acrylic tube and rock dust. (left) The drill, metal core, clear tube, and rock powder during a vacuum pumpdown. (right) Prior to gas flushing, the drill was lowered into the tube while rotating.

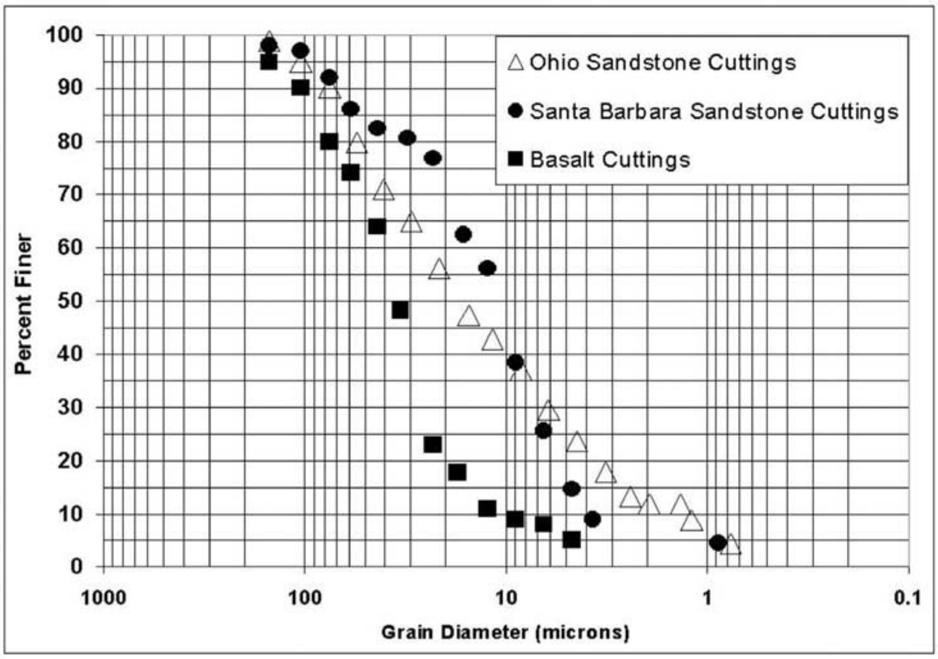

Figure 3. Particle size distribution of the three rock powders used during experiments.

[7] The drill string used in all the experiments was the same as used during drilling tests under Martian conditions reported by *Zacny et al.* [2004]. The drill was developed by the NASA Johnson Space Center and its industry partner.

[8] Figure 2a shows the actual test arrangement just before the gas flushing experiment. In this particular case, the diameter of the tube was 50 mm and the length of the tube was 150 mm. The diameter of the bit was 44 mm while that of the auger was 39 mm.

[9] The authors were concurrently investigating the behavior of drill bits under Martian conditions. The drill in Figure 14 was one of the actual drills being used for Mars drilling tests. All the results presented in this paper pertain strictly to this bit geometry and most probably will differ if the geometry of the bit is changed. Therefore it is imperative to redo the tests for the new bit geometry in order to obtain accurate results.

2.1. Parameters Investigated

[10] The following is a list of the independent variables or test parameters that were investigated. In all tests, the independent variable was the differential pressure, i.e., the pressure between the 0.93 L chamber pressure and the ambient or the main chamber pressure. The volume of gas was always kept constant at 0.93 L (0.93 dm^3).

2.1.1. Rock Powder Used in the Experiments

[11] Three different rock powders (also referred to as rock cuttings) were used for the gas blast experiments. These were rock cuttings obtained from diamond coring of Ohio Sandstone (OHSS), Santa Barbara Sandstone (SBSS) and Basalt rocks. Particle size distribution was measured using wet sieving and a Hydrometer analysis according to the American Society for Testing and Materials standards ASTM D421-85 and D422-63 and the results are plotted in Figure 3. More than 90% of all particles were smaller than 100 microns and in the case of the sandstones almost 50% of all particles were smaller than 10 microns. In addition the Basalt rock particles were larger than either of the sandstone rock particles. In particular, for Basalt D_{10} = 10% and for Santa Barbara Sandstone D_{10} = 50%. This had a major effect on the efficiency of the gas flushing.

2.1.2. Chamber or Ambient Pressure

[12] The chamber pressure was defined as the ambient pressure inside the main vacuum chamber shown in Figure 1. This pressure was kept within the range of pressures found on Mars. Three different pressure values were investigated: 5 torr, 7 torr and 10 torr (1 torr = 133 Pa).

2.1.3. Gap Distance or Gap Height

[13] Gap height, also refereed to as the gap distance, was the distance between the bottom of the bit and the surface of the hole bottom as shown in "Detail B" in Figure 1 and in Figure 14. Two gap heights were investigated: 2.5 mm and 5 mm. The purpose of the experiments was to determine how and to what extent the gap height affect the efficiency of cuttings removal. The question asked was whether lifting the drill of the bottom hole would improve the efficiency of the gas flushing or not.

2.1.4. Gas Type

[14] Two gas types were used for gas flushing: atmospheric air and carbon dioxide (CO_2). The goal was to determine whether atmospheric air can be a conservative substitute for CO_2 in gas flushing experiments conducted on Earth.

2.1.5. Annular Clearance

[15] The bit diameter was 44 mm and the auger diameter was 39 mm, as shown in Figure 1. Figure 2a shows a set up prior to the test. Shown are a clear acrylic tube, the drill and the rock powder. The tube was used to simulate a casing or a borehole. Two different tube diameters were used, namely 44 mm and 50 mm. Although, in order for the 50 mm diameter hole, the bit itself had to be 50 mm, the goal was to determine whether and to what extent the annulus clearance

Figure 4. Depth of the rock powder above the hole bottom. Scale is in inches.

between the 39 mm diameter auger and the tube affects the efficiency of the cuttings removal process.

2.1.6. Initial Mass of Powder

[16] The purpose of using different powder mass was to determine the relationship between the initial mass of cuttings and the differential pressure and whether there exists an optimum mass value that is easiest to flush out.

[17] Figure 4 shows a close up of the drill, the clear acrylic tube, representing the bore hole wall or a casing, and the rock powder inside the acrylic tube prior to the test. The ruler on the right-hand side shows the depth in inches. The depth of the rock powder covering the drill was a function of the mass of the rock powder. In Figure 4, 25 g of rock powder covered the drill to the depth of 28 mm. Figure 5 shows the depth of the rock powder as a function of the mass in the 50 mm diameter acrylic tube. The data points were generated by taking photographs like those shown in Figure 4 and reading the depth off the ruler. Prior to the measurement, the drill was turned several times to stir the powder. This was to simulate the conditions that exist during the gas flushing tests. It was assumed that the powder porosity was similar in all tests.

2.1.7. Effect of Tube Surface Roughness

[18] After each test there was a residue of the dust left behind on the inner surface of the tube. In order to determine the effect of this thin dust layer adhering to the tube it was decided to perform a series of tests with a clean and a dusty tube. Since the surface roughness affected the friction drag, the difference between the clean and a dirty tubes was expected to be significant.

2.2. Testing Procedures

[19] The initial tests showed that even small changes in parameters could affect the final result. Thus it was imperative to adhere to the same conditions and to follow the same steps in all the tests. This not only included the same test conditions but also the way in which the rock dust was cleaned off the acrylic tube after each test and the way the drill bit was lowered into the rock powder.

[20] The testing procedures described below refer to Figure 1. Each test took approximately 10 min to set up and execute and a total of 282 tests was performed. Not all the data points were included in this paper. Some tests were duplicated to see whether the results were consistent, i.e., to determine the precision of the tests. For a summary of different test conditions, refer to Appendix A.

2.2.1. Procedures for Tests With Atmospheric Air as a Flushing Gas

[21] The following steps refer to the tests conducted with atmospheric air as the flushing medium:

[22] 1. The required mass of rock cuttings was weighed out and poured into the casing.

[23] 2. Valves 1, 2, and 3 were opened, and the main vacuum chamber was pumped down to the desired inlet pressure.

[24] 3. Valves 2 and 3 were closed to keep the 0.93 L chamber at the desired inlet pressure.

[25] 4. The main chamber was pumped down to 5 or 7 torr and then valve 1 was closed, sealing the chamber.

[26] 5. The bit was brought down into the cuttings, 2.5 or 5 mm from the bottom of the borehole.

[27] 6. Valve 3 was opened to eject the cuttings from the borehole.

[28] 7. The main chamber was vented, and the amount of cuttings left in the borehole was weighed to determine the amount ejected.

2.2.2. Procedures for Tests With Carbon Dioxide as a Flushing Gas

[29] The following steps refer to the tests conducted with the carbon dioxide as the flushing medium:

[30] 1. The required mass of rock cuttings was weighed out and poured into the casing.

[31] 2. Valves 1, 2, and 3 were opened, and the main vacuum chamber was pumped down to 3 torr.

[32] 3. Valve 3 was closed, valve 4 was opened, and the chamber was filled with carbon dioxide.

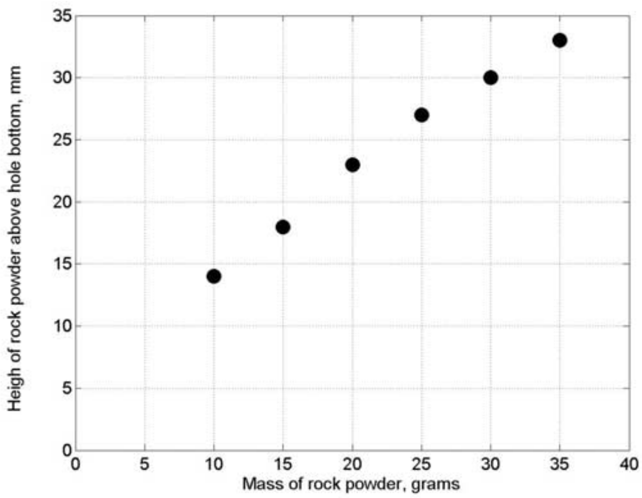

Figure 5. Depth of the rock powder as a function of the rock powder mass in a 50 mm diameter tube.

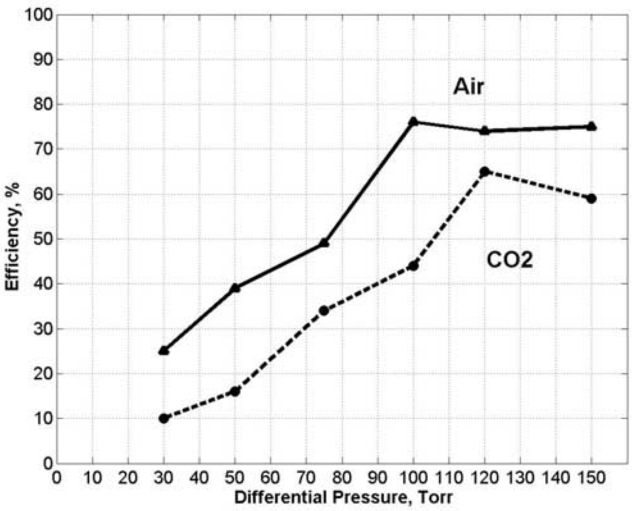

Figure 6. Efficiency of air versus CO_2. Mass of Ohio Sandstone rock powder: 15 g. Test conditions: ambient pressure: 7 torr; gap height: 5 mm; tube diameter: 50 mm.

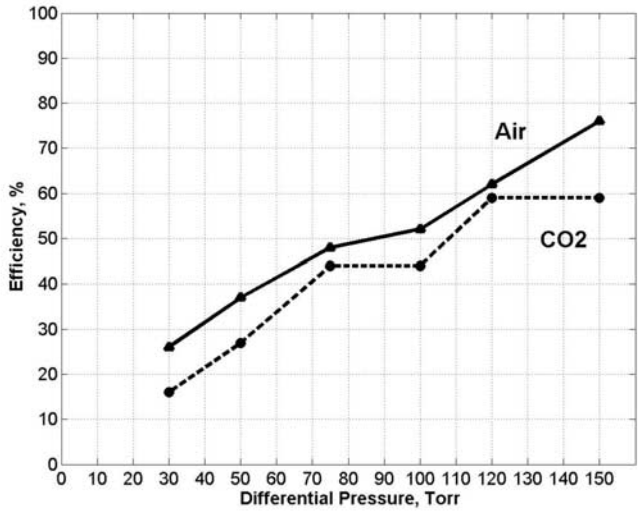

Figure 7. Efficiency of air versus CO_2. Mass of Ohio Sandstone rock powder: 25 g. Test conditions: ambient pressure: 7 torr; gap height: 5 mm; tube diameter: 50 mm.

[33] 4. Valve 4 was closed when the chamber pressure reached 700 torr.

[34] 5. Valve 1 was opened again and the chamber was pumped down to the desired inlet pressure.

[35] 6. Valves 2 and 3 were closed to keep the 0.93 L chamber at the desired inlet pressure.

[36] 7. The main chamber was pumped down to 5 torr and then valve 1 was closed, sealing the chamber.

[37] 8. The bit was brought down into the cuttings, 2.5 or 5 mm from the bottom of the borehole.

[38] 9. Valve 3 was opened to eject the cuttings from the borehole.

[39] 10. The main chamber was vented, and the amount of cuttings left in the borehole was weighed to determine the amount ejected.

3. Results

3.1. Effect of Different Gas on the Clearing Efficiency

[40] For CO_2 flushing, the chamber was pumped down to three torr, filled with CO_2 up to 700 torr, and then pumped down again to the desired chamber pressure. These steps ensured that what remained in the main chamber and in the 0.93 L chamber was almost pure CO_2 (99.5%).

3.1.1. Gas Flushing of Ohio Sandstone Rock Powder

[41] Figures 6, 7, and 8 show the results of gas flushing tests with Ohio Sandstone rock powder in the 50 mm diameter tube. The gap between the drill and the bottom hole was 5 mm and the main chamber pressure was 7 torr. The mass of rock powder in Figures 6, 7, and 8 was 15 g, 25 g, and 35 g, respectively. In all cases the efficiency was higher with air than with CO_2, the largest difference being recorded for 15 g of rock powder (Figure 6). The efficiency also increased gradually as a function of differential pressure.

3.1.2. Gas Flushing of Basalt Rock Powder

[42] Figures 9, 10, and 11 show the results of the gas flushing tests with Basalt rock powder, in the 45 mm diameter tube and at 5 torr ambient pressure. The gap height between the drill and the hole bottom was 2.5 mm. The mass of rock powder in Figures 9, 10, and 11 was 15 g, 25 g, and 30 g, respectively.

[43] All figures showed a cut-off pressure or threshold pressure phenomenon. Below the threshold pressure no cuttings were flushed out of the hole, while above the threshold pressure there was a sudden increase in the cuttings clearing efficiency. This was especially apparent in Figure 10. For the 15 g and 25 g curves (Figures 9 and 10, respectively) the threshold pressure was much lower when air was used as a flushing gas. However, when the initial amount of rock powder was 35 g (Figure 11), the two curves (Air and CO_2) coincided at lower values of differential pressures. At higher values, the CO_2 efficiency became larger. The main trend was that as the initial amount of rock

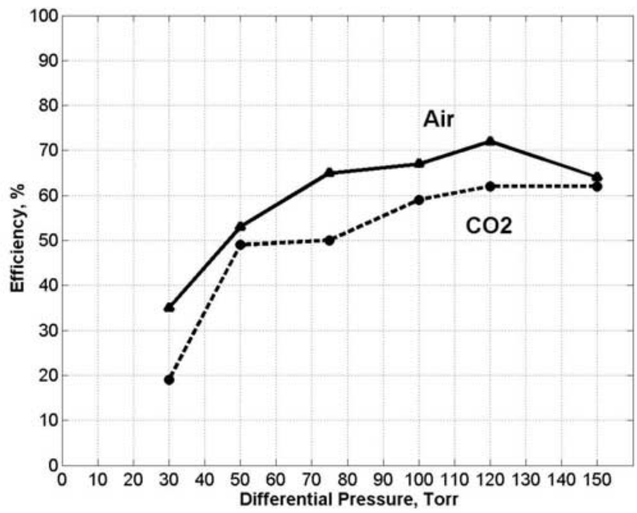

Figure 8. Efficiency of air versus CO_2. Mass of Ohio Sandstone rock powder: 35 g. Test conditions: ambient pressure: 7 torr; gap height: 5 mm; tube diameter: 50 mm.

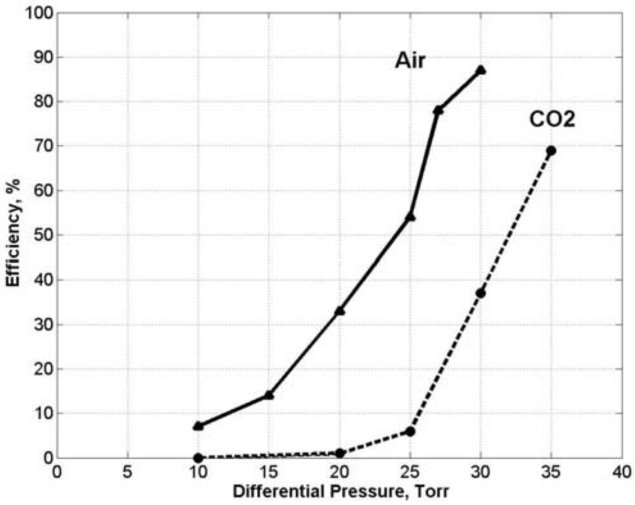

Figure 9. Efficiency of air versus CO_2. Mass of basalt rock powder: 15 g. Test conditions: ambient pressure: 5 torr; gap height: 2.5 mm; tube diameter: 45 mm.

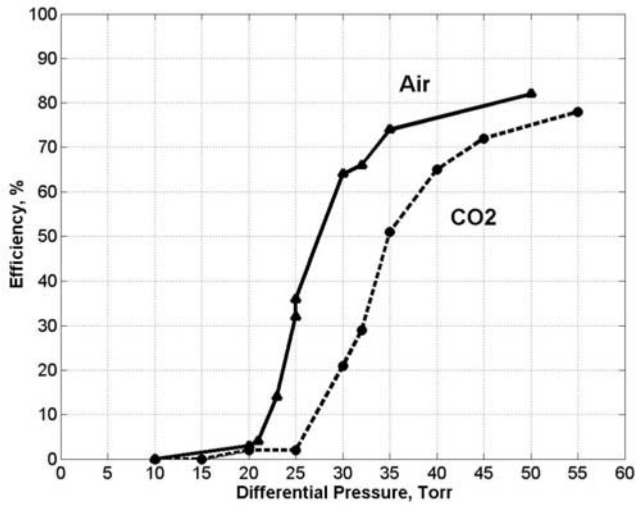

Figure 10. Efficiency of air versus CO_2. Mass of basalt rock powder: 25 g. Test conditions: ambient pressure: 5 torr; gap height: 2.5 mm; tube diameter: 45 mm.

powder increased, the difference between the efficiencies of Air and CO_2 decreased.

3.1.3. Discussion

[44] The exchange of momentum is believed to be the main drive in the clearing of cuttings during gas blasts [*Adewumi and Tian*, 1990; *Tian and Adewumi*, 1992]. First order calculations were made to find out whether the momentum of CO_2 or Air was higher. Using the Bernoulli equation, the momentum equation can be rewritten as

$$mv = (\rho V)\sqrt{\frac{2\Delta P}{\rho}}. \tag{1}$$

[45] The ratio of momentum of two gases is then

$$\frac{(mv)_{CO_2}}{(mv)_{Air}} = \sqrt{\frac{(\rho_{CO_2})}{(\rho_{Air})}}. \tag{2}$$

[46] The molar mass of CO_2(M_{CO_2} = 44 g/mol) is 50% larger than that of the air (M_{air} = 28.8 g/mol). Assuming that both gases behave as an ideal gas, the number of moles of each gas under the same conditions is the same. Therefore the mass and density of the CO_2 gas under the same conditions is 50% larger than the mass or density of Air. Therefore

$$\frac{(mv)_{CO_2}}{(mv)_{Air}} = \sqrt{1.5} = 1.2. \tag{3}$$

[47] Thus the CO_2 has a 20% larger momentum than air and should give higher efficiencies. However, the tests proved otherwise. It is atmospheric air that gives higher efficiency of the gas flushing rather than CO_2. It has been found by others (M. Adewumi, personal communication, 2004) that the velocity of the gas plays a larger role than the mass of the gas molecules. Therefore the conservation of momentum equations must have different coefficients next to the mass and velocity components. These coefficients it seems, differ depending on the gas flushing conditions.

[48] As mentioned previously, the velocity component is more significant, as it explains why air gave higher efficiencies in all but one test.

[49] With Ohio sandstone powder, the difference in efficiencies was highest for 15 g of rock powder. The same was found for Basalt powder. In addition, the difference in efficiencies decreased with the increase in the amount of rock powder. Thus, when the layer of rock powder was relatively small, the gas with a higher velocity gave higher efficiencies. On the other hand, when the layer of rock powder was deeper, it was a gas with higher molecular weight that was more effective.

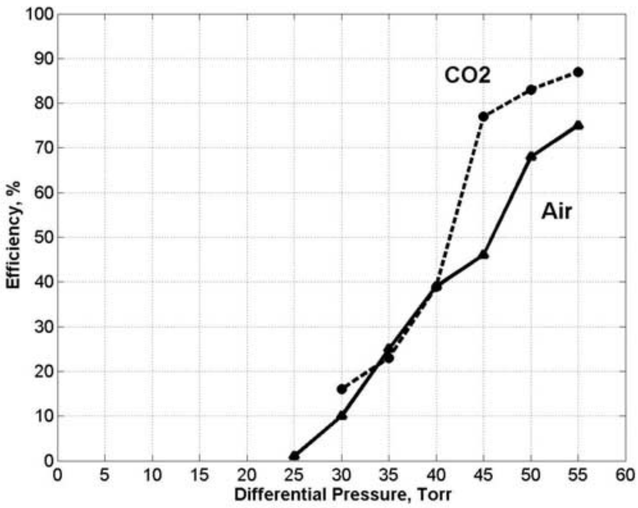

Figure 11. Efficiency of air versus CO_2. Mass of basalt rock powder: 30 g. Test conditions: ambient pressure: 5 torr; gap height: 2.5 mm; tube diameter: 45 mm.

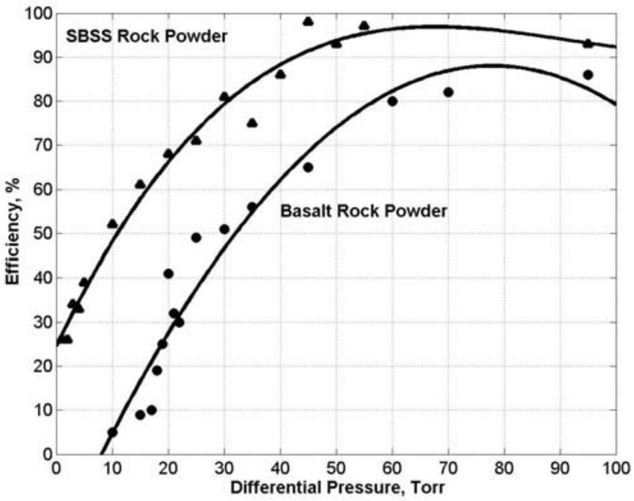

Figure 12. Behavior of Santa Barbara Sandstone and Basalt rock powders as a function of differential pressure. Test conditions: ambient pressure: 5 torr; gap height: 2.5 mm; gas: air; tube diameter: 50 mm; mass of powder: 25 g.

[50] Another way to analyze the above results is by considering the Reynolds number. The Reynolds numbers for Air and CO_2 at 290 K, 6 m/s and 5 torr are 16 and 30, respectively. At 290K, 10 m/s and 30 torr they are 160 for Air and 302 for CO_2. Thus at all pressures, the Reynolds number for air is almost a half of that for carbon dioxide. A lower Reynolds number implies that the viscous forces are dominant over the inertial forces. When considering cuttings removal efficiencies for a low initial mass of rock powder, it is clear that the efficiency with air is much higher. On the other hand, for a larger initial mass of rock cuttings the efficiencies for air and CO_2 are similar. Therefore it can be concluded that the viscous forces are primarily responsible for lifting the smaller amount of cuttings, whereas inertia forces dominate where the layer of rock cuttings is much deeper.

[51] As the above tests showed, the results with air flushing were not conservative. Therefore atmospheric air cannot be used in place of CO_2 when conducting gas flushing tests for Martian drilling applications, unless the data are later adjusted to account for the difference.

3.2. Effect of Different Powders on the Clearing Efficiency

[52] Figure 12 shows the efficiency of the air flushing as a function of the differential pressure for two types of rock powders: Basalt and Santa Barbara sandstone rock powders. The efficiency for the sandstone was much higher, between 10% and 40% better than basalt. This could be explained by the fact that the sandstone had a much larger proportion of finer particles (see Figure 3), which were easier to be flush out. In addition, the particle distribution in the case of sandstone was more uniform, which led to a more packed, less porous structure. The direct effect of this could be seen in Figure 13. The picture shows two tubes placed inside a vacuum at the pressure below the triple point of water. The tube on the right-hand side contained sandstone cuttings,

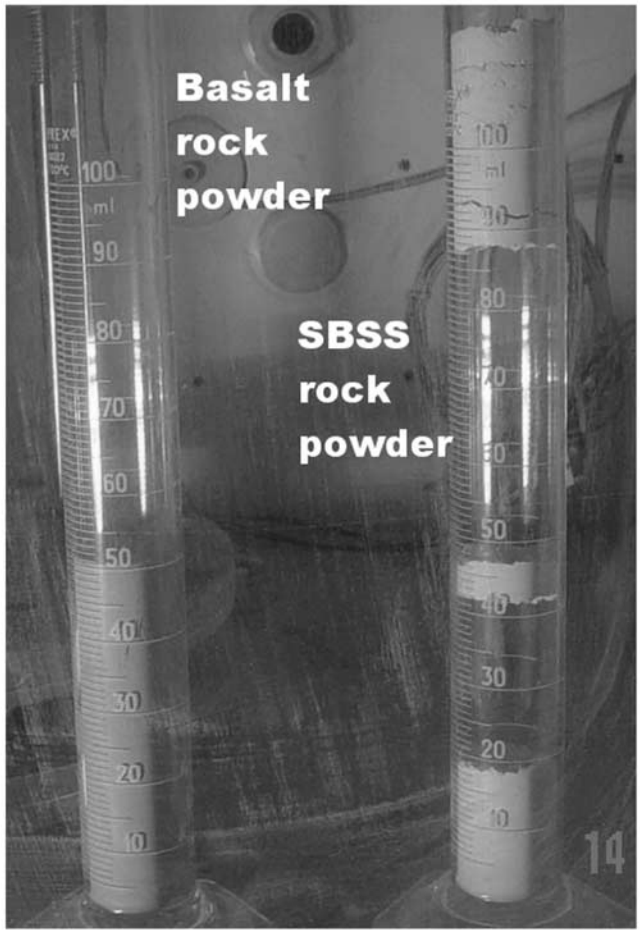

Figure 13. Effect of particle size distribution on powder permeability.

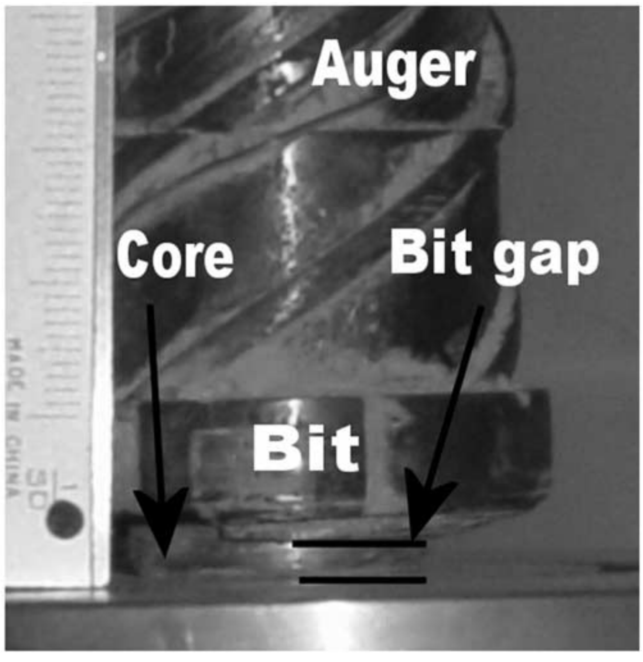

Figure 14. Gap height is between the lowest part of the drill and the surface of the hole bottom. Scale is in inches.

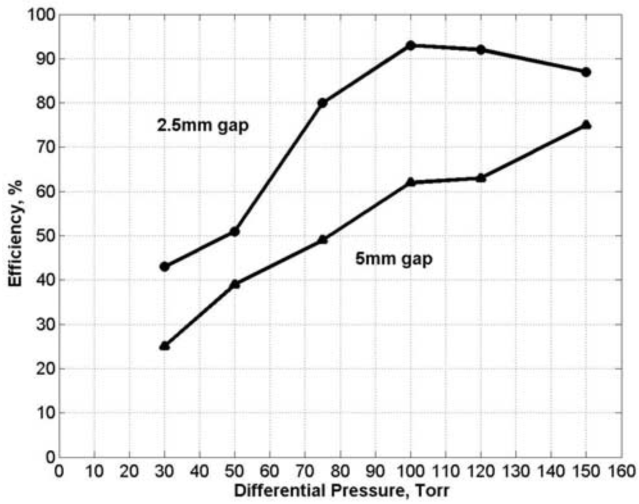

Figure 15. Effect of bottom hole gap height. Mass of powder: 15 g; gas: air. Test conditions: rock powder: OHSS; ambient pressure: 7 torr; tube diameter: 50 mm.

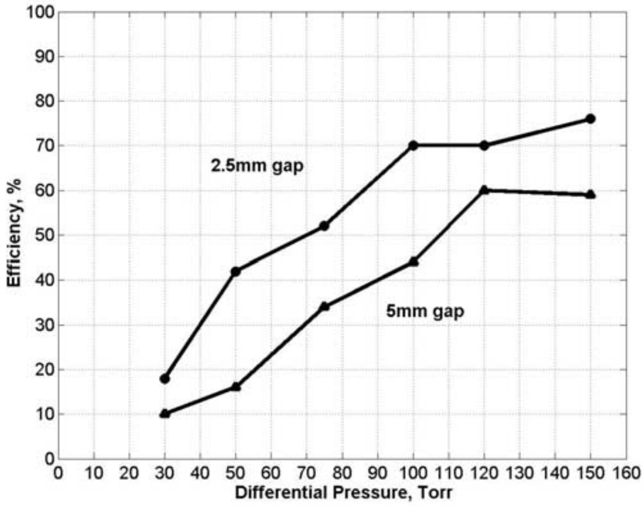

Figure 17. Effect of hole bottom gap height. Mass of powder: 15 g; gas: CO_2. Test conditions: rock powder: OHSS; ambient pressure: 7 torr, tube diameter: 50 mm.

while the tube on the left-hand side contained basalt cuttings. Both rock cuttings contained trapped moisture, which turned into water vapor once the pressure dropped below the triple point of water. In the case of basalt rock powder, the water vapor percolated out of the basalt cuttings. On the other hand, the water vapor inside the sandstone powder became trapped in pockets and percolated out very slowly. This is clearly shown in Figure 13 where the pockets of water vapor split the rock powder into layers. With time, these layers of rock dust would fall back to the bottom of the tube.

[53] To summarize, the basalt cuttings formed a much more porous structure than sandstone cuttings and the direct effect of this was that sandstone cuttings were lifted out of the hole much more easily.

[54] Another way to analyze the above results is by considering the mean free path of the gas molecules. The mean free path of carbon dioxide and nitrogen (the main constituent of air) are very similar. Thus the mean free path analysis should be the same for both gases. Since it was too difficult to determine the actual pressure and the temperature of the gas prior to the gas hitting the rock cuttings it was assumed that the temperature was 290 K and the pressure 10 torr. At these conditions the mean free path of a gas molecule is around 5 microns. As pointed out earlier, the sandstone cuttings are very fine (50% are finer than 11 microns or so). Therefore the gas molecule is more likely to hit the sandstone rock particles than another gas molecule. On the other hand, for basalt cuttings, which are much coarser, the gas molecule is more likely to hit another gas molecule than a basalt particle. The above analysis might thus explain why the efficiency of removing sandstone cuttings was higher than the efficiency for basalt cuttings.

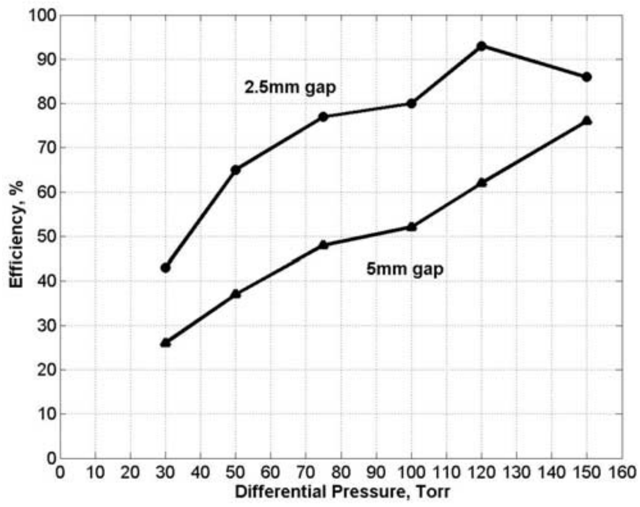

Figure 16. Effect of bottom hole gap height. Mass of powder: 25 g; gas: air. Test conditions: rock powder: OHSS; ambient pressure: 7 torr, tube diameter: 50 mm.

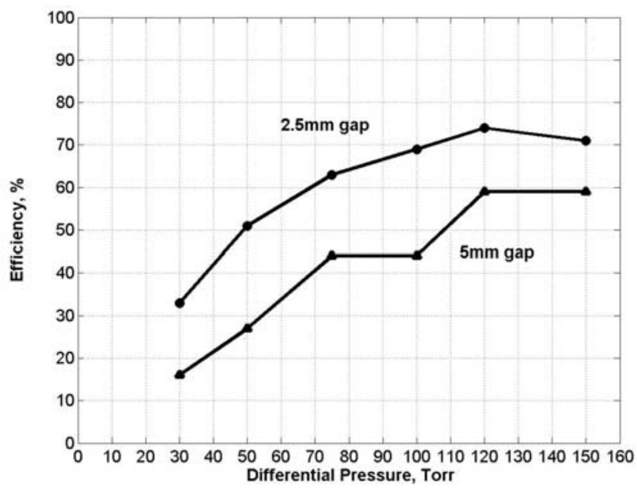

Figure 18. Effect of hole bottom gap height. Mass of powder: 25 g; gas: CO_2. Test conditions: rock powder: OHSS; ambient pressure: 7 torr, tube diameter: 50 mm.

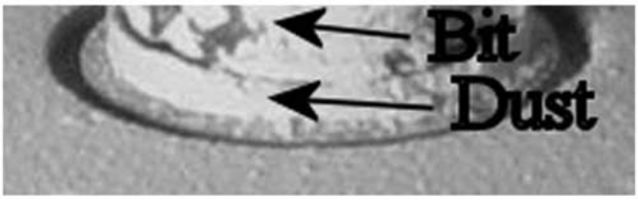

Figure 19. Rock cuttings left behind after the test.

[55] In general, it was found that the efficiency of the system depended on the size distributions of the particles. For a uniform distribution with a larger fraction of smaller particles the efficiency was higher. This finding contributes to the complexity of the modeling of gas blasting of cuttings from the borehole as it is difficult to predict at this stage, what cuttings distribution will be produced by diamond drilling on Mars. For example, if the cuttings removal system is inefficient, the rock debris will be continuously reground by the drill, getting smaller all the time. On the other hand, if the cuttings are removed as soon as they are produced, they will more likely be of a larger size.

3.3. Effect of Bottom Gap Clearance on the Efficiency

[56] Figure 14 shows the gap clearance, defined as the distance between the bottom of the drill and the bottom surface of the hole. In the set of experiments two gap distances were investigated: 2.5 mm and 5 mm. The results are shown in Figures 15, 16, 17, and 18. Figures 15 and 16 show the results with air flushing for 15 g and 25 g rock powders, respectively. Figures 17 and 18 show the results with CO_2 flushing for 15 g and 25 g rock powders, respectively. In all tests the efficiency of the cuttings removal was 10% to 30% higher with a 2.5 mm gap distance. Intuitively, this is plausible as with a smaller gap distance, there is a thicker layer of rock powder above the bottom of the bit and in the way of the gas flow. Figure 19 shows the cuttings left behind after the test. For the larger gap distance, there was a larger layer of cuttings left behind.

[57] Since the efficiency difference was 10% to 30% higher in all the tests, this showed that neither the initial mass of the cuttings nor the type of gas affected the test results very much.

3.4. Effect of Annular Clearance on the Efficiency

[58] Figure 20 shows the effect of different annular clearances on the cuttings removal efficiency. The drill bit was 44 mm in diameter while the auger section of the drill was 37 mm in diameter (refer to Figure 14 for the difference between the auger and the drill bit). Therefore for the 45 mm casing, there was a half a millimeter clearance between the drill bit and the hole wall (casing) and a 4 mm clearance between the auger and the hole wall (casing). For the 50 mm diameter casing, the clearances were 2 mm at the drill bit and 6.5 mm at the auger.

[59] With relation to Figure 20 it can be seen that the threshold pressure was lower for the 45 mm casing and larger for the 50 mm casing and this trend continued up to a differential pressure of around 30 torr. Above 30 torr, the efficiency of the 45 mm casing was higher.

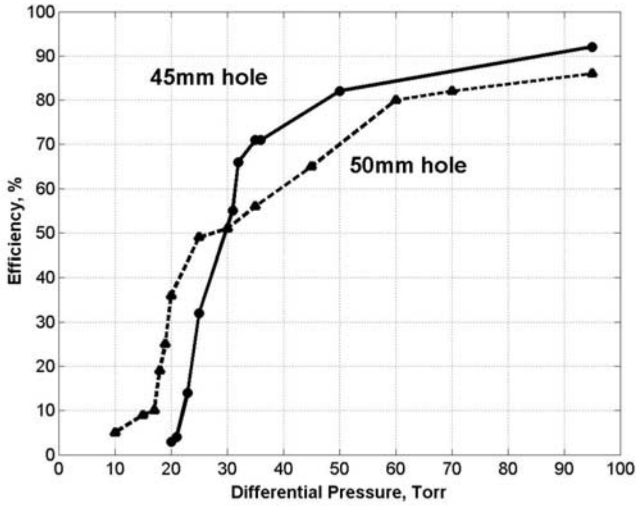

Figure 20. Effect of annulus gap. Test conditions: rock powder: basalt; ambient pressure: 5 torr; gap height: 2.5 mm; gas: air; mass of powder: 25 g.

[60] The threshold pressure for a 45 mm casing was well defined. At a differential pressure of 20 torr, the efficiency was almost 0%. Once the pressure increased by 10 torr, the efficiency increased to almost 70%.

[61] The 45 mm tube was more realistic, as it conformed to the outer bit diameter. In that case, the annular clearance was negligible. This must be a reason, why at low differential pressures, the efficiency was zero and why at higher differential pressures, which gave the gas enough momentum to pass through the small annular gap, the efficiency suddenly increased. For a 50 mm tube, the increase in efficiency was more gradual. This was because the annular gap was much bigger and therefore the gas could flow past more easily.

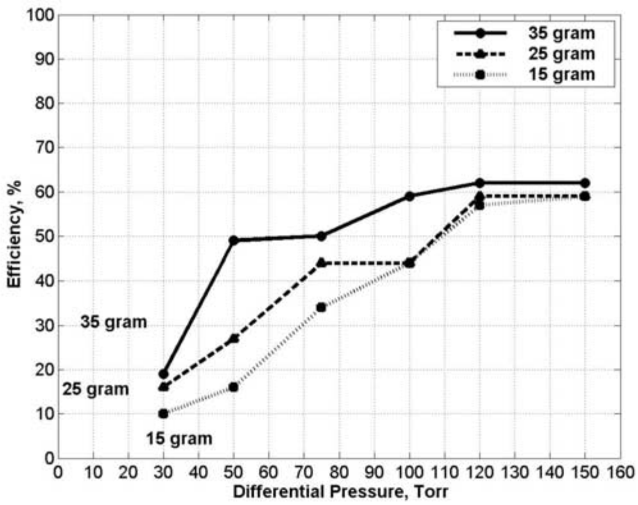

Figure 21. Effect of different initial mass. Gas: CO_2. Test conditions: ambient pressure: 7 torr; gap height: 5 mm; tube diameter: 50 mm.

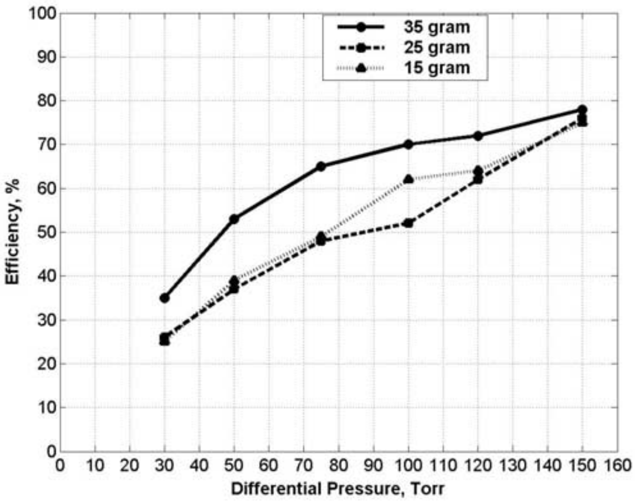

Figure 22. Effect of different initial mass. Gas: air. Test conditions: ambient pressure: 7 torr; gap height: 5 mm; tube diameter: 50 mm.

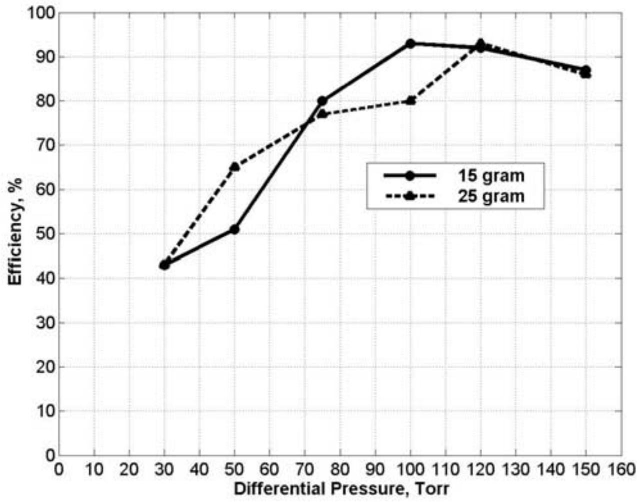

Figure 24. Effect of different initial mass. Gas: air. Test conditions: ambient pressure: 7 torr; gap height: 2.5 mm; tube diameter: 50 mm.

3.5. Effect of Initial Mass of Powder on the Efficiency

[62] In addition to investigating the effects of different amounts of rock powder, two different rock powders were also used. These were the Ohio sandstone and Basalt rock powders. The purpose of using two different rock powders was to determine how the trend in the efficiency of the cuttings removal differs as a function of the particle size distribution.

3.5.1. Flushing of Ohio Sandstone Rock Powder

[63] Figures 21 and 22 show the test results conducted on Ohio sandstone rock powder with a tube diameter of 50 mm and a gap height of 5 mm. The difference was not as apparent between the 15 g and 25 g curves as between the latter two and the 35 g curve. Figures 23 and 24 show results conducted under the same conditions as in Figures 21 and 22, with the only difference being a gap height of 2.5 mm. Again, the 15 g and 25 g curves did not differ much. In all cases, the predominant trend was that the efficiency was higher for the larger initial mass of the rock powder. Thus the amount of rock powder removed increased with the increase in the initial amount of powder inside the hole. This meant that the gas was most likely wasted when there was a small amount of rock powder inside the hole. A larger amount of rock powder formed a more effective barrier to the gas flow. Therefore the gas had to lift this cohesive layer up in order to flow to the top. For the smaller amount of rock dust, the gas would easily break up the powder and escape through the cracks.

3.5.2. Flushing of Basalt Rock Powder

[64] Figures 25 and 26 show the test results obtained with Basalt rock powder.

[65] There was a clear cut off pressure below which no cuttings were removed. Once the pressure exceeded this

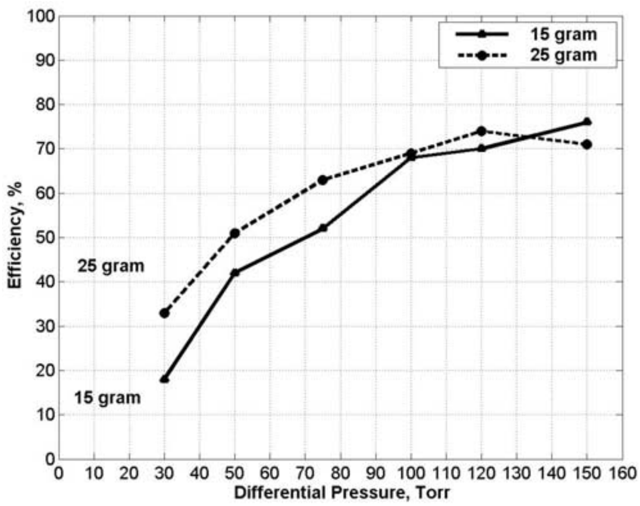

Figure 23. Effect of different initial mass. Gas: CO_2. Test conditions: ambient pressure: 7 torr; gap height: 2.5 mm; tube diameter: 50 mm.

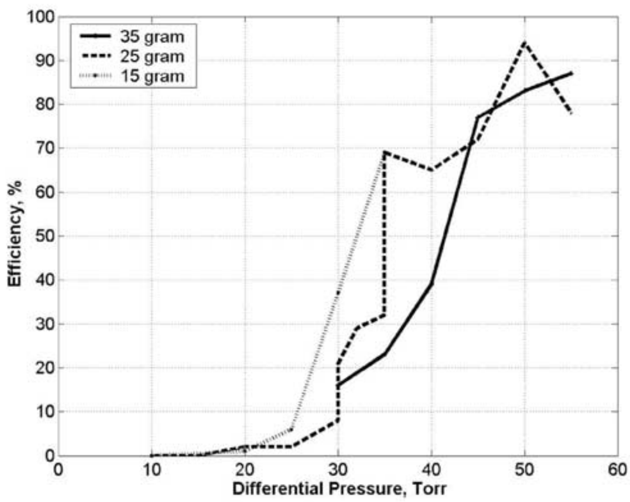

Figure 25. Effect of different initial mass. Gas: CO_2. Test conditions: ambient pressure: 5 torr; gap height: 2.5 mm; tube diameter: 45 mm.

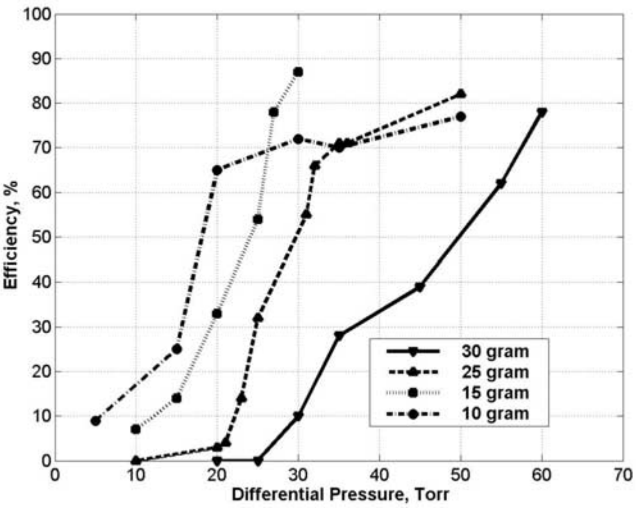

Figure 26. Effect of different initial mass. Gas: air. Test conditions: ambient pressure: 5 torr; gap height: 2.5 mm; tube diameter: 45 mm.

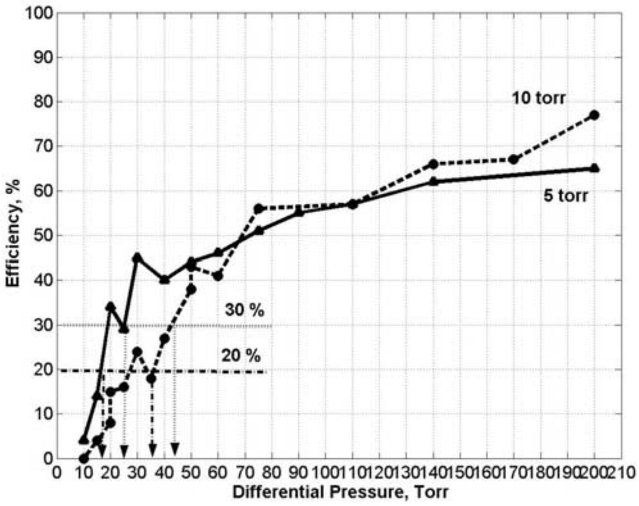

Figure 27. Effect of ambient pressure. Efficiency versus differential pressure. Test conditions: Rock powder: OHSS; gap height: 2.5 mm; gas: air; tube diameter: 50 mm; mass of powder: 25 g.

threshold pressure, very quickly the efficiency increased to almost 80%. The point where the graph just began to level off corresponds to the optimal threshold pressure or in other words the optimal gas velocity.

[66] Irrespective of the gas used, the trends were the same; i.e., smaller initial mass of powder resulted in larger efficiencies. The explanation could be found by looking at the hole-bit geometry. In this particular case the tube and the bit were of the same diameter. Thus the friction drag in this narrow annular region was very high. Since the majority of gas momentum was lost, only a fraction was available for lifting the cuttings out. For the small amount of powder present, that was enough to lift the cuttings out of the hole. However, for the larger amount, the momentum was insufficient. The differential pressure had to be increased to overcome both the friction drag in the annular space and to lift the larger amount of cuttings.

[67] Note that the data in Figure 25 were taken during the conditions that most closely resembled the conditions that the actual gas flushing system might one day use. In particular, the gas used was carbon dioxide, the tube diameter was the same as the bit diameter and the gap height was only 2.5 mm. The differential pressure required to remove most of the rock powder was only 50 torr.

3.6. Effect of Ambient Pressure on the Efficiency

[68] Figure 27 shows the effect of the ambient pressure (pressure inside the main vacuum chamber) on the efficiency of the cuttings removal. The only difference between the five and ten torr ambient pressures was noticeable at low differential pressures of up to 50 torr or so. Above 50 torr, the two curves coincided. Therefore, for Mars application, provided a differential pressure of more than 50 torr is used, there should be no performance difference when the ambient pressure on Mars fluctuates.

[69] Another way to look at this graph is to consider the efficiency as a function of the volumetric expansion of the gas. The volumetric expansion can be defined as the ratio of the difference in pressure over ambient pressure or $\Delta P/P$. Figure 28 shows the efficiency as a function of volumetric expansion. The results appear quite different. When the volumetric expansion was larger than 8, the efficiency of gas flushing in the 10 torr pressure environment was higher.

[70] The power required to compress the Martian atmosphere 8 times at an ambient pressure of 10 torr is twice as high as than at an ambient pressure of 5 torr. Therefore from the power requirements standpoint, the volumetric expansion of around 14 at an ambient pressure of 5 torr is equivalent to a volumetric expansion of 8 at an ambient pressure of 10 torr. However, as shown in Figure 28, the efficiency of the 5 torr curve at the differential pressure of 14 was still smaller than that of the 10 torr curve at the differential pressure of 8. Thus the energy approach is not

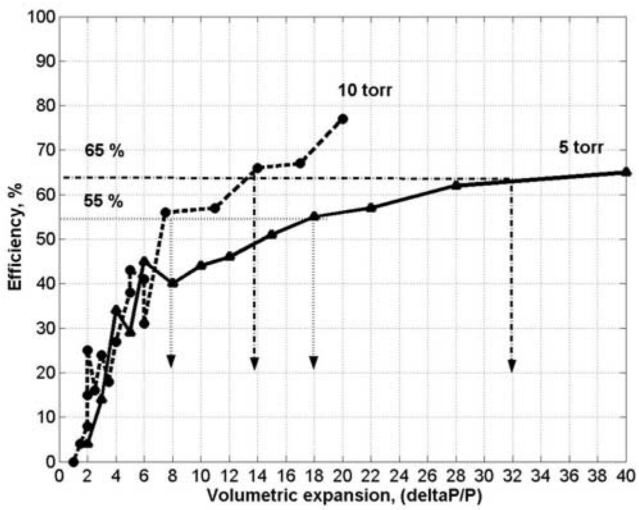

Figure 28. Effect of ambient pressure. Efficiency versus volumetric expansion. Test conditions: rock powder: OHSS; gap height: 2.5 mm; gas: air; tube diameter: 50 mm; mass of powder: 25 g.

Figure 29. Effect of the differential pressure on the amount of dust left on the inside of the tube. (left) At high differential pressure the tube remains clean. (right) At low differential pressure the tube becomes covered with the dust.

the answer as to why there is a large efficiency gap between the two ambient pressures.

[71] With reference to Figure 28, there are two horizontal lines at 55% and at 65% efficiencies. They intercept the 5 torr and a 10 torr curves at the volumetric expansion values indicated by the arrows. It appears that the pressure in the 0.93 L chamber required to give the same or similar efficiencies for both the 5 torr and the 10 torr ambient pressures, was almost the same. In the case of the 55% line, the 0.93 L chamber pressure for the 5 torr and a 10 torr ambient pressures was 165 torr and 150 torr, respectively. On the other hand, for the 65% line, the 0.93 L chamber pressure for the 5 torr and a 10 torr ambient pressures was 95 torr and 90 torr, respectively. Therefore in each case there was the same mass of gas used for flushing; thus it is reasonable to conclude that at larger differential pressures it is the mass of the available gas that controls the efficiency. This was also observed in CO_2 versus Air results in section 3.1.

[72] Similarly, in Figure 27 there are two horizontal lines at 20% and 30% efficiencies. These two lines intersect the 5 torr and 10 torr curves at the corresponding differential pressure values shown by the arrows. For the 20% efficiency, the values of volumetric expansion (ΔP/5 torr or ΔP/10 torr) for the 5 torr and 10 torr curves are 3 and 3.5, respectively. On the other hand, for the 30% efficiency, the values of volumetric expansion (ΔP/5 torr or ΔP/10 torr) for the 5 torr and 10 torr curves are 5 and 4.5, respectively. Thus it is a volumetric expansion that has a major effect on the efficiency. Since the volumetric expansion also determines the exit velocity of the gas, it can be concluded that at low differential pressures, it is the velocity of the gas that plays a more prominent role in the efficiency of the cuttings removal. This was also observed in section 3.1.

[73] In summary, at low differential pressures, it is gas velocity that plays a more prominent effect in the momentum balance equation. For the larger differential pressure, the mass of the gas becomes more influential.

3.7. Effect of Tube Surface Roughness

[74] Figure 29 shows the effect of the differential pressure on the amount of dust residue left after a test. When the differential pressure was high, the gas flow tended to blow all the cuttings out and leave very little dust adhering onto the wall of the tube. However, when the differential pressure was relatively low, the rock powder was lifted only a short distance up with a tendency to adhere to the tube or fall back down. This is also referred to as choking. Since the pressure was low and the particles were relatively small, the surface charge together with static electricity was believed to play a significant role in this effect.

[75] Figure 30 shows two data sets obtained under the same conditions with the only difference being the cleanliness of the tube. The efficiency with the clean tube was over 30% higher. Thus the surface roughness had a large effect on the friction drag. This has serious consequences for the actual Mars gas flushing applications, since the surface of

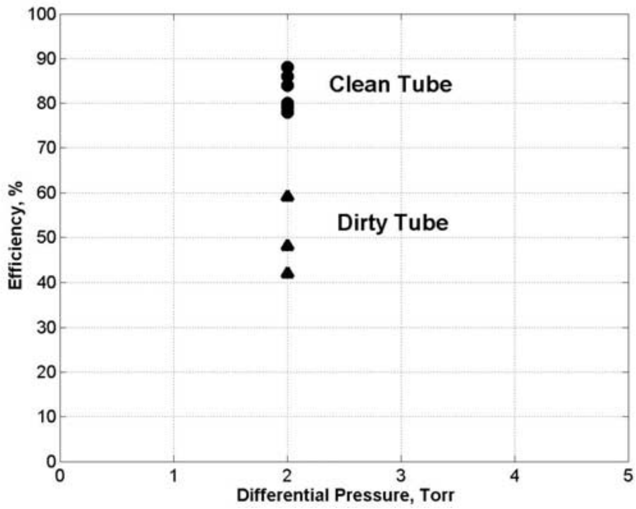

Figure 30. Effect of tube cleanness. Test conditions: rock powder: OHSS; gap height: unknown; gas: air; tube diameter: 50 mm; tube length: 250 mm; mass of powder: 25 g.

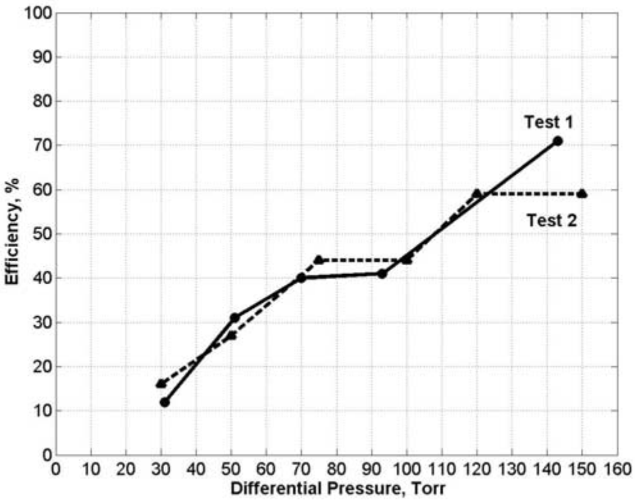

Figure 31. Test 1 and test 2 were conducted under the same conditions at different times. Gas: CO_2. Test conditions: ambient pressure: 7 torr; gap height: 5 mm; tube diameter: 50 mm; mass of powder: 25 g.

the Martian borehole will more likely resemble the "dirty" tube conditions.

3.8. Reproducibility of Tests

[76] Figures 31 and 32 show two sets of data taken under the same conditions on two different occasions. Tests in Figure 31 were conducted with CO_2, while the tests in Figure 32 were conducted with Air. The purpose of conducting two sets of tests under the same conditions on two different occasions was to determine whether the results were reproducible.

[77] Although tests 1 and 2 in Figure 31 gave almost the same curve, this was not the case in Figure 32. The data scatter was more significant, which meant that there were other factors that affected the results and which were not taken into account. As mentioned previously, all experimental procedures were kept the same in all the tests. However, clearly that was not good enough to achieve a 100% precision.

[78] Figure 32 illustrates again that it is very difficult to model or predict the efficiency of the gas flushing and reinforces requirements for performing experiments under actual conditions in which the drill will operate.

[79] In Figure 30, two sets of tests were conducted under virtually the same conditions. In the first set of six data points, the lowest value was 78% and the highest was 88% with the average of 83% and a standard deviation of 4%. On the other for the three point set, the average was 50% with a standard deviation of 8%. The highest value was 59% and the lowest value was 42%. Therefore it can be concluded that most of the data have approximately 8% uncertainty.

4. Velocity of the Rock Powder

[80] All tests conducted at five and ten torr ambient pressure (row numbers 7 and 8 in Figure A1, Appendix A) were videotaped and the movies were used to determine the maximum velocity of the rock powder as well as the total duration of the experiments. Figures 33 and 34 show four consecutive movie frames taken in 1/15 s intervals from one of the tests. During this particular experiment, the pressure inside the main chamber was 5 torr, while the differential pressure was 30 torr. In all tests, two distinct regimes were observed. Both lasted approximately 1 s, a single test lasting for approximately 2 s. During the first regime, the cuttings achieved the highest velocity and most of the cuttings were lifted out of the hole. The second regime was characterized by the small flow of the reminder of the gas. During this stage only a small fraction of the dust was lifted out.

[81] It was found that the exit velocity of the rock powder was around 6 m/s at a differential pressure of 25 torr and an ambient pressure of 5 torr. For large differential pressure, it was difficult to calculate the exact particles velocity, not only because the movie frames were taken only at the 1/15 s intervals, but also because the chamber height was small. A visual observation of the chamber ceiling revealed dust particles strongly adhering to its surface. Indeed, the momentum of the dust particles was very high.

[82] Rough calculations using Bernoulli's equation and a mass continuity equation were used to determine the theoretical exit velocity of the gas at the top of the tube. From the Bernoulli flow equation

$$v = \sqrt{\frac{2\Delta P}{\rho}}, \tag{4}$$

where ΔP = 25 torr × 133 = 3325 Pa and $\rho_{air-at-5torr}$ = 0.1 kg/m^3. Thus velocity of gas leaving the 0.93 L chamber was v = 260 m/s.

[83] From the mass continuity equation,

$$A_1 v_1 = A_2 v_2, \tag{5}$$

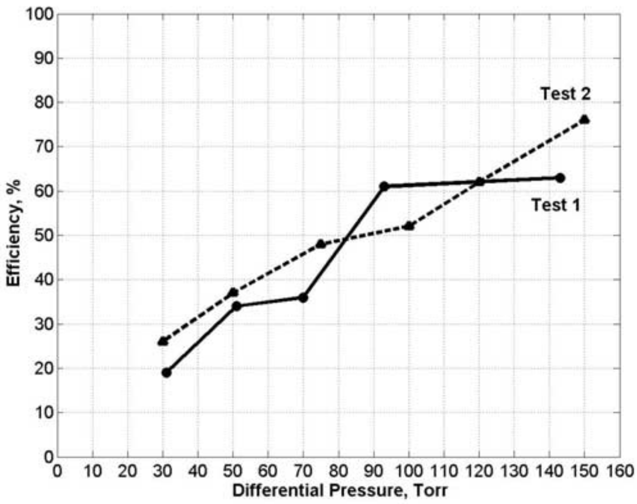

Figure 32. Test 1 and test 2 were conducted under the same conditions at different times. Gas: air. Test conditions: ambient pressure: 7 torr; gap height: 5 mm; tube diameter: 50 mm; mass of powder: 25 g.

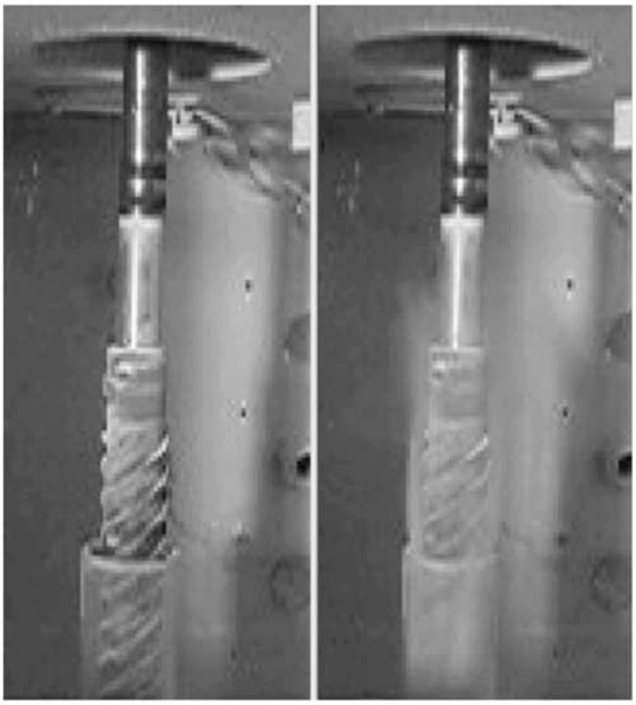

Figure 33. Frames from the movie taken during air flushing experiment. The ambient pressure was 5 torr, and the differential pressure was 30 torr. (left) Time = 0 s. (right) Time = 1/15 s.

where A_1 = 0.2 cm^2, A_2 = 9 cm^2, and v_1 = 260 m/s, which gives v_2 = 5.7 m/s. The recorded velocity from the tests was very close to this, at 6 m/s.

5. Modeling of Gas Flushing

[84] Flushing of cuttings with a continuous flow of gas has been modeled quite successful before by *Tian and Adewumi* [1991, 1992], *Temple et al.* [1996], and *Puon and Ameri* [1984]. These models were based on the empirical equations developed by studying the actual flow of gas in the controlled environment.

[85] In general, two forces affect the gas flushing and these are gravitational and frictional. Below the optimal pressure, gravitational forces dominate the cuttings removal: the pressure gradient set up by the gas flow is not sufficient to lift the cuttings out of the tube. This phenomena is also refereed to as choking. This critical differential pressure depends not only on the gas used and the geometry of the drill and the hole but also on the original amount of mass present. Above the threshold pressure it is the frictional forces that dominate. Here, friction limits the efficiency of the cuttings removal, with the end result that, in this regime, an increase in differential pressure does not necessarily correspond to an increase in mass removed.

[86] Blasts of gas, however, are more difficult to model in theory as the gas does not have the time to reach a continuous flow. Similarly to the continuous flow, there are three different flow regimes that need to be considered separately. The three flow regimes differ for continuous flow. For the gas blasts these regimes are (1) the initial single flow acceleration regime when the gas leaves the 0.93 L control volume and flows toward the hole bottom, (2) highly turbulent flow in the transition region from a single flow to a two phase flow regime when the gas hits the hole bottom and starts flowing upward, and (3) two phase acceleration regime when the gas lifts the particles up and out of the tube.

[87] In addition the model has to include the effects of many other factors such as the particle size distribution, the initial volume and the porosity of rock powder at the bottom of the hole, the geometry of the hole bottom and the drill, the geometry of the hole itself and the drill string assembly and the surface roughness of the hole surface, to mention a few.

6. Conclusions

[88] In these sets of experiments, 0.93 L of gas at various pressures was used to clear rock dust from the hole bottom. The drill and the hole were arranged in such a way as to simulate the actual geometry and actual drilling conditions. It was found that the efficiency of cuttings removal depends on many factors and this makes it very difficult to develop accurate flow models. Thus it is imperative for the success of the mission to test the gas flushing under the conditions in which the actual drill will operate.

6.1. Rock Powder Used in the Experiments

[89] The efficiency of the gas flushing was found to depend on the size of the particles and the size distribution of the particles in the rock powder. It was found that smaller particles were easier to lift because they form a more dense packing.

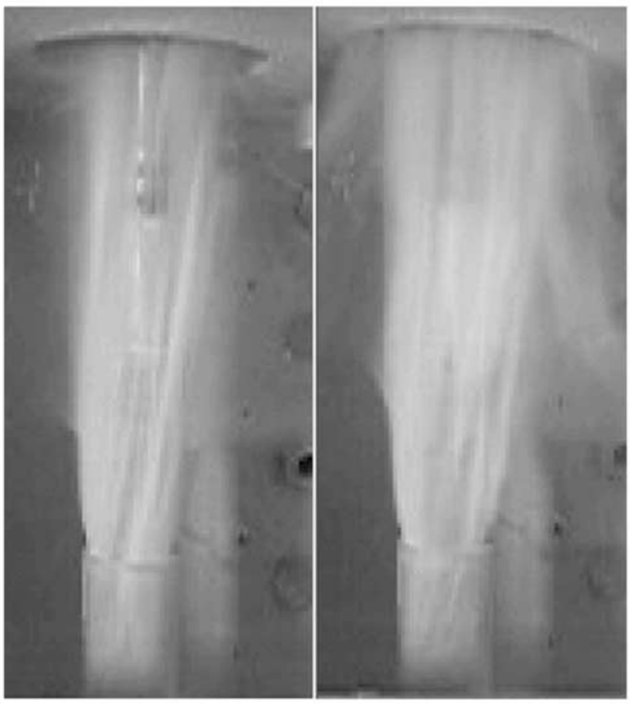

Figure 34. Frames from the movie taken during air flushing experiment. The ambient pressure was 5 torr, and the differential pressure was 30 torr. (left) Time = 2/15 s. (right) Time = 3/15 s.

Rock Powder			Chamber/Ambient Pressure			Gap Height		Gas type		Hole Dimension (DiaXLength)			Initial Mass of the Powder (Number of tests)				
OHSS	SBSS	Basalt	5 torr	7 torr	10 torr	2.5 mm	5 mm	Air	CO2	45x150 mm	50x150 mm	50X250 mm	10 g	15 g	25 g	30 g	35 g
x				x		x		x			x			6	6		1
x				x		x			x		x			6	6		1
x				x			x	x			x			6	6		6
x				x			x		x		x			6	6		6
x			x				x	x			x		11				
x			x				x		x		x		19				
x			x			x		x			x				13		
x					x	x		x			x				18		
		x	x			x		x			x				16		
		x	x			x		x		x			6	14	26	25	
		x	x			x			x	x				5	16	8	
	x		x			x		x				x			33		

Figure A1. Summary of the test conditions and number of data points taken for each set of conditions. Note, not all data sets were used in this paper.

6.2. Chamber or Ambient Pressure

[90] The ambient pressure was significant only at low differential pressures. The efficiency was found to be higher if the ambient pressure was lower.

6.3. Gap Distance or Gap Height

[91] A smaller gap distance between the bottom of the drill and the bottom surface of the hole was found to be more beneficial than a larger gap height. This makes intuitive sense as with a smaller gap height there was a thicker layer of cuttings in the way of the gas flow.

6.4. Gas Type

[92] It was found that atmospheric air performs better than carbon dioxide. Under certain conditions the efficiency with air was found to be as much as 40% higher. This finding precludes the use of air as a substitute for CO_2 in the experiments, unless the results are adjusted to account for the difference in the performance of two gases.

6.5. Annular Clearance

[93] The larger hole diameter was found to require a lower threshold pressure for cuttings removal, but the maximum efficiency achieved was lower than that of the smaller diameter hole.

6.6. Initial Mass of Powder

[94] The efficiency of cuttings removal at various initial mass values depends on the size distribution of the rock powder. When the cuttings were larger and nonuniformly distributed (as was the case with Basalt powder), the efficiency was higher for lower initial masses of rock powder. When the cuttings were smaller, more uniformly distributed and thus well packed, the efficiency was higher with higher initial cuttings mass.

6.7. Velocity of Rock Particle Blown Out of the Hole

[95] The velocity of cuttings exiting the hole was found to be 6 m/s for a differential pressure of 25 torr and an ambient pressure of 5 torr. Calculations based on the mass continuity and Bernoulli equations gave a velocity of the same order of magnitude. In addition, the velocity of rock cuttings being blown out of the hole by sublimed water vapor while rock coring in water saturated, frozen rock under Martian pressure was also found to be of the same order of magnitude [*Zacny et al.*, 2004]. The velocity of the experiments was found to increase with the increase in the differential pressure and the average duration of most tests was 2 s.

6.8. Effect of Hole Surface Roughness

[96] It was found that a surface residue on the inside of the tube significantly affects the friction drag. For the same set of conditions, the efficiency with the clean tube was 85% while the efficiency with the tube that had a dust residue on the inside was only around 50%. The surface of a borehole drilled on Mars will more closely resemble the dirty tube conditions.

6.9. Modeling of the Gas Flushing

[97] Trying to model the gas flushing out of the borehole is very difficult. There is a large amount of conditions and parameters that need to be taken into account. To model the transient conditions investigated in the experiments reported here may be very difficult, and more time-consuming than actually to run experiments under the conditions expected to be encountered.

6.10. Final Remarks

[98] Several tests showed that at low differential pressures, it is a gas velocity that plays a more prominent effect in the momentum balance equation. For the larger differential pressure, the mass of the gas becomes more influential.

[99] Test conditions that will most resemble the actual conditions on Mars are ambient pressure of 5 torr, CO_2 gas as a flushing medium, Gap height of a few millimeters or none (depending on the distribution of the cuttings segment on the bit face) and a hole diameter equal to the bit diameter (no reaming). Data in Figure 25 most closely fits the above conditions. Therefore, for the current bit geometry and the test conditions used to obtain data in Figure 25, it can be concluded that a differential pressure of 50 torr is sufficient for lifting most of the rock powder generated during the drilling. Assuming a conservative value for the rate of penetration of the drill into the rock of 10 cm/hr (rates of four times as high were recorded during the actual experiments conducted under Martian conditions [*Zacny et al.*, 2004] and the kerf area of 1000 mm^2, 2.5 g of rock powder will be generated every minute. Thus the gas blast has to be activated every 10 min or so. The energy required to isothermally compress Martian atmosphere into a 0.93 L reservoir, from the ambient pressure of 5 torr to the reservoir pressure of 55 torr is 17 Joules. If the compressor's efficiency is only 10% and the compressor runs for only 1 min, the power requirement is around 3 W. Therefore, even if the gas blasts will not be a primary way of removing the rock cuttings from the borehole, it is worth having a compressor that can send the gas blasts every so often

to enhance the cuttings removal or in times where the mechanical cuttings removal system fails.

Appendix A

[100] Figure A1 shows the summary of all test conditions and the number of tests for the given set of conditions. The headings in the table show independent variables. The differential pressure, i.e., the pressure between the 0.93 L chamber pressure and the main chamber pressure, was a dependent variable.

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