FAECAL SLUDGE TREATMENT BY VISCOUS HEATING

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ABSTRACT

We have demonstrated that viscous heating of faeces through an extruder works well. Our first prototype, designed by computational fluid dynamics to obtain performance data over a range of operating conditions, was tested in the laboratory with simulant materials. The laboratory-scale unit is 10 cm long with a rotating central core and a space with the shell wall adjustable from 0.75 to 1.25 mm. Experiments with 5 Pascal-second viscosity simulants and the smallest spacing achieve 200°C within 3-4 minutes. Additional time to process the mass generated by an individual requires only a few additional seconds. At larger spacing the observed temperature is lower, but shear stress and pressure remain as microbial destruction mechanisms. If the unit is operated continuously the 10 cm size is sufficient to treat the mass produced by more than 1000 people. With the current geometry the simulant leaves the extruder as a moist, hot mass. While moist heat is effective in destroying microorganisms, water must escape to dry the solid. A possible design variation that dries the solid includes spreading the mass into a thin layer for water evaporation. This concept will be addressed prior to completion of Phase 1. A challenge is that spacing between the shell and the core is small and objects, gravel or sand in faeces will require screening prior to extrusion. Alternative geometries are being considered for high-volume sludge processing and pit extraction applications. Extrusion may also be integrated with other treatment technologies if parasite destruction would benefit the overall process. A second-generation prototype is under construction for presentation at the Reinvent the Toilet Fair that is simpler and easier to visualize in a small-scale toilet application.

Keywords: EXTRUSION**,** FAECES, POTATO, PARASITE, VISCOSITY, VISCOUS HEATING

INTRODUCTION

Diarrheal diseases kill annually approximately 1.3 million people, of whom the majorities are children aged 0-4 years (World Health Organization 2004). The helminthes and parasitic protozoa that are spread throughout the environment with human faeces include *Ascaris lumbricoides, Giardia intestinalis, Trichuris trichiura, Cryptosporidium spp. and Taenia spp*. Children of age 2-12 are the target victim of *Trichuris trichiura and Ascaris lumbricoides* Smith (2001). In areas where sanitation is non-existent or ineffective (Trönnberg, Hawksworth et al. 2010), these parasites and protozoa cause diseases such as, cholera, diarrhea, and typhoid. The helminthes (parasitic worm) infections in the human stomach caused by the microbes listed above are *ascariasis, truchuriasis* (whipworm)*,* and hookworm. These diseases cause both physical harm and reduce scholarly and cognitive development (Bethony et al. 2006).

We are evaluating the concept of viscous heating to define applications for sanitation. Any highly viscous mass will generate heat when shear stress is applied. Similar devices have been reported to heat other viscous materials. For example, Yesilata (2002) worked on the rotation of mass between two parallel disks. We have generated heat with both animal faeces and faecal simulants by applying shear stress with auger/extruder types of equipment. These experiments have generated sufficient heat to sanitize the mass. For watery solids with insufficient viscosity we believe it is possible to add paper, sawdust or grass clippings, or operate with solids recycle, to achieve a sufficient rise in temperature. Once treated, the faeces will be safe to handle or transport and can subsequently be used in energy conversion or agricultural processes.

BACKGROUND

Viscous heating is a well-known phenomenon; technologies include polymer melts and sludge dewatering. Rock formation is also associated with viscous heating in nature. An important contribution of viscous heating in the field of geology is discussed along with modelling the effects by Burg (2005). Also, the contribution of viscous heating in magma deformation is studied by Hess (2008).

In considering viscous heating, temperature rise is caused by internal friction at high flow velocities (Sunden, 1992). Sunden showed viscous heating effects in forced convective flow across a circular cylinder at low Reynolds number. Faecal simulates can be used to evaluate the viscous heating technology. Structural, thermal, and viscoelastic properties for potatoes (Singh et al. 2008) indicate there potential as a simulant for human faeces. Yavuz et al. (2011) investigated the heat transfer characteristics of laminar duct flow with viscous dissipation for a Newtonian fluid with constant properties for temperature distribution in annular pipes. Finite difference analysis of the heat transfer mechanisms for non-Newtonian fluids in circular tubes establishes that viscous dissipation leads to high temperature in processing fluids. Viscous heating affects fluids having temperature dependent viscosity due to a combination of energy and momentum transport. Heat generated by this process decreases the viscosity of the fluid and results in less temperature rise than constant viscosity materials (Costa and Macedonio 2005).

Hooman and Ejlali (2010) included viscous heating in a correlation to give better flow simulation. They explained liquid viscosity decreases with an increment of temperature which results in lower pressure drop. Although the article provides a theoretical solution for both no-slip and slip flow in cases with forced convection of liquid in a micro channel flow, no experimentation was included. Their correlation accounts for viscous heating by theoretical derivation. However, an analytical solution for nonisothermal flow of viscosplastic fluids with wall slip is found in Lawal and Kalyon (1997) that provides a better understanding of temperature rise in die flow for viscoelastic fluids. This analytical solution has the advantage of application over a varied range of viscosplastic fluids; including our simulant material and human faeces. The mathematical solution indicates the ability to measure the accompanied viscosity. Temperature distribution due to viscous heating is reported thoroughly by Collins (1983).

METHODS

In order to measure the viscosity of different types of potatoes and wheat flour, we used a rheometer from Bohlin Instruments Model CVOR 200, East Brunswick, NJ (Figure 1). A sample was placed in a plastic cup within a ball mill for a THINKY grinder from Phoenix Equipment, Rochester, NY to create a paste. A sample of 2.5 ml by syringe was passed inside the serrated cylinder within the rheometer. After setting a 150-micron gap and a temperature of 40°C, the experiment was started. Data were saved on computer hard drive.

Figure 1. Rheometer from Bohlin Instruments

Our study shows that starch from potatoes and flour resembles the viscous properties of faecal matter of animals. Figure 2 presents viscosity data for pig caecal, chicken caecal, and human stool compared with several starchy materials. The graphical representation for faecal matter follows a similar trend line as potato and flour except for potato starch. Based on Figure 2 data we selected red potato as our faecal simulant.

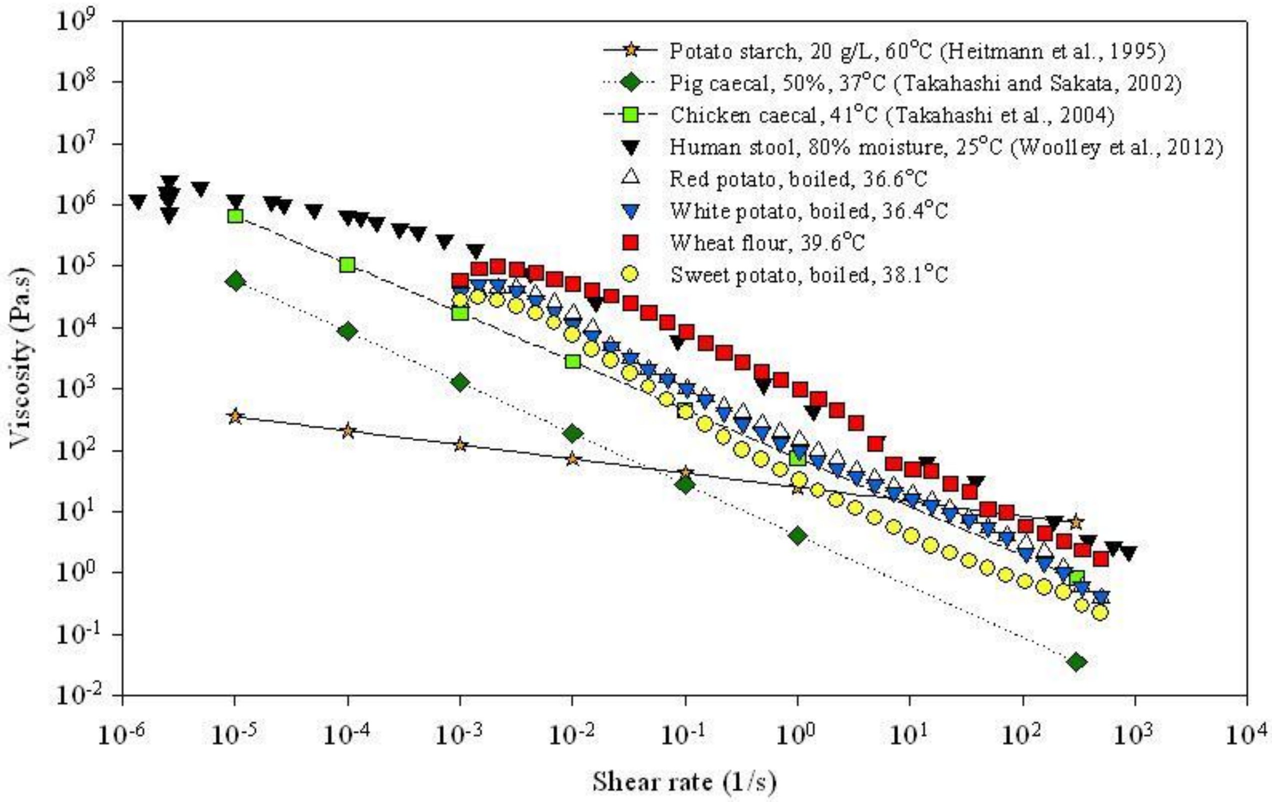

Figure 2. Shear rate decrease with viscosity for various faeces and simulants

Red Potatoes were bought from a local retailer. The potatoes were placed in a stainless steel stockpot, covered with water, and boiled at least one hour over a stove. The stove was turned off and the potatoes were collected with a ladle from the hot water. After 10-15 minutes, the skin was removed and potatoes were mashed in a ricer (Figure 3).

Figure 3. Mashing boiled red potatoes with a ricer

Operation technique

Our first generation viscous heating unit is shown in figure 4. The machine operates with a variable pressure (0-100 psig) for feed rate control, spacing (0.75-1.25mm) between the rotating inner core and the fixed outer shell and rotations per minute (rpm) (0-1700). For a typical operation, the room temperature is assumed constant and feed completely occupies the spacing during operation. The simulant mass is placed inside the feed chamber, the spacing is adjusted, pressure and rpm are set and the extruder is activated. A separate electric switch opens the air valve and moves the plunger that pushes the simulant or faeces into the gap. Once some initial mass was observed to exit the shell, a rubber stop cork was used to close the outlet for a time (hold up time) to allow the equipment and the mass to heat due to friction. After the desired temperature is achieved the stopcock is removed and mass flow can be established. The feed stays between the annular space for a certain holdup time. During experimentation temperature is recorded by a thermocouple; an Omega HHM 31 Digital Multimeter. Air pressure, spacing, rpm, and torque data are also collected.

Figure 4. Instrumented reactor to process faecal and simulant solids

The plunger in figure 4 moves inside a cylindrical feed chamber to press the feed inside the shell. A hole on the cylindrical chamber allows the operator to charge the feed. The plunger is air driven and can push the feed with a gauge pressure from 0 to 100 psi. In the figure, the pressure gauge is hanged on the metallic vertical wall. Below the gauge, the yellow regulator controls the pressure. On the right side of figure 4 a Hitachi WJ200 Series 200 V single phase inverter is attached on the vertical wall to set the required rpm in the AC motor shown at bottom right side of the figure. The shaft from the motor is connected with the cone stem by a Lovejoy coupling joint. The required rpm can be set on digital panel. An emergency stop button is fixed on the vertical wall in order to stop the operation suddenly.

Figure 5. The cone (left) rotates inside the housing (right).

The cone and the shell are shown in figure 5. The fixed shell has a spacing calibration ranging from 0 to 1.25 mm. The cone moves inside the shell. In contact with the inner cone surface, mashed potato starts rotating and deforms the simulant layers and creates friction between. The moveable bearing is attached around the stem of the cone with a black circular plastic rubber seal. The combination aligns the cone in a concentric position inside the cylindrical shell. The black hole shown on the shell in figure 4 serves as an outlet. The shell was calibrated for three positions: 0.75, 1.00 and 1.25 mm.

Figure 6. A typical setup of the cone inside the housing with spacing controller and outlet corked (black)

Spacing between the rotating cone and the stationary shell (right side in Figure 5) is fixed by the operator. The assembled components are presented in Figure 6. A metallic handle is moved to set the desired spacing based on the calibration. The spacing between the housing and rotating shaft will be increased if the metal handle is pushed forward to the vertical metal wall (anticlockwise direction if you look at from the side of air cylinder inlet).

We used a Biosafety Level 2(BSL-2) laboratory in the National Center for Veterinary Parasitology on campus to perform tests on baboon faeces using the extruder. The faeces were infected with *Trichuris trichiura.* Since the baboon population is treated for this infection on occasion, the organism loading levels were quantified by observation under microscope. This process requires a sample of known mass placed in water, gently agitated to allow parasite eggs to float to the surface. Following the same operational procedure as used for simulants, the faeces was placed in the extruder and subjected to viscous heating. After a hold up time from 3 to 4 minutes, to allow for initial heating, the faeces was allowed to pass out of the extruder at near steady state. Temperature data were obtained with a thermocouple. Samples of the effluent were collected; remaining eggs were floated and counted under the microscope.

RESULTS AND DISCUSSION

<u>Heat Generation</u>

As the core rotates inside the housing, the mashed potatoes pass between the two metallic surfaces. The outlet is closed for certain time and the potatoes gain heat due to viscous heating. When allowed to exit the reactor, the elevated temperature initially observed reduces as the mass cools due to water evaporation and release to atmospheric pressure. Table 1 shows data for experiments at 1700 rpm with a spacing of 0.75 mm and feed pressure of 100 psig. As the holdup time increases the temperature increases. The initial temperature shown (34 °C) was due to a previous experiment. A preheating effect on feed always raised the temperature more than without preheat. Though all viscosity should be decreased at high temperature, a certain amount of preheat is necessary to start layer deformation and cause viscous heating.

Table 1. Temperature data with time at constant feed pressure, rpm and spacing

Feed	Pressure	rpm	Spacing	Time	Temperature Outlet
	psig		mm	seconds	°C
Red Potato	100	1700	0.75	0	34
				60	64
				120	74
				180	86
				240	162
				260	190

The temperature increases linearly with the holdup time, indicating that longer holdup time would result in higher temperature. A temperature reading of 190°C was obtained at 260 seconds hold up time. This temperature exceeds that required to kill all microorganisms found in human faeces. Figure 7 presents results for experiments with the reactor feed pressure at 100 psig, 1150 rpm and 0.75 mm spacing. We performed additional experiments – not presented – at constant rpm and spacing and found a similar linear trend for each case.

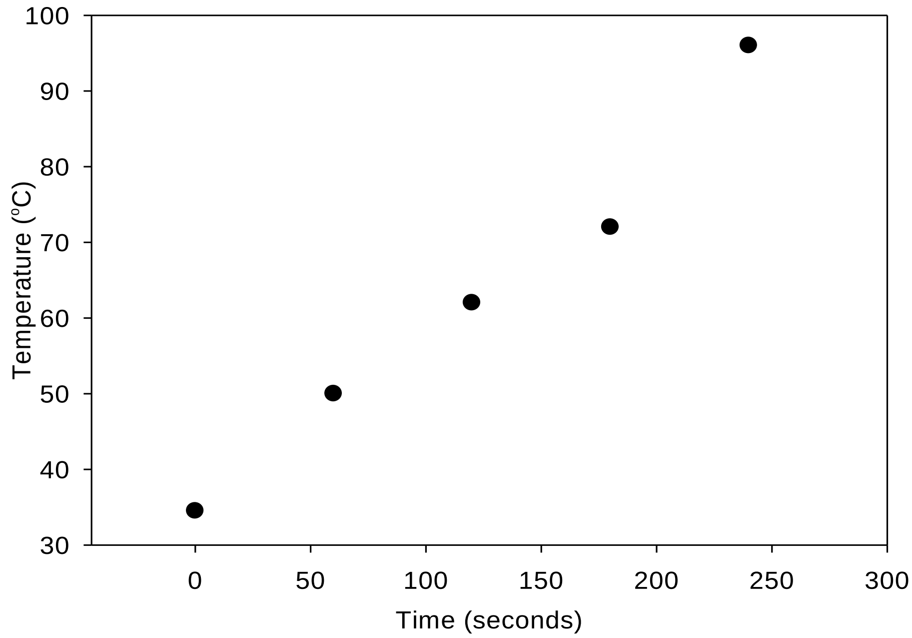

Figure 7. Temperature with time at constant 100 psig, 1150 rpm and 0.75mm spacing

In table 1 and figure 7 results were presented for constant pressure, rpm, and spacing. Changing these variables for further analysis is possible. Table 2 presents a set of data where spacing was varied while pressure, rpm, and holdup time are held constant. Temperature rise was observed with decreasing spacing.

Table 2. Temperature data with the change of spacing at constant pressure, rpm and holdup time

Feed	Pressure	RPM	Holdup Time	Spacing	Temperature Outlet
	psig		seconds	mm	°C
Red Potato	100	1150	180	0.75	72
				1	70
				1.25	50

From Table 2, the decrease in temperature with increasing spacing is apparent. These results indicate the likelihood that lower spacing less than 0.75 mm will generated even higher temperature. This plot is at constant feed pressure of 100 psig, 1150 rpm and 180 seconds holdup time. After 180 seconds, the rubber stop cork was removed and the mass was allowed to leave to the environment. The mass was observed to be hot and moist, and dried quickly when left open in the air.

If we summarize the results from results, higher hold up time and lower spacing enhances outlet temperature. In the next attempt, the effect of rpm on temperature rise is evaluated (table 3). We see at 100 psig feed pressure, 0.75 mm spacing, and 180 seconds hold up time, that the temperature rises linearly.

Table 3. Temperature with rpm change at constant pressure, holdup time and spacing

Feed	Pressure	Spacing	Hold up Time	rpm	Outlet temperature
	psig	mm	seconds		°C
Red Potato	100	0.75	180	875	55
				1150	72
				1430	104

Parasite Destruction

The kill rate is shown in table 4. Although the rpm shown in table 4 is according to the reading from the rpm value correlated with power input to the inverter, the speed presented might be lower because of the presence of a considerable amount of baboon hair present in the sample, which is typical for baboon faeces due to their grooming habits. This affects the ability of the outlet product to achieve high temperature.

Table 4. Percentage parasite egg destruction with variable settings

rpm	Spacing	Temperature	Pretreatment	Post Treatment	Percentage kill
	mm	°C	EPG	EPG	%
875	1.20	42	107.1	7.7	93
1700	0.75	51	166.5	1.7	99
1700	0.75	86	58.0	2.8	95

**Trichuris trichiura* Eggs per Gram of baboon faeces

A destruction approaching 99% was achieved for the *Trichuris trichiura* eggs. The temperature achieved for smallest spacing (0.75 mm) and the highest rpm setting (1700 calculated, but believed to be lower in actuality.) was not as high as the red potato samples. However, the kill rate of *Trichuris trichiura* was satisfactory, indicating destruction at lower temperature using shear stress alone. Figure 10 and 11 show photomicrographs for the destruction of the *Trichuris trichiura*. The pressure used in the study of table 5 is not known since a manual, variable pressure was applied due to the lack of available building gas in the BSL-2 laboratory. Repeated experiments will have an equipment modification to allow for controlled pressure.

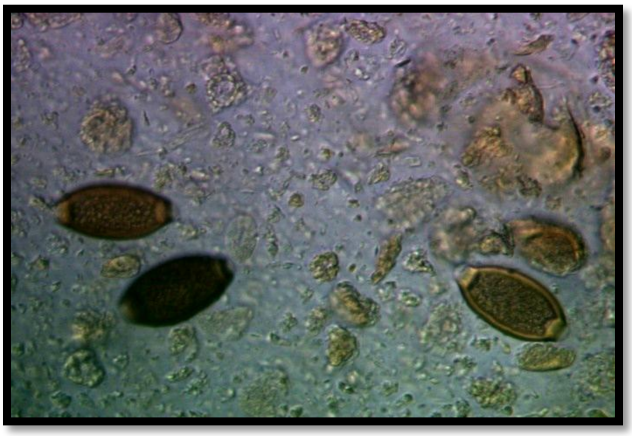

Figure 8. Photomicrographs of *Trichuris trichiura* eggs from helium before being processed through the extruder 400 x magnifications

Figure 8 shows some *Trichuris trichiura* eggs present in a processed sample of Baboon faeces. The eggs generally take 70 days to mature. Diseases related to *Trichuris trichiura* include diarrhea, anemia, and dehydration. This microorganism is also found in cats throughout the United States). The eggs hatch and the larvae mature as adults nourishing on the blood in the large intestine wall. The matured organisms lay eggs that are carried by the faeces of the infected individual to the environment where they can survive in soil for years. Examining either the faeces or blood in the faeces allows the organisms to be detected. Bundy et al. (1985) studied *Trichuris* and *Ascaris* in Jamaica and found more people are susceptible to *Trichuris.* The cognitive response in children was also shown affected (Nokes et al. 1992).

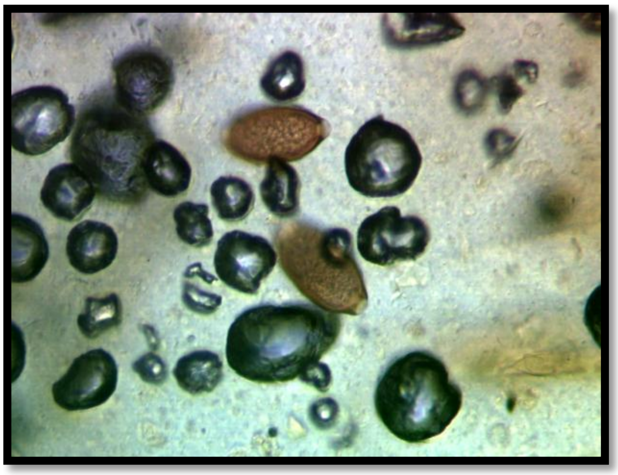

Figure 9. Photomicrographs of *Trichuris trichiura* eggs from Helium after being processed through 400 x magnifications

Figure 9 shows that air bubbles because of processing through the device accompany the destruction of *Trichuris truchuira*. Air enters through the hole (feed inlet) while the plunger pushes the feed inside the chamber. Under high rotation, air bubbles form and mix with the feed. As air is not highly viscous, there is a potential negative effect on the high viscosity desired of the mixture. The reduced viscosity due to the presence of air may be a contributing factor in the lower temperatures observed with baboon faeces. For future faecal experiments, a way to prevent air entering the reactor will be used.

CONCLUSIONS

Basic understanding of augers and extruders led us to hypothesize that viscous heating may be effective in decontaminating faecal wastes. Construction of an extruder to treat both stimulants and baboon faeces proved successful. For each experiment, fixing two variables from among rpm, holdup time, and gap spacing allowed one variable to be compared with the resulting temperature change. Temperature was observed to increase with decreasing gap distance, increasing rpm and increasing contact time. Shear force and viscous heat are sufficient to kill diseases causing microorganisms. The maximum temperature achieving was 190°C within 3-4 minutes with mashed red potatoes.

The hot moist simulant product from the reactor dried in open air within 10-15 minutes. In contact with the reactor surface, a thin film of moist thawed potato was turned into crunchy chips. A primary challenge to dewater the effluent is being addressed. Destruction of *Trichuris Trichiura* eggs were observed despite elevated temperatures being achieved, indicating destruction of the parasite by sheer stress alone. Since extrusion is proven, application of the technology is likely to have a place for specific situations. Combination with other treatment technologies may be appropriate.

A significant factor is the requirement of high viscosity to generate heat. For cases where people have diarrhoea, where urine is not separated nor when water is added by rain or other means, this technology will require modification. To handle these situations requires recycle of some of the drier solid waste to maintain or increase the viscosity of the entering material. By balancing the ratio of recycle to fresh feed the required viscosity can always be achieved; even in the case of only water fed to the inlet. Even with all water feed and high recycle the technology still has the advantage of generating viscous heating sufficient to vaporize the water for sanitized condensation.

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