Viscous heating effect on deactivation of helminth eggs in ventilated improved pit sludge

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ABSTRACT

Viscous heating by extrusion of faecal material obtained from ventilated improved pit (VIP) latrines can be used to deactivate soil-transmitted helminth (STH) eggs by increasing the temperature of faecal sludge uniformly. Viscous heating can deactivate STH eggs present in sludge to make the material safer to transport, dispose of, or use in agricultural applications or as an energy source. The mechanical energy required to generate the shear rate can originate from any source. No other heat source or additive is required. Here we determined a baseline for the deactivation of STH eggs using viscous heating. To characterize equipment performance, three parameters were investigated: (1) minimum temperature required for deactivation; (2) local maximum temperatures for various flow rates and moisture contents (MCs); and (3) thermal efficiency. Excess water is undesirable since low viscosities require extended residence time and increased energy input. The minimum temperature to achieve greater than 90% helminth egg deactivation is 70°C. For the laboratory-scale equipment tested, the maximum allowable mass flow rate for VIP sludge with 77% MC was found to be 3.6 g/s.

Key words | Ascaris, helminth eggs, viscous heating

INTRODUCTION

Soil-transmitted helminths (STHs) are parasites transmitted via eggs or larvae which are deposited in soil through open defecation. In 2002 the World Health Organization (WHO) estimated 39 million disability-adjusted life-years lost as a result of STH infections (WHO 2002). In regions where sanitation is poor, the soil is often contaminated by open defecation. The STH eggs and larvae have long survival in the environment resulting in rapid reinfection rates. Methods to ‘interrupt the vicious cycle of disease transmission’ are desired (Campbell et al. 2014). Prevention of helminth infections on a global level requires sustainable solutions that reduce exposure. Destroying eggs at the point of deposition has the potential to reduce infection rates.

Residents in the outlying areas of the eThekwini Municipality (Durban), South Africa, are served with dry on-site sanitation systems (both ventilated improved pit (VIP) latrines and urine diversion (UD) toilets). A description of the VIP latrines has been provided in earlier investigations (Bakare et al. 2012; Brouckaert et al. 2013), while an investigation into UD toilets has been provided by Trönnberg et al. (2010). In this latter study the contents of 120 urine-diversion family UD toilets to the south of Durban revealed that only 14% of the households were negative for STHs. The particular location of the toilets in this study is Besters, which is to the north of Durban. Thus, it can be expected that the safe management of the removal of the material from full VIPs needs to take into account the risks associated with STHs and that procedures need to be established to mitigate these risks.

Recent methods for deactivation of STHs in faecal waste have implemented batch style processing. These processes require both operating times ranging from 1 to 100 hours depending on temperature (Aitken et al. 2005; Popat et al. 2010; Thomas et al. in press) and additional mixing or agitation to heat the sludge uniformly. Viscous heating can be used to increase the temperature of faecal sludge uniformly (Podichetty et al. 2014). Commercial technologies that use...
Viscous heating include polymer injection moulding and food processing. When a viscous fluid is placed in a high-shear field, friction among the molecules generates heat. A high-shear field can be generated by placing a fluid between a rapidly moving surface and a stationary surface. Here, viscous heating is produced by placing the fluid in the annulus between a stationary outer cylinder and a rapidly rotating inner cylinder. The amount of heat generated is a function of the fluid viscosity, system pressure, and shear rate. Effluent temperature ranges can be achieved from pasteurization to well above the boiling point of water, depending on the mass flow rate, heat generation rate and the heat loss transfer rate. Defining effective operating conditions specific to STH deactivation is part of this effort. The viscous heating device can be integrated with compression screening equipment that separates tramp material from the faecal wastes prior to pasteurization. In addition, continuous, high-throughput processes have the potential to reduce the risk of STH reinfection by reducing the amount of active material processed in the system. Viscous heating processes may be integrated with extraction technologies, such as those described by Mikhail et al. (2014), to provide onsite sanitation of faecal waste prior to processing.

**MATERIALS AND METHODS**

**Sludge source and processing**

Sludge was obtained from VIP latrines located in Durban, KwaZulu-Natal, South Africa. The VIP sludges were manually sorted and screened at 50 mm to remove household waste and other large objects such as textiles, stiff plastics, and stones. To prevent clogging in the viscous heater, the VIP sludges were then screened to 1.2 mm using a shake tray and mechanical sieving. Samples (20 g) of the sludge were examined by light microscopy to estimate the number of viable eggs. Sludges were also analysed to determine the stage of decomposition. Two samples that met these criteria were obtained: (A) 25 L sample of VIP sludge without viable STH eggs, and (B) 1.5 L sample of VIP sludge with greater than 10,000 eggs per 10 g of sludge. Sludge samples A and B were mixed at a 100:1 ratio to obtain a sample with 300–500 eggs per 10 g for testing. Samples were homogenized in a kitchen blender at moderate rotational speeds for 5 minutes. Dried potato flakes were used as a simulant to increase the viscosity and total volume of the combined sample (Woolley et al. 2014) as follows: 30 mL of sample B was diluted in 4 L of water and loaded into a kitchen mixer; 500 g of dried potato flakes was slowly added to the diluted sample B while stirring at low speeds. The inoculated potatoes were then mixed with the sludge samples in a 2.5:1 ratio. Approximately 37 L of sample were prepared for processing. The sludge samples were refrigerated at 5 °C when not being processed.

**Viscous heating device specifications**

Based on previous work, a new viscous heater was designed using computational fluid dynamics (Podichetty et al. 2014). Viscous heating occurs when passing a viscous fluid through a narrow annulus positioned between a stationary outer shell and a rapidly rotating inner core. The target viscosity for the sludge was that expected for human stool (Woolley et al. 2014). The device was built at the Pollution Research Group laboratories in Durban, South Africa. A schematic for the viscous heater design is shown in Figure 1. Sludge is loaded into a 12 L aluminium hopper that feeds a positive displacement pump. The pump is driven by a 2 kW electric motor with an accompanying speed controller to fix the pump capacity. The pump injects the sludge through a 60 mm long, 12.6 mm ID (internal diameter) steel pipe. Inlet temperature is approximated with a thermocouple.
mounted to the exterior of the inlet pipe. The pipe feeds directly into the annulus of a concentric cylinder extruder section with a rotating inner core and fixed housing. The gap between the cylinders measures 1.25 mm and the diameter of the inner core measures 97.6 mm. The length of the extruder section measures 70 mm and the body is insulated with 40 mm of fibreglass/foil. The flanges on the exterior are uninsulated to monitor potential leaks. Two pressure release screws are located in-line with the inlet and outlet. The shaft fitting was designed such that the inner core may easily be removed for cleaning. The rotating inner core is powered by a steel drive shaft attached to a 1.5 kW electric motor. The electric motor is controlled with a LabVIEW interfaced power control. Power consumption is monitored with a display on the power control. The core-rotational speed is measured by a magnetic position sensor mounted to the stationary guard. At the end of the extruder section the sludge is transported to a 500 mm long, 12.6 mm ID steel pipe. The heated effluent temperature is measured with a thermocouple placed 10 mm from the end of the extruder section. Pressure is measured with a gauge mounted 120 mm from the end of the extruder section.

Outlet temperatures are limited to less than 85 °C based on the manufacturer requirements for the pressure transducer. Back pressure is controlled with a regulator valve at the end of the exit pipe, and the effluent flow rate is measured by collecting the mass in a receptacle on a laboratory balance. Data for temperature, pressure, and core-rotational speed are acquired with LabVIEW and stored for analysis. Data are acquired and stored once per second.

**Equipment operation**

Deactivation of helminth eggs was evaluated by operating the viscous heating mechanism at 3.5 degree intervals from 50 to 85 °C at various mass flow rates and rotational speeds. Mass flow rates were tested at 1, 4, and 8 g/s. Rotational speeds were tested at 1,100, 1,300, and 1,400 rpm. To reduce the amount of sludge required, the run order was organized to prioritize trials with low volumetric flow rates and high motor rotational speeds. During each trial the power consumption by the viscous shear motor was recorded. Experiments were begun by loading 8 L of sludge into the feed hopper. Each time the machine was loaded, a 20 g sample of the unprocessed sludge was set aside for STH analysis. Sludge was pumped through the mechanism until the active volume of the extruder was filled. The pump was then disabled and the core-rotational motor was allowed to operate at high rotational speeds until the outlet temperature reached 50 °C. The pump was activated at the desired mass flow rate setting. Approximately 1 L of material was purged from the system before 20 g samples were collected. If a steady-state temperature less than 85 °C was observed, samples were collected every 2 minutes until a total of 10 samples had been taken for each mass flow rate and rotational speed. Samples were sealed and placed in a water bath at 13 °C; however, samples decreased in temperature rapidly upon exit to atmospheric pressure due to evaporative cooling. The time for samples to reach room temperature is a function of the outlet temperature and the thermal diffusivity of the sludge, but typically took 2 to 4 minutes. Between trials the equipment was allowed to cool to 50 °C. During each trial 1 L of processed material was set aside for rheology and moisture content (MC) tests. Mean residence time was estimated by calculating the volume from known viscous heater dimensions and dividing by the volumetric flow rate of the outlet material.

**Maximum steady-state temperature**

Maximum steady-state temperature was determined at various MCs and mass flow rates at maximum energy input from the extruder motor. Mashed potatoes – determined to be an acceptable simulant (Podichetty et al. 2014) – were used due to limitations on the quantity of available sludge. MC of the potatoes was maintained to match the target viscosity of human stool (Woolley et al. 2014). Processed potatoes were prepared at MCs of 60, 65, and 77%. From initial characterizations of extruder performance, four mass flow rates were investigated at 1, 2, 4, and 8 g/s. Processed potatoes were stored at 5 °C overnight to match the initial temperature of the sludge. The simulant was loaded in the hopper and the core-rotational power input was set to the highest level. The equipment was allowed to operate until approximate steady-state temperatures were achieved. Between trials the equipment was allowed to cool to 50 °C.

**Sample analysis**

A total of 64 samples were obtained from the deactivation experiments. Samples (20 g wet mass) before and after the viscous heater were collected at specific operating conditions and processed by the Hawksworth–Archer AmBic method described by Moodley et al. (2008) and modified by Pebsworth et al. (2012). This method involves a washing step with ammonium bicarbonate to dissociate the helminth eggs from the waste; a sieving step to separate larger particles from the helminth eggs and smaller particles; and a flotation
step with zinc sulphate, specific gravity of 1.3, to allow for collection of all species of parasite eggs with a relative density lower than 1.3. After processing, each sample deposit was measured and equally halved. Half was examined microscopically soon after preparation and the other half incubated for 30 days at 28°C and then examined. STH egg counts included *Ascaris lumbricoides*, *Trichuris trichiura*, and *Taenia* spp. As *Ascaris* is used as a marker for the safe reuse of sanitation waste, the eggs are always reported in two main categories, viz. potentially viable and non-viable. The former category is divided into three groups: undeveloped or developing through the two-cell, four-cell, etc. stages; containing an immotile but healthy looking larva; and containing a motile larva. The latter category is also subdivided into three groups: containing a necrotic larva, dead, and infertile. A schematic of this analysis is in Figure 2. *Trichuris* eggs are reported as non-viable or potentially viable, likewise with *Taenia* spp. eggs. In addition, six 1 L samples were set aside for rheological analysis.

### Data analysis

#### Deactivation kinetics

The concentration of viable STH eggs as a function of time can be modelled as a first-order deactivation (Aitken et al. 2005)

\[
\frac{C}{C_0} = \Theta(t, K) = \exp(-tK)
\]  

where \(C\) is the concentration of viable STH eggs/gram, \(C_0\) is the estimated initial concentration of STH eggs/gram, \(t\) is the contact time (s), and \(K\) is the first-order deactivation rate coefficient (s\(^{-1}\)). The effect of temperature on the first-order deactivation rate coefficient may then be evaluated by the Arrhenius equation (Popat et al. 2010)

\[
K(T) = A_{app} \exp\left(\frac{E_a}{RT}\right)
\]

where \(T\) is the temperature (K), \(A_{app}\) is the apparent pre-exponential factor, \(E_a\) is the deactivation energy (J/mol), and \(R\) is the gas constant (8.314 J/mol*K). For a constant volumetric flow rate the contact time will remain constant. The concentration of STH eggs can then expressed as a function of temperature.

\[
\Theta(T) = \exp\left(-tA_{app} \exp\left(\frac{E_a}{RT}\right)\right)
\]

The apparent pre-exponential factor and activation energy was estimated by non-linear regression using the Excel and JMP statistics software. Constants determined by fitting this equation to experimental data will be unique to each particular helminth (e.g. *Ascaris*). Model fit is evaluated based on the root mean square error (RMSE), sum of squares (SSE), and the corrected Akaike’s information criterion (AICc) (Motulsky & Christopoulos 2004).

The minimum temperature required for a given flow rate is calculated by solving for temperature using the model described in Equation (3). Here the contact time is assumed to be constant.
to be the mean residence time. The minimum temperature requirement is shown in Equation (4),

$$T(\text{C}) = \frac{R}{E_a} \ln \left( -\frac{V}{\rho m} A_{\text{app}} \ln (\Theta) \right) - 273.15$$ (4)

where $V$ is the estimated active volume of the viscous heater (mL), $\dot{m}$ is the mass flow rate through the viscous heater (g/s), and $\rho$ is the density of the sludge (g/mL). Here the density of the sludge is determined by measuring the mass of a filled container with a known volume of sludge.

**Thermal efficiency**

The thermal efficiency ($\eta$) of the viscous heater is calculated by taking the ratio of thermal energy imparted to the sludge and the energy consumed by the roller motor,

$$\eta = \frac{Q_{\text{sludge}}}{Q_{\text{in}}}$$ (5)

where $Q_{\text{in}}$ is determined by the power drawn from the motor. The thermal energy imparted to the sludge is calculated from the following equation:

$$Q_{\text{sludge}} = (h_{\text{out}} - h_{\text{in}}) \dot{m}$$ (6)

where $\dot{m}$ is the mass flow rate of the sludge at the outlet (g/s), $h_{\text{out}}$ is the enthalpy of the sludge at the outlet (kJ/g), and $h_{\text{in}}$ is the enthalpy of the sludge at the inlet (kJ/g). The specific heat of sludge is assumed to be by approximately similar to water (Turovskiy & Mathai 2006). In addition, the specific heat of water varies by less than 10% from 50 to 85 °C (Thurnay 1995). Therefore, the enthalpy can be calculated from the following equation:

$$h_{\text{i}} = T_i C$$ (7)

where $T$ is the temperature (K) and $C$ is the specific heat of water approximated from 50 to 85 °C ($8.8 \times 10^{-4}$kJ/g·K) (Thurnay 1995).

**Results**

**Deactivation kinetics**

An extended table based on Figure 2 was generated for the 64 samples analysed, but due to its size is not presented here, but rather described. Column one was for the sample ID number, followed by 10 columns where data were presented. For example, *Ascaris* results were tabulated into three pre-incubation columns (total eggs, potentially viable eggs, and non-viable eggs), plus three identical columns for post-incubation. Next the percentages of total viable and non-viable eggs occupied two columns for pre-incubation and two for post-incubation. Egg concentrations ranged from approximately 300 to 600 eggs per 10 g of sludge. All data were used within the model and are presented in subsequent figures.

The concentration of viable STH eggs in pre-incubation samples was significantly greater than the concentration of viable eggs in post-incubation samples for all temperatures, core-rotational speeds, and mass flow rates ($p = 0.0057$ (value)). The reason for this is that many eggs in the undeveloped stage which were recently killed by viscous heating appeared ‘healthy’ when examined microscopically, prior to incubation. After incubation none of these eggs developed further. For all trials, temperatures less than 62.5 °C had no effect on the concentration of viable STH eggs ($p = 0.9878$). Pre-incubation controls had a significantly greater concentration of viable STH eggs than the post-incubation controls ($p < 0.0001$). No significant difference was observed between the concentration of viable STH eggs in the control and sample with effluent temperatures less than 62.5 °C for both pre- and post-incubation samples ($p = 0.9926$ and $p = 0.1289$, respectively). Initial concentrations were assumed as the average concentration of viable STH eggs for samples collected at less than 62.5 °C. The trial group for each sample had a statistically significant effect on the initial concentration ($p = 0.0001$); therefore, initial concentrations were independently evaluated for each trial. The model was evaluated using a process of non-linear regression in JMP (a statistical software package) and Excel. Values for the model parameters and regression tests are shown in Table 1. Model parameters are adequate from 50 to 85 °C and from 1 to 4 g/s.

Graphical representations of the deactivation models with comparison to data for both pre- and post-incubation

<table>
<thead>
<tr>
<th>Sample</th>
<th>Pre-incubation</th>
<th>Post-incubation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_a$ (J/mol)</td>
<td>$-2.5 \times 10^4$</td>
<td>$-2.5 \times 10^4$</td>
</tr>
<tr>
<td>$A$ (s$^{-1}$)</td>
<td>$4.0 \times 10^{35}$</td>
<td>$4.0 \times 10^{35}$</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.172</td>
<td>0.123</td>
</tr>
<tr>
<td>SSE</td>
<td>0.769</td>
<td>0.348</td>
</tr>
</tbody>
</table>
concentrations are shown in Figure 3. The data points in Figure 3(a) show egg concentrations by microscopic examination of half the collected sample after processing relative to the average of independent unprocessed samples. With independent pre- and post-treatment samples some ratios are expected to exceed 1.0, as observed. Figure 3(b) shows the concentrations in the other half of the same samples examined after 30-day incubation. Concentrations in Figure 3(a) are eggs that may be viable whether they are or not, while Figure 3(b) are eggs that appeared viable after incubation. While there is variability of total eggs in each sample; in general, data in Figure 3(b) show lower concentrations than Figure 3(a) because non-viable eggs are not included.

The curves in Figure 3 are from model Equation (3) and are not fits of the data. While the solid curve shows the expectation from the model at the tested flow rate of 2 g/s, additional curves are presented for half and double the flow rate. At lower flow rate, residence time is greater and eggs would be exposed to that temperature longer. This should result in lower viability (curve moves left). At higher flow rate, residence time and exposure at temperature are less and higher viability is predicted (curve moves right). The data follow the general trend of the model and demonstrate the significance of temperature, but suggest that further study on residence time is required since variability extends across all three curves.

Maximum steady-state temperature

Flow rate and MC have a statistically significant effect on the maximum steady-state temperature (for \(N = 12\) observations) and \(df = 2\) (degrees of freedom): mass flow rate gave \(F = 107.8\) (value) and \(p < 0.0001\) (significance level) and MC gave \(F = 33.5\) and \(p = 0.0003\). Temperature (\(C\) varied linearly with MC and logarithmically with mass flow rate as shown in Equation (8) (adjusted \(R^2 = 0.93\):

\[
T = 147.9 - 11.6 \ln (\overline{m}) - 75.1MC
\]

The relationship between the model shown in Equation (8) and the experimental values is shown in Figure 4.

Maximum operating flow rates

The maximum steady-state temperature from Equation (8) and the minimum temperature required for deactivation (pre-incubation) from Equation (4) were evaluated as a function of the mass flow rate. The minimum temperature required for inactivation was evaluated at 99.9% deactivation. The intersection of these models provides an estimate for the maximum allowable mass flow rate as shown in Figure 5. For the sludge and equipment tested,
maximum allowable mass flow rate was estimated at 3.3 g/s. Maximum allowable flow rate was estimated at 5.9 g/s and 7.4 g/s for the 65% and 60% MC potato simulant, respectively.

Efficiency

For sludge with 77% MC, thermal efficiency (heat as temperature rise of the sludge to the electrical input of the device) was found to range from 20 to 50%. Mass flow rate was determined to have a statistically significant effect on the efficiency \(N = 6, \, df = 1, \, F = 188.77, \, p = 0.0002\). The sludge tested in this experiment (MC = 77%) had on average significantly lower viscosity than other samples and the target sludge (Woolley et al. 2014). Efficiency varied logarithmically with the mass flow rate from 1 to 4 g/s. Core-rotational speed and power input had no statistically significant effect on the thermal efficiency. A graph of the thermal efficiency as a function of mass flow rate is shown in Figure 6.

Equipment performance

The positive displacement pump supported mass flow rates greater than 15 g/s; however, feed hopper capacity limited mass flow rates to values no greater than 12 g/s. When the pressure of the effluent exceeded 200 kPa, leaks occurred at the shaft fitting and pressure relief screws. Clogging at the outlet did not occur at any of the operating conditions.

CONCLUSIONS

As expected, temperature has a significant effect on deactivation kinetics. In both pre- and post-incubated samples, 90% of the STH eggs were inactivated at temperatures greater than 70 °C. No samples were observed to contain viable eggs at effluent temperatures at or above 85 °C. For equipment operation, high MC is undesirable since lower viscosity requires the reduction of mass flow rate or increased power input to achieve the same target temperature. The results from these experiments define a baseline for processing viscous VIP sludges (MC = 77%) at 3.3 g/s. In addition, the mean residence time (seconds) required for deactivation by viscous heating is much less than the time required (hours) for deactivation in batch systems (Aitken et al. 2005; Popat et al. 2010).

The viscous heating system described in this study has predicted, optimal mass flow rate within a range from 3.3 to 7.4 g/s, dependent on sludge MC. In comparison, pit extraction systems can achieve sludge flow rates greater than 60 g/s (Mikhael et al. 2014). To integrate these technologies, higher throughput rate at the same effluent temperature can be achieved by increasing the viscosity of the material, minimizing heat lost, increasing the core rpm and/or preheating the sludge from an external source, such as with truck exhaust or vented steam from the viscous heater.

Viscous heating is limited by the particle size distribution of the faecal sludge. If the particle sizes are greater than the width of the annulus, then clogging may occur. In this study, the faecal sludge was screened to reduce the number of particles with a diameter greater than 1.2 mm. Methods to limit large particles include macerating pumps...
or screens, and these should be considered as a pre-process step in a commercial device.

ACKNOWLEDGEMENTS

Funding from the Bill and Melinda Gates Foundation is greatly appreciated. Laboratory assistance from Danica Naidoo was essential for timely results.

REFERENCES


First received 1 March 2015; accepted in revised form 27 May 2015. Available online 18 June 2015.