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Influence of Temperature on the Spatial Distribution of Macro-Organisms in the GSAP† Microflush Toilet Digester and On Extended Applications of the Technology

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ABSTRACT

Composting macro-organisms such as those found in the GSAP (Global Sustainable Aid Project) Microflush toilet prefer habitats based on a number of factors including temperature, pH, soil moisture, oxygen, C/N ratio in the waste, light intensity, propagule pressure and competition from other detritus feeders. One such organism, e-fetida (Eisenia-fetida), is especially important in composting human feces in the filter-digester. Casual observations of several installed systems find a high density of this macro-organism in the perimeter area of the bed. Even though the measured temperatures across the bed are rather constant and within the range of acceptable habitats for this composting worm, among the possible factors, temperature was thought to be the likely cause. The heat conduction (Poisson) equation in 3-dimensions was solved for the geometry, structural elements and installed depth of the digester with boundary conditions typical of the tropical regions where the toilet is used. Results show temperature gradients in the narrow region near the perimeter of the bed supporting the hypothesis. The role of digester construction material in impacting transient temperatures, temperature gradients and hence performance of the system has also been explored and the potential for application of the technology in colder climates has been studied.

Key words: E-fetida habitat, Temperature gradients, GSAP-Microflush, Sustainable sanitation.

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INTRODUCTION

The GSAP microflush toilet (Mecca et al., 2012; Mecca et al., 2014) is an off-grid locally sourced locally fabricated system featuring a toilet valve that flushes on just 150 cc of recycled water (from the prior user's hand wash) directly releasing human waste into a filter-digester bed. The liquids are rapidly separated from the solids, which are composted in a macro-organism enhanced aerobic process that efficiently reduces the mass and pathogen load and results in organically rich compost with harvesting taking place every 2 to 3 years. The fly- and odor- free toilet was prototyped under a Grand Challenges Exploration award from the Bill and Melinda Gates Foundation and has been winning acceptance in the developing world with MAKERs, as they have been called, trained in 18 countries to date from Ghana to Kenya in sub-Saharan Africa, in Haiti and Bolivia to name just a few. The advantages of vermicomposting over typical pit latrines have been well established (Hill et al., 2012; Su Lin et al., 2016; Ali et al., 2015).
The use of e-fetida for composting human feces is likewise well known (Dominguez and Edwards, 2011). The authors have observed beneficial effects with other micro-

organisms as well including; Black Soldier Fly larvae, Dung Beetles, Wood Lice and even the pesty German cockroach. Since GSAP introduced its microflush toilet with the macro-organism, e-fetida, there were other off-grid designs, for example, the Tiger Toilet, that began with the black soldier fly larvae instead, but since the GSAP design, has recently changed to the vermiculture approach (Furlong et al., 2016). Composting macro-organisms prefer habitats based on a number of factors including temperature, pH, soil moisture, oxygen, C/N ratio (Ndegwa and Thompson, 2000) in the waste, propagule pressure and competition from other detritus feeders (Jicong et al., 2005; Lavelle, 1983; Loehr et al.,1985; Reinecke et al., 1992). Casual observations of the digester bed of some installed microflush systems have found a high density of this macro-organism in the perimeter area of the bed. Many of the aforementioned factors affecting habitat are uniform in the digester.

In equilibrium or steady state conditions in the bed area, the C/N ratio of the waste stream remains the same as does the pH and soil moisture. The bed surface experiences momentary changes in oxygen especially during the release of waste from the user interface but this too is uniform across the bed area. This suggests a focus on the temperature of the bed volume to explain the curious distribution of the worms. Studies on temperature tolerance of e-fetida (and other earthworm organisms) are found in the literature (Tripathi et al, 2004; Dominguez and Edwards, 2011). Some of these studies (Costello et al, 2008; Bohlen et al., 2004) mostly have been carried out in the context of ecosystem effects from earthworm invasion. While field-measurements of temperatures across the bed appear rather constant and within the range of acceptable habitats for this composting worm, temperature is nevertheless hypothesized to be the likely cause of the unusual spatial distribution of the e-fetida. The heat conduction (Poisson) equation in 3 dimensions was solved for the geometrical, structural and placement elements of the digester with boundary conditions typical of the tropical regions where the GSAP microflush toilet is being used. The effort has three goals in mind: first, to assess the aforementioned influence of temperature on the spatial distribution of macro-organisms in the GSAP Microflush toilet digester; secondly, to apply the model to study the use of alternative building materials; and thirdly, to explore the applicability of the GSAP microflush toilet in cold climates.

METHODOLOGY

Heat Conduction Model

The partial differential equation for transient heat conduction in three dimensions in Cartesian coordinates can be written

$$\lambda \frac{\partial}{\partial x}\left(\frac{\partial T}{\partial x}\right) + \lambda \frac{\partial}{\partial y}\left(\frac{\partial T}{\partial y}\right) + \lambda \frac{\partial}{\partial z}\left(\frac{\partial T}{\partial z}\right) + I(x,y,z,t) = C\frac{\partial T}{\partial t} \qquad (1)$$

Where, $T = T(x,y,z,t)$ is the temperature at coordinate x,y,z at time t in K^o, λ = the thermal conductivity in W/m-K^o, I is the rate of heat generation within the system in W/m^2, C = the heat capacity in J/m3- K^o (= the density, ρ, x the specific heat, c). The model was executed using the Blocon Heat3 code (Blomberg, 2005), which uses standard procedures discretizing Equation 1 with time and space variable steps and the usual stability demand criteria linking conductance in time and space increments in all cells (Eftring, 1990). The size, structural elements and materials drive the geometry; thermal parameters and the (Dirichlet) boundary conditions were set to typical environmental conditions found in rural tropical sites. This is discussed in the following section.

MICROFLUSH TOILET

The essential elements of the GSAP microflush toilet consist of a multi-component filter-digester, user interface integrated with the valve and a facility (enclosure). Only the filter-digester is important here and a sketch is shown in Figure 1 with the back slab and vent pipe removed to show a segment of the bed. The upper segment is the user interface containing the valve. A toilet seat can be installed on this or it can be scaled down vertically for use of a squat fixture. The outside standard dimensions of this household sized system less the user interface are 6’ long x 3’ wide x 27” to 36” deep. School block stalls are a bit larger at 7’ x 4’ with the same depth range. Perimeter materials and slabs are brick, block and cement; the heat capacities and thermal conductivities of these elements are well known as are those for the multi-layer filter materials. Fecal sludge and compost conductivities and heat capacities were estimated using handbook values for typical material quantities and qualities of sludge, compost mixture and moisture content found after one year of use at 15 uses per day. Maximum values for the thermal energy generation were estimated by considering the total mass reduction involved in the process. (124 gms of fecal solids ultimately composts to less than 15 gms of compost). However, much of this reduction goes into volatiles that escape; the internal rate of heat generation was used to calibrate the model to the observed average surface temperature of a working digester bed.

The aforementioned maximum value was calculated as 500 W/m^2 and the value used in the simulations was 180 W/m^2. Boundary conditions are specified as exterior temperatures governed by weather at the site and the installation depth of the digester, which specification is governed by the local water table. Further, the Dirichlet conditions here are partly time dependent following average diurnal cycles. We chose to use cyclic boundary temperatures reflecting the influence of solar insolation rate cycles. So, air to digester wall temperature was set to a sinusoidal function with a period of 24 h, an average temperature of 23ºC and temperature amplitude of 3ºC. The ground to digester wall temperature was set to a

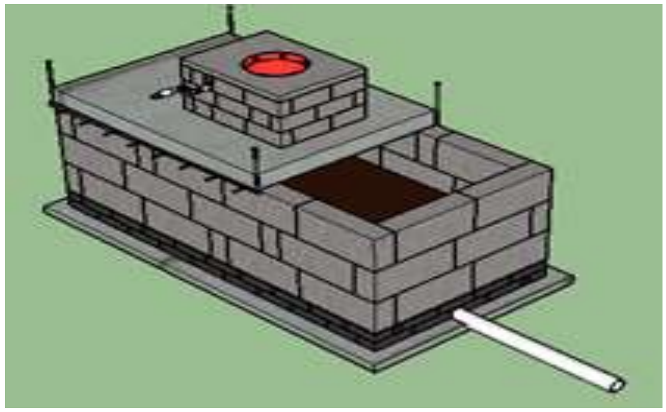

Figure 1. GSAP Microflush locally sourced household-level digester shown less the back slab and vent to reveal a section of the filter-digester bed.

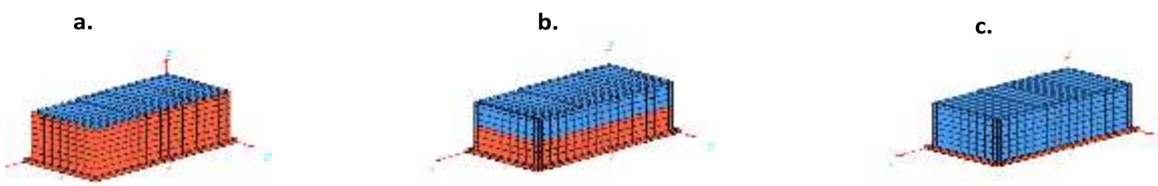

Figure 2. Digester installation (a) depth fully in the ground) (b) depth half in the ground and (c) on the top of the ground.

constant temperature of 20ºC. The installation depth of the GSAP microflush depends on local water table conditions. Hence, the model was run for 3 sets of installation depths: completely in the ground, Figure 2a, half in the ground, Figure 2b and on the surface of the ground, Figure 2c. For each of these depths, the aforementioned boundary conditions were appropriately applied and 24 h simulations run with mesh size of 4”x 4.5” x 4.5”and time steps of just under 10 sec.

RESULTS AND RELATIONSHIP TO THE SPATIAL HABITAT OF THE MACRO-ORGANISMS

Temperature results for the surfaces of the digester are shown in Figure 3 for the full-out, half-in and full-in installation depths top to bottom images, respectively over a 24 h period for a mature digester, that is, a digester that has evolved to a more or less equilibrium population of macro-organisms. It is clear from these results that the deeper the digester is installed the cooler the surface temperatures become. When installed near ground level, peak surface temperatures are in the range of 32 to 34ºC. While not relevant to the present study, we note in passing that temperatures of the filtrate chambers when the system is installed partially or fully in-ground reflect the cool and more or less constant temperature of the soil 40+ cm below the surface. A single temperature profile along the length of the digester at the level of the filter for an above ground installation is shown in Figure 4. It is clear from the this single line profile that the perimeter temperatures are a few degrees lower than those in the interior space supporting the hypothesis that the higher density of e-fetida near the perimeter of the digester is likely due to more preferable temperatures there. Temperature profiles along the width of the bed are similar though result in slightly higher end point temperatures at the boundaries. While e-fetida can handle a fairly wide range of temperature, according to Jicong et al. (2005), it prefers temperatures that are closer to 20ºC; other studies, Dominguez and Edwards, (2011), for example, suggest that 25ºC is the optimum temperature habitat for this organism. (The aforementioned Jicong et al. (2005) study actually note a pH-Temperature-moisture level parameter set optimum) So, in a bed of 31ºC core temperature, e-fetida would prefer to be in the cooler perimeter regions, which according to our results are at or near the optimum temperature for this macro-organism.

APPLICATION TO USE OF DIFFERENT BUILDING MATERIALS

The model was applied to the question of working temperatures for different building materials. The structural requirements for the digester box above the filter layer are not at all strict except for digesters that must support a solid masonry skeleton and enclosure. In fact there are

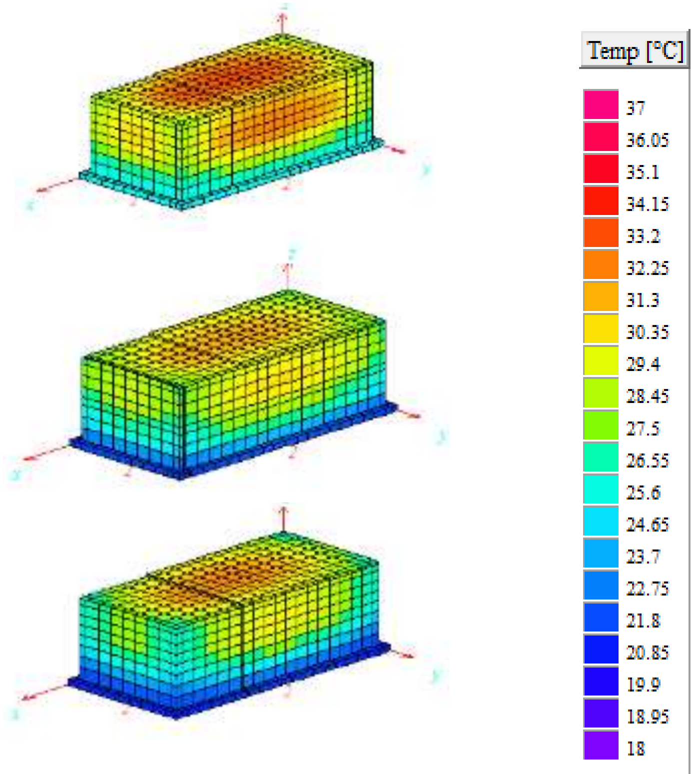

Figure 3. Surface temperature profiles for digesters place on the surface (top) halfway in the ground (middle) and completely in the ground (bottom).

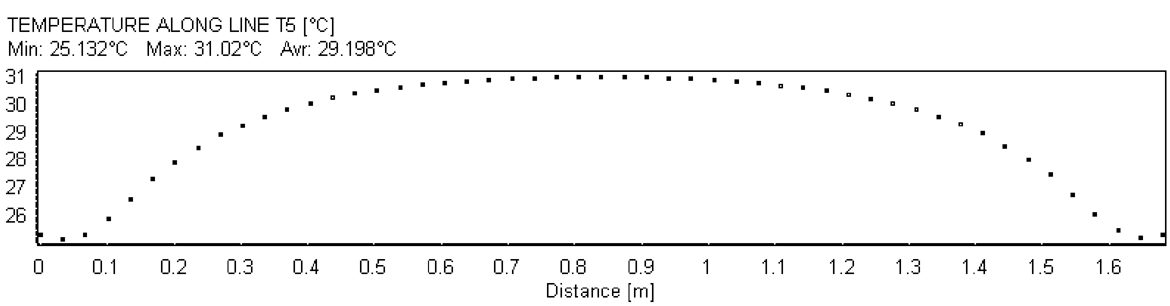

Figure 4. Temperature profile along a line (called T5) down the center of the filter-digester bed.

physically light enclosure options, such as wood frame skeletons with T and G (Tongue and Groove) siding, that are sometimes used. Such options with a typical adult live load are easily supported with a plastic enclosure that might be produced with lightweight concrete or even injection molded plastic. The question is how would such digesters perform under typical tropical conditions? Models for both materials were run until steady state conditions for a 24 h cycle were achieved. The results for early day temperatures are shown in Figure 5 for lightweight concrete (left) and plastic (right), respectively for a filter-digester installed (on the surface) at ground level. Peak temperatures for the lightweight concrete system are 32 to 33ºC while the plastic system results in temperatures from 36 to 37ºC. The lightweight concrete results are similar to those for the heavier standard mix.

This offers encouraging evidence that lightweight concrete, perhaps even concrete made with an aggregate of plastic waste (Siddique, 2008), could function nicely as a building feedstock for the digester. Results for a plastic digester, however, raise concern about the effect on survival of organisms such as e-fetida, the common 'worker' in the GSAP Microflush system. The higher temperatures in a plastic digester installed at ground level are well beyond the optimum for e-fetida and beyond the high end of what they can tolerate over a long period. It is interesting to note that a recent study (Fahrenkamp-Uppenbrink, 2016) found that earthworms introduced in a

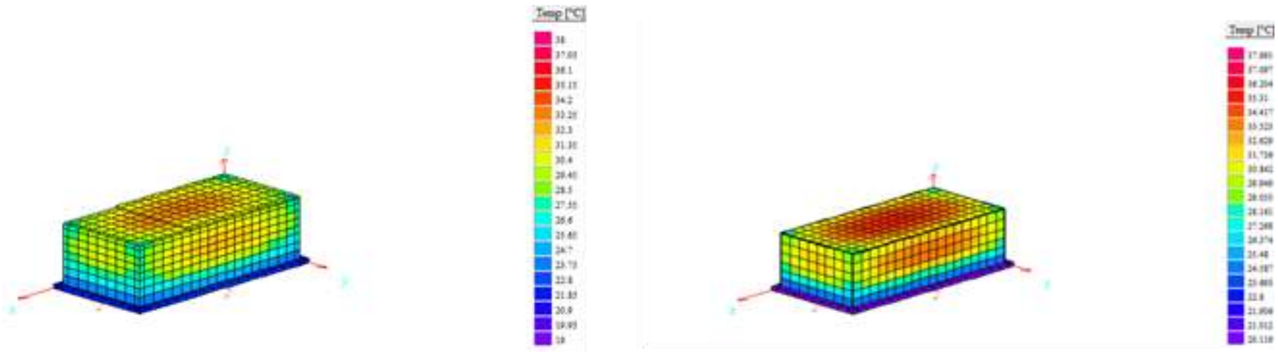

Figure 5. Surface temperatures for am above ground digester fabricated with lightweight concrete (left) and plastic (right).

Table 1. Maximum, minimum and mean temperatures of the Bekaa Valley in Lebanon.

Months	Jan	Feb	Mar	Apr	May	June	July	August	Sep	Oct	Nov	Dec
Temp.Max (ºC)	11.5	12.7	16.6	21.3	27.3	31.4	33.8	34.3	31.1	26.1	18.7	13.8
Temp.Min (ºC)	-1.2	-0.4	1.3	3.8	6.8	9.1	11.5	11.8	9.8	7.1	2.6	0
Temp.Mean (ºC)	5.2	6.1	12.6	12.6	17	20.3	22.7	23	20.4	16.6	10.6	6.9

plant environment with micro-plastics resulted in mortality and reduced growth of the macro-organisms. Such a factor in a plastic fabricated and encased filter-digester over time could influence the efficacy of the digestion process as well as impact soils and groundwater into which filtrate is released. The natural vermiculture process operating so well in an otherwise sustainable design could be compromised by a plastic intensive structure.

APPLICATION TO DIFFERENT CLIMATES

The S-Lab has been asked about the applicability of the GSAP microflush toilet in regions where freezing conditions prevail during winter months. Here, average temperatures and the extent and duration of temperature swings are more important than questions relating to temperature distributions. One of these analyses was carried out for the Bekaa Valley in eastern Lebanon, where GSAP microflush toilets are being considered at resettlement camp dwellings for refugees of the Syrian war. The monthly temperatures for this region are shown in Table 1. A number of simulations were carried out for the harshest month, January, using the temperature data. The extreme conditions in the coldest month were used in the model. This month, January, sees freezing degree days hovering just above zero. A stepped temperature gradient from air to 3 feet into the ground was used for the surface boundary conditions. The model was run using time steps of 9.8 sec until equilibrium diurnal results were seen. Surface temperature profiles for an optimally used in ground digester are shown in Figure 6. The habitable temperature range for e-fetida is 0 to 35ºC. Below 10ºC, there is little feeding and below 4 or 5ºC, the organism hibernates (Dominguez and Edwards, 2011). The progressive results over time shown in Figure 6 display temperatures that are always above the hibernation temperature. The maximum temperatures, ~16ºC, is about 10ºC below that found in tropical installations but within the habitable zone for e-fetida. Hence, the digester will function in conditions such as those found in the Bekaa Valley; during January, the coldest month, the macro-organisms will survive without hibernation though there will be a slowdown in composting activity as their feeding rate slows.

Conclusions

Solutions of the heat conduction equations for the GSAP microflush filter-digester have been carried out for multiple installation conditions and appropriate boundary conditions for both tropical and colder environments with multiple purposes in mind. Simulations for tropical conditions clearly demonstrate that perimeter regions of the bed have temperatures that are optimal for e-fetida, the macro-organism most frequently used in the system. The results are consistent with reported observations of higher densities of e-fetida in this region of the filter-digester bed. In concluding this piece of the study, we note that, while one might expect a household waste stream to be fairly constant with respect to digester loading and C/N ratio, these can change over time with a resulting impact on all of the factors important to the efficiency of the digester process (T, pH, moisture and oxygen). The question of an optimal (with respect to these parameters) habitat is the

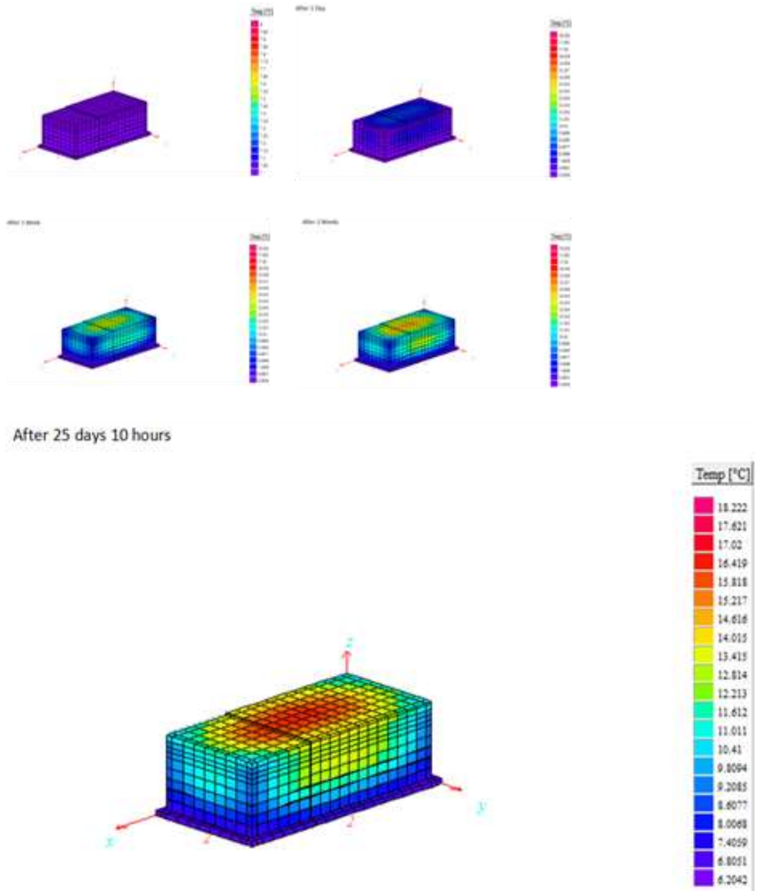

Figure 6. Temperatures for an in-ground digester simulated from an arbitrary initial temperature state to the steady state for weather conditions for the coldest period in the Bekaa valley in eastern Lebanon. Upper left, initial state - scale is 7 to 8ºC); upper right, after 1 day; middle left, after 1 week; middle right, after 2 weeks scales for these three is 6.2 to 18.2ºC); equilibrium after 25 days, 10 h scale is 6.8 to 18.2ºC).

subject of an ongoing long-term effort in the S-Lab. Cold weather simulations were carried out for the eastern region of Lebanon. While the GSAP Microflush toilet was designed for warm weather conditions, the simulations for Lebanon suggest internal temperatures that, while not optimum, are habitable for e-fetida and useful for the decomposition process. Finally, alternative digester materials were studied with the result that lightweight concrete might be useful but all plastic construction under certain installation conditions could result in temperature swings that would be deadly for the key macro-organism, e-fetida, and a result that is also consistent with recent studies showing development and mortality impacts of plastic exposure in a vermiculture bed.

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