Ultrasound Assisted Stand Alone Toilet for Rural Areas

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***Abstract*—Application of Ultrasound to a new concept of toilet in assisting waste removal with reduced water is being attempted. Ultrasound is also used to assist waste processing by subjecting smaller batch volumes of waste to short bursts of high power ultrasonic waves. A standalone toilet concept is being developed for rural areas without access to sanitary or water connections. The concept makes use of a solar panel for powering the ultrasound electronics. Aerobic composting of the ultrasound treated waste and water recycling for assisting wash water reduction is also employed.**

Keywords—Ultrasound, Cavitation, Low power, Design of Experiments (DoE), Degree of Freedom (DoF), Transducer.

I. Introduction

Ultrasound has been tried earlier as a method to treat sewage sludge and disinfection of waste. In this prototype development, Ultrasound is used to displace faecal waste with lower wash water in a redesigned toilet seat. High power ultrasound is also used to reduce the waste content volume to assist in reducing the size of the storage container for waste. Several factors influence the displacement of waste and waste volume reduction and a design of experiments was evaluated to identify the main influencing factors. Based on the outcome of the design of factors, the parameters were selected for developing the functional proof of concept prototype. The design consists of two main parts, a squat style toilet seat and a settling tank for collecting the faecal waste. The development was split into two phases, a Design of Experiments phase and a Prototype development phase. The Design of experiments was required to access the main influencing factors which were then used for the prototype development.

At this stage, the Design of experiments is completed and the prototype testing is in progress.

II. Design of experiments (DoE)

A. Identifying Factors and Response

In a toilet seat, several factors influence the effect of ultrasound on displacement of waste across a medium. 7 factors were identified after initial research and reviewing, and the corresponding range of values that would be feasible to implement in a toilet seat were also listed. These factors and the levels are listed in Table 1 and Table 2.

Table 1: Factors and levels for the Seat DoE

Factors	Levels		Remarks
	1	*2*	
Finish / Coat	Polished	Teflon	Affordable finish on metal surfaces.
Transducer Frequency	25 kHZ	54 kHZ	Frequencies around 45kHZ are effective.
Transmit Power	0.5 W/cm^2	1.0 W/cm^2	Lower power used for near field ultrasonic.
Surface inclination	65 degree	85 degree	Side walls of toilet seat will be within this range.
Waste water content	50%	80%	Typical water content in faecal waste is 77%.
Volume of waste	10 ml	30 ml	The volume of waste affects adherence.
Water flow rate per transducer	0 ml	10 ml / min	Displacement with no water and a flow for ultrasound coupling.

The measurable responses would be the displacement of waste in a fixed time of 30 secs and the audible sound level.

Similarly, factors and levels were established for the second set of Design of experiments aimed at the Settling tank. They are listed below:

Table 2: Factors and levels for Settling tank DoE

Factors	Levels			Notes / Remarks
	1	*2*	*3*	
SS Polished Material Thickness	1.0 mm	1.6 mm	2.0 mm	This range is typically used in high power ultrasound cleaners.
Transducer Frequency	20 kHZ	30 kHZ	40 kHZ	Low frequency Ultrasound is effective for cell disintegration.
Transmit Power	50W	75W	100W	Power input into transducer, typical power ratings of a single transducer.
On Time	30 min	60 min	90 min	Longer time of sonification helps breaking down of the solid waste.
Off time	30 min	60 min	90 min	Off time allows broken down waste to settle down.

The measurable response for the settling tank design of experiments would be reduction in overall waste volume.

A test plan each for the toilet seat, 7 factors and 12 runs, and the settling tank, 5 factors and 19 runs, was arrived at based on the number of factors, levels and the possible interaction of factors. These are listed in the following tables. Standard Taguchi Orthogonal arrays were used to prepare the test sequence and combination of parameters.

TABLE 3: EXPERIMENTAL LIST FOR TOILET SEAT DOE

Factors	**Levels**		**Degree of Freedom**
	1	***2***	
Finish / Coat	Polished	Teflon	1
Transducer Freq	25 kHZ	54 kHZ	1
Transmit Power	0.5 W / cm^2	1.0 W / cm^2	1
Surface inclination	65 deg	85 deg	1
Waste water content	50%	80%	1
Volume of waste	10 ml	30 ml	1
Water flow rate	0 ml	10 ml / min	1
Interactions considered:			
Interaction 1	Water Flow Rate	Power	1
Interaction 2	Volume of Waste	Frequency	1
Interaction 3	Volume of Waste	Power	1
Total Degree of Freedom (DOF)			10
Total Factors			7
Maximum number of levels			2
Suitable Taguchi Orthogonal Array			L12

TABLE 4: EXPERIMENTAL LIST FOR SETTLING TANK DOE

Factors	**Levels**			**Degree of Freedom**
	1	***2***	***3***	
SS Thickness	1.0 mm	*1.60 mm*	2.0 mm	2
Transducer Freq	20 kHZ	*30 kHZ*	40 kHZ	2
Transmit Power	50W	*75W*	100W	2
On Time	30 min	*60 min*	90 min	2
Off time	30 min	*60 min*	90 min	2
Interactions Considered:				
Interaction 1	Frequency	On Time		2
Interaction 2	Power	On Time		2
Interaction 3	On Time	Off Time		2
Total Degree of Freedom (DOF)				16
Total Factors				5
Maximum number of Levels				3
Suitable Taguchi Orthogonal Array				L19

B. *Design of Experiments Setup*

Simulated waste was used for conducting the design of experiments. It was prepared using commercially available items, according to a standard recipe described in the link http://mentalfloss.com/article/56003/recipe-fake-poop.

Test templates were used to simulate the side walls of a toilet seat. Multiple templates were made of stainless steel sheet of 1.0mm thickness, grade SS316. The inner surface of the template was finished with either a polished surface or coated with hydrophobic spray, Scotch Insulating spray type 1602-R, and assembled with the respective ultrasound transducer of 25 kHz and 54 kHz. A fixture to hold the test place in place provided a means to adjust the slope of the test face to 65 and 85 degree. A set of water nozzles at the top of the test plate connected to a valve provided a means of adjusting the water flow. An adjustable frequency ultrasound transducer driver is used to drive the transducer mounted on the test plate. Simulated waste was prepared before the start of the experiment and placed manually at a known location on the test plate. After exciting the transducer for the fixed time, the displacement of the waste was measured with a measuring tape.

The settling tanks were fabricated from stainless steel with thickness of 1.0, 1.6 and 2.0 mm. The bottom surface of the tanks were fitted with ultrasound transducers with the help of stubs welded to the tank and hard setting epoxy. A measured volume of simulated waste and an equal amount of water was used for each experiment. The volume of the waste was measured, as a function of height, before and after the ultrasound excitation. The transducers were driven with adjustable frequency ultrasound transducer driver and current through the transducer was measured to calculate the power.

The test setups are shown in Fig. 1 and Fig. 2.

Figure 1: Test setup for the Toilet Seat Design of Experiments

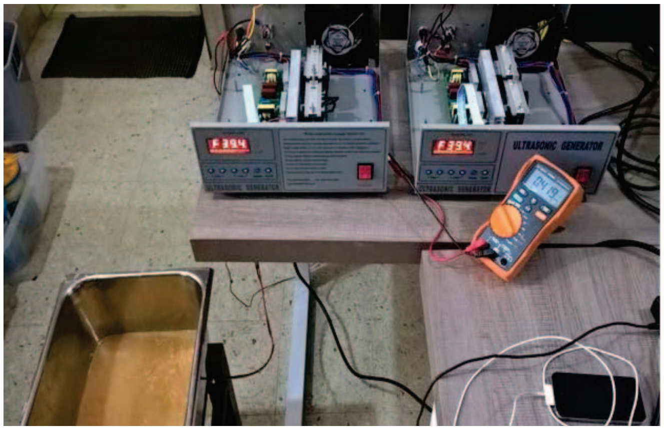

Figure 2: Test setup for Settling tank Design of Experiments

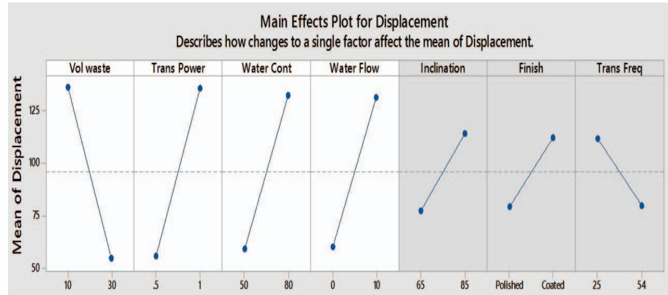

Figure 4: Effects plot for waste displacement in Toilet seat

C. *Design of Experiments Results*

The results of the toilet seat Design of Experiments show that the factors, which are not controllable, influencing maximum displacement of waste in the toilet seat are lower volume of waste, higher water content in the waste. A lower volume of waste has smaller area of adhesion to the surface of the toilet, which is loosened easily with the ultrasound waves. Higher content of water in waste helps in coupling ultrasound waves effectively. The controllable factors influencing higher displacement are higher transducer power and higher water flow. Higher transducer power helps in loosening the waste from the surface. Higher water flow provides better coupling of ultrasound and helps in moving the waste down by gravity.

The Pareto chart of the effects is shown in Fig. 3 and the comparison of effects is shown in Fig. 4.

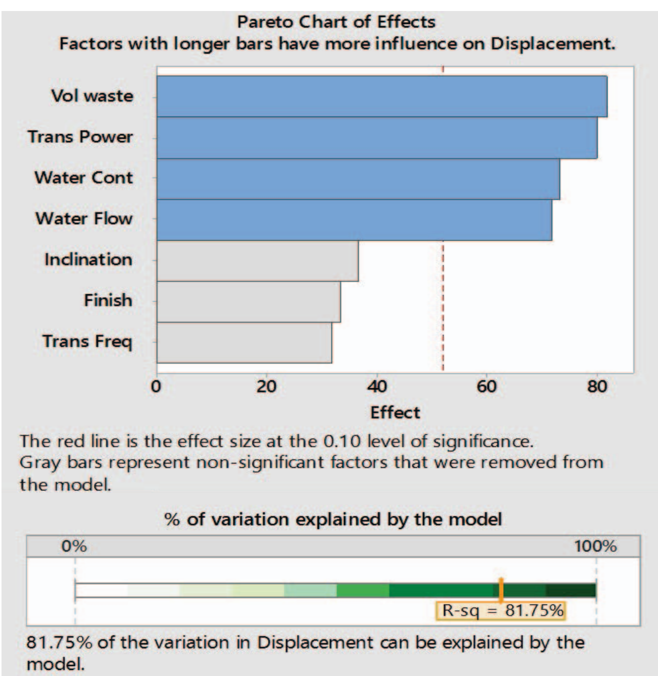

Figure 3: Pareto chart of the influence of factors on waste displacement

Audible noise was measured around the test template using a mobile phone and a measuring application. Frequency had a negligible effect on the audible noise.

The results of the settling tank Design of Experiments show that the factors influencing maximum volume reduction are the combination of higher transducer frequency and low transducer power, higher material thickness, lower transducer on time and lower transducer off time. Higher ultrasound frequency creates smaller cavitation bubbles, which implode with relatively less energy. The higher frequency creates higher number of small sized cavitation bubbles in the same volume when compared to larger cavitation bubbles created by lower frequency. The higher thickness of 2.0mm helps in propagating the ultrasound waves over a larger area of the waste. Lower power and shorter on time help in higher volume reduction when compared to higher ultrasound power and longer on times. This can be explained by the agitation caused with the higher power for longer times, while the lower power and shorter time disintegrates the larger waste blocks and assists flocculation.

The Pareto chart of the effects is shown in Fig. 5 and the comparison of effects is shown in Fig. 6.

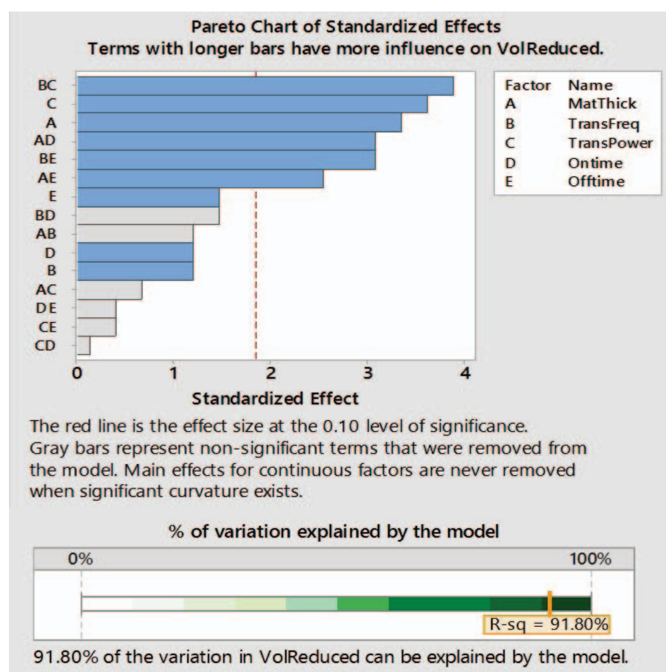

Figure 5: Pareto chart of the influence of factors on volume reduction

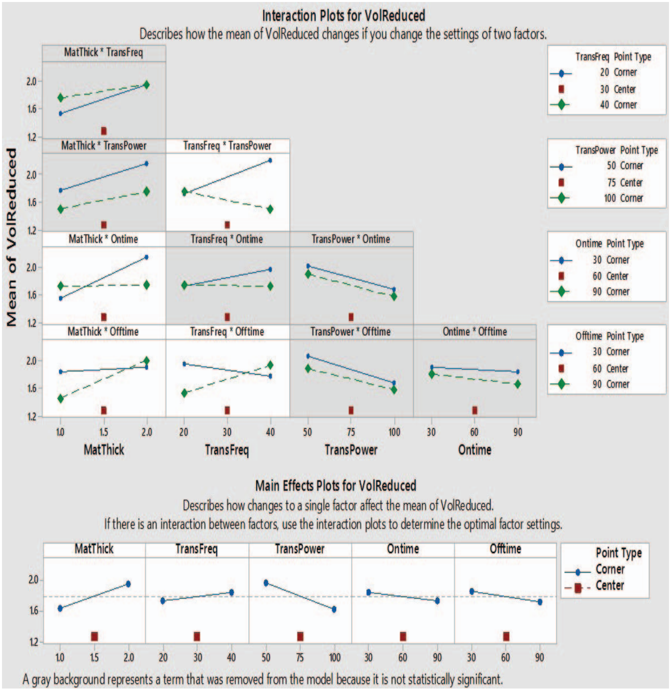

Figure 6: Interaction and main effects plot for volume reduction

A burst mode operation of the ultrasound transducer was tried with different on and off times. It was observed that the waste movement was maximized after about 4 seconds of ultrasound activation combined with a water flow, and maintaining it as long as the displacement was required.

The on time of ultrasound transducer was reduced further below 30 minutes in the settling tank setup to extend the Design of Experiments boundary. It was observed an on time of 20 minutes provided the maximum volume reduction.

Using the results of the Design of Experiments, the following parameters were narrowed down to be used in the prototype design.

For toilet seat, a transducer frequency of 40 kHZ, power of 1W per transducer and a provision to provide a water flow were chosen. For the settling tank, a material thickness of 2.0mm, a transducer frequency of 40 kHZ, power of 50W per transducer and an on time of 20 minutes were chosen.

III. Prototype Design and Fabrication

Based on the parameters used in the Design of Experiments, an initial prototype was designed which included a squat type toilet seat and a settling tank. The prototype was designed to be fabricated from stainless steel sheet metal, cut into shape, bent and seam welded. At a production level, these operations can be replaced with drawing in a die press.

The side and bottom walls of the squat toilet are made of flat surfaces to enable mounting of ultrasound transducers and maximize coupling of ultrasound waves. 40 kHz sandwich type transducers are mounted on the outer surfaces of the side and bottom walls using a hard setting epoxy. The inner surface of the squat toilet walls are coated with a suitable hydrophobic coating. Four spray nozzles are mounted on the side walls to provide a controlled water flow. The transducers are driven with a fixed frequency ultrasonic driver module. A water pump is used to force water into the four nozzles which spray water along the surface of the walls of the toilet. The water flow can be controlled by the speed of the water pump.

The settling tank is similar to the tanks used in the Design of Experiments, with the side walls flared at an angle to assist flow of waste from the toilet seat. The shape also enables uniform ultrasound waves without the side wall reflections and prevents creating zones of high and low intensity. The seat is covered with a lid with rubber sealing to prevent odour escaping into the surrounding structure. An opening in the lid connects to an exhaust pipe with a fan for forced air venting. Air is drawn from the opening in the squat toilet and sucked out to the atmosphere through the settling tank. This prevents odour from the settling tank going back into the squat toilet and surrounding area. The long exhaust pipe also facilitates natural air movement.

A low cost microcontroller is used to control the water flow and transducer drive, with feedback from sensors to detect the operational status of use of squat toilet. Transducers are driven at a lower 0.5W power during use to reduce power and audible noise. The transducers are driven at a higher 1.0W power along with higher water flow during the flushing action to facilitate removal of waste from the toilet seat. The electronics is powered from a 100W solar panel which also charges a small battery. A maximum power of 80W is required to drive the two transducers of the settling tank. The settling transducers are powered when maximum power is generated from the solar panel. A water storage tank is used to pump water into the nozzles. Sensors are used to monitor the levels of water storage tank and the waste settling tank.

A block diagram of the prototype is shown in Fig. 7.

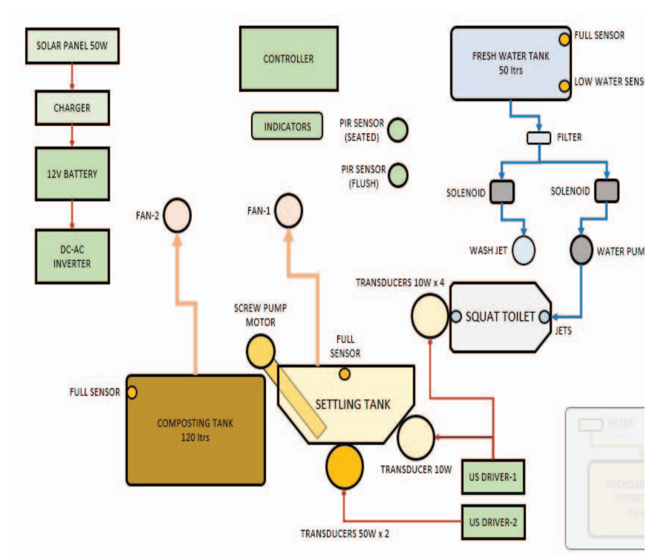

Figure 7: Block diagram of the prototype

The settling tank has a capacity of approximately 20 litres, sufficient to hold waste from a small family of six persons per day. The ultrasound transducers on the settling tank are excited when the toilet is not in use and maximum output is available from the solar panel. The waste contents are then shifted to a larger composting tank by using a screw pump, driven by a DC motor. A second exhaust with natural air convection, assisted by forced air flow using a dc fan, helps in aerobic composting and removing odour away from the enclosure. An infrared sensor is used to detect the presence of a user and start the water flow and driving of ultrasound transducers at a low power level. A second IR sensor is used to detect a flush request and increase the water flow, drive the transducers at a higher power output. Level sensors detect the contents of the water tank, settling tank, composting tank and provide indications to the user.

The CAD representations of the toilet seat and settling tank are shown in Fig. 8. The pictures of the fabricated parts are shown in Fig. 9 and Fig. 10.

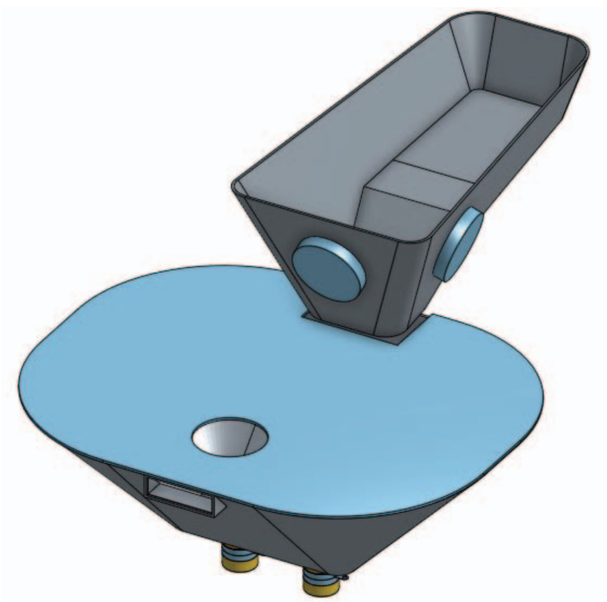

Figure 8: Squat toilet and settling tank modelling

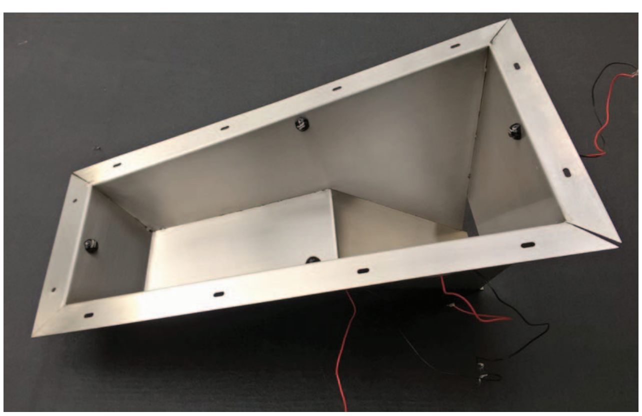

Figure 9: Fabricated part of squat toilet with transducers assembled

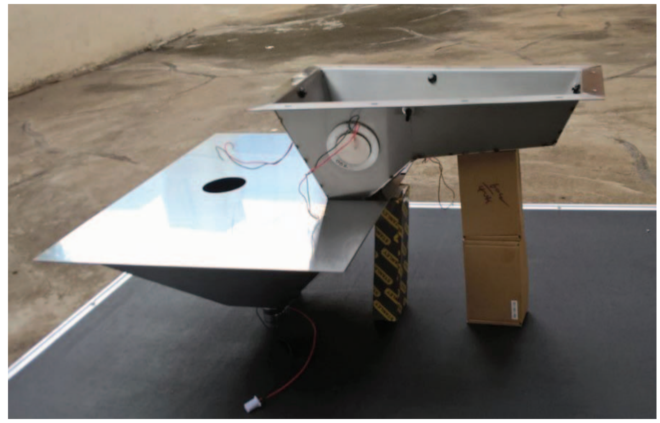

Figure 10: Preliminary assembly of the fabricated parts

Fabrication of the prototype toilet seat and settling tank is done using readily available SS316 grade stainless steel sheets which are laser cut, bent to shape and then seam welded at the outer edges. The low power sandwich transducers are mounted on the outer surface of the toilet seat using epoxy resin. Water jet nozzles are mounted near the top edge of the four walls of the toilet seat and are connected by rubber tubing to a single solenoid valve. The solenoid valve is also connected to an overhead water storage tank and controlled by a microcontroller. Threaded stubs are welded on the outer bottom surface of the settling tank and the high power Langevin type transducers are secured on to these stubs, along with epoxy. The toilet seat and settling tank assemblies are held in place by mounting them on a tubular PVC frame. The transducers are connected to the outputs of separate ultrasound transducer driver boards which are controlled by the microcontroller. A picture of the assembled prototype on the tubular frame is shown in Fig. 11.

Testing of the prototype to measure wash water in the toilet seat, settling and compaction of waste in the settling tank is in progress.

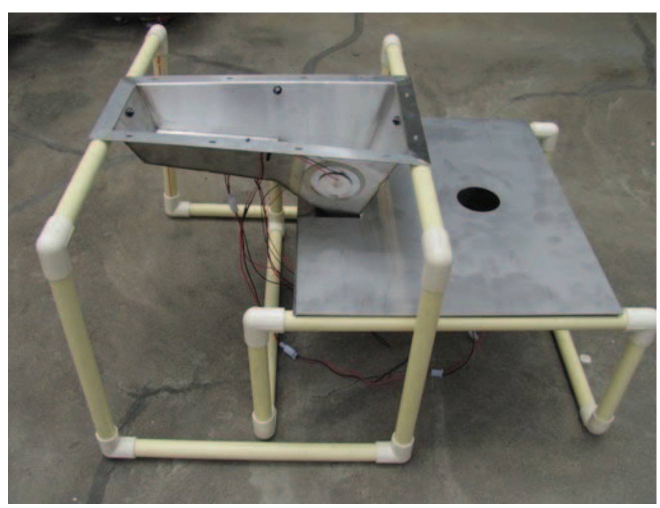

Figure 11: Assembly of the prototype Seat and Tank on PVC tube

IV. CONCLUSION

Ultrasound can be effectively used in a stand alone toilet system to reduce wash water significantly and reduce the volume of waste to be stored and treated. The design of experiments helps identify the influencing factors and their levels for maximizing waste displacement and volume reduction. The Design of Experiments also provide an initial estimate of the water and power requirements. With a proposed water flow of 50mL per minute for the four walls mounted with transducers, it is expected to have total water consumption of approximately 250mL during a 5 minute use. With an additional 100mL for a power flush at the end of use, the total water usage per use is expected to be within 350mL. The average power consumed for the ultrasound transducers and other electronics during use will be 3W with a peak power of 5W during power flush, which can be powered from a portable battery. The peak power consumed by the settling tank will be 100W for a 30 minute duration, which can be powered from a solar panel. This will help design a toilet system with reduced wash water, smaller waste holding and processing tanks. Designing for batch treatment of waste, the power required to drive the transducers can be lowered in order to enable use of solar panels.

Testing of the prototype will help verify the water and power requirements estimated by the results obtained from Design of Experiments.

ACKNOWLEDGMENT

The Authors like to acknowledge Biotechnology Industry Research Assistance Council, Department of Biotechnology, India for sponsoring the project. The Authors also like to acknowledge Bill and Melinda Gates foundation for supporting the activities in design and development of the prototype.

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