ISEIS

Journal of Environmental Informatics Letters 6(2) 68-74 (2021)

Journal of Environmental Informatics Letters

www.iseis.org/jeil

Design and Performance for A Novel Low-Tech Water Filter System

E. McBean[1 *] and C. Farrow[1]

[1] *School of Engineering, University of Guelph, Guelph, Ontario, N1G 2W1, Canada*

Received 17 January 2021; revised 07 February 2021; accepted 14 February 2021; published online 02 June 2021

ABSTRACT. A low-tech water treatment system with a novel configuration is described which delivers safe water (>3 log-removal of *E. coli*), has low cost, provides safe water in quantities for a household for substantial time periods, is easy to maintain, robust against breakage, and avoids recontamination. Due to the unique design, the Guelph Water Filtration system (Guelph Water Filter) remains functional for periods substantially longer than previous technologies, providing ~6 years for delivery of treated water at flow rates exceeding 1 L/hr (for low turbidity (0.05 ~ 1.00 NTU) source water). The ceramic filter components of the system are easily replaceable in the filter housing and the Guelph Water Filter is feasible as a village-level production/employment opportunity. The long-term performance of the ceramic filter component of the Guelph system improves longevity of performance by reducing clogging and enables two filter elements to be used in a single filter housing (doubling the surface area through which filtration occurs). Placing the filter in a large reservoir (pail) also significantly reduces the frequency of the need to refill raw water (alternative filter designs require refilling and monitoring multiple times per day).

Keywords: low-tech, ceramic filter, clay pot filter, point-of-use water filtration, Guelph Water Filter

1. Introduction

Although access to safe drinking water is defined as a basic human right (WHO/UNICEF, 2015), approximately 10% of the world's population lacks this access (access is defined herein as an improved drinking water source within a 30-minute travel time) (WHO, 2019). As McBean (2017) describes, issues making this even more concerning include: increases in population, climate change resulting in desertification, and widespread population migration and poverty, all of which are inhibiting access to safe water. Currently, 29% of the global population lacks consistent access to a safe potable water supply (located on premises, free of microbial and chemical contaminants and available at all times) (WHO, 2019). Clearly, the situation regarding access to safe drinking water is deteriorating and promises to become an even more dramatic challenge in the future.

With widespread faecal contamination of water sources due to lack of proper sanitation facilities, diarrheal disease is a major obstacle. Two billion people rely on a drinking water source with faecal contamination (WHO, 2019). Waterborne pathogen diseases continue to be amongst the largest cause of death of children under five years of age. Diarrhoeal diseases, caused by the faecal contamination of drinking water sources, is estimated to cause 485,000 deaths annually (WHO, 2019). Fatalities due to diarrhoeal diseases are typically the result of severe dehydration and fluid loss, with malnourished children and immune-compromised individuals being at the highest risk (WHO/UNICEF, 2015). Among the world's populations where poverty is most severe, diarrheal diseases are the second leading cause of death (WHO, 2017).

For the many reasons indicated above, there is a clear need for improved, safe water provision for the increasingly burdened rural poor. To make matters worse, centralized water treatment and distribution systems are becoming increasingly less common (e.g., in Argentina, many in the suburbs of Buenos Aires are no longer receiving piped water to households, as a cost-cutting measure (Lenton, 2020)). Hence, rural and impoverished persons' access to safe water is rapidly deteriorateing, and improved, affordable point-of-use (POU) technologies are becoming increasingly essential.

A substantial array of ceramic filters (e.g., Franz, 2005; Halem et al., 2007; Brown and Sobsey, 2010; Farrow et al., 2018) have been used for several decades, in the search for a water treatment technology to deliver safe water. Moderate success has been achieved but failures of such water treatment systems continue.

This paper describes a novel technology design for water treatment as a 'system'. Important reliance is still upon the ceramic filter, but it is the housing of the filters and the functionality of the combination of components involved in the Guelph system that is key to its success. This novel water treatment system captures many dimensions, all introduced with the aim of facilitating the provision of safe water supplies for rural, impoverished persons.

* Corresponding author. Tel.: +1 206 369 3679.
E-mail address: emcbean@uoguelph.ca (E. McBean).

ISSN: 2663-6859 print/2663-6867 online
 doi:10.3808/jeil.202100059

2. Description of Important Characteristics of A Low-Tech Water Treatment System Including A Literature Review of Previous Technologies

While technologies for delivery of safe water at POU are increasing in importance, the most important dimensions of a treatment system include:

(i) Affordability — The people at most risk and need are in villages and suburbs (limited access to centralized water treatment solutions), with limited financial resources. Ongoing costs of chemical additions (e.g. chlorine tablets for disinfection), chemical filtration media and other consumable products are extremely challenging;

(ii) Ability to Deliver Safe Water in Quantities Needed for a Household — This is typically taken as 3-log removal or 99.9% removal of waterborne bacteria and protozoa, and the ability to deliver safe water at a rate of at least 1 L/hour to the household. This translates to having sufficient water for consumption and cooking, for a family;

(iii) Ease and Simplicity of Operation and Maintenance — The technology must be simple to operate and, when something malfunctions, local knowledge and parts must be available;

(iv) Robustness Against Breakage — The water treatment technology must be able to be maintained, as needed, and resistant to major breakage during required periodic maintenance;

(v) Avoid Recontamination of the Treated Water — A successful technology needs to avoid/minimize opportunities for recontamination of the treated water; and,

(vi) Have a reliably long, functional life.

The above list is a challenging list of dimensions, but all have importance in whether a low-tech water treatment technology system will truly have a significant beneficial impact for POU users.

While awareness of the needs for improving water quality has evolved over thousands of years (McBean, 2019), the necessary technologies to deliver safe water to consumers have been largely attained for large water treatment systems; however, the provision of safe water for the rural poor continues to be a major issue. With limited financial resources, continuing purchases of chemicals and filters of different character remains an ongoing challenge. In response, about 20 years ago, the ‘clay pot’ as illustrated in Figure 1 was created and, for the time, represented a major improvement.

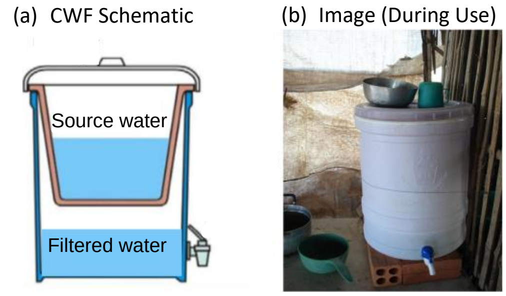

Figure 1. (a) Ceramic water filter schematic, and (b) Image during use.

The primary component of a clay pot water filter is the source material utilized to form the ceramic filter element, involveing a mixture of clay and a sacrificial material (commonly rice husk, coffee grounds or sawdust) formed into the shape of a pot and then kiln-fired at 850 °C. Sacrificial material typically comprises 15 ~ 20% of the source material by weight to allow adequate filtration rate while maintaining acceptable levels of bacterial filtration.

Pore size distribution is controlled by milling/grinding of the sacrificial material (Annan et al., 2018). Once fired, the resulting porosity of the clay pot ceramic filter can provide filtration capable of 3-log removal of bacteria and protozoa (see Table 1). Development of the clay pot was an important breakthrough, providing removal by filtration of many waterborne

Table 1. Summary of Ceramic Water Filters: Pathogen Removal

Reference	CWF Design	Pathogen	Flow Rate (L/hr)	Influent concentration (CFU/100 mL, PFU/100 mL)	Log Removal Value (LRV)
Simonis and Basson, 2011	Pot	*E. coli*	1 ~ 2	6.0×10^6	5.5
		S. feacalis		1.5×10^4	4.2
		B. cerues		1.1×10^6	3.6
		Poliovirus		7.25×10^4	1.9
Bielefeldt et al., 2009	Pot	*E. coli*	1.7	1.0×10^4	3.7
		E. coli	1.9	1.0×10^4	4.0
		0.5 µm microsphere	2.0	1.0×10^8	2.0
		0.02 µm microsphere	2.0	1.0×10^8	1.5
		10 µm microsphere	2.0	1.0×10^8	3.3
		Bacteriophage MS_2	2.0	$1.0 \times 10^2 \sim 1.0 \times 10^5$	1.2 ~ 4.1
Halem et al., 2007	Pot	*E. coli*	2.0 ~ 5.0	5×10^1	0.5 ~ 3
Franz, 2005	Candle	*E. coli*	0.035 ~ 0.454	-	2.1 ~ 5
Brown and Sobsey, 2010	Pot	*E. coli*	-	1×10^3	2 ~ 6
Murphy et al., 2010	Pot	*E. coli*	1 ~ 3	-	0.5 ~ 2.5

pathogens, and evolved to be widely used (e.g., Murphy et al., 2010a, 2010b; Farrow et al., 2014; Mellor et al., 2014). However, challenges with the clay pot technology include clogging due to waterborne sediments in the raw water (resulting in decreased flow rate through the filter), requiring frequent brushing of the interior of the clay pot. Brushing is difficult due to the substantial weight of the pot, and the exterior of the pot (the side that must be maintained as 'clean') is easily contaminated by the enduser during the cleaning/brushing procedure due to the need to support the pot while cleaning.

Ceramic water filters (CWFs) in the form of pots are conventionally 6 ~ 7 kg in weight and are therefore cumbersome, leading to accidental damage during maintenance, moving, etc. Additionally, ceramic water pots only hold approximately 10 L of raw water at any time, therefore requiring frequent refilling.

Compounding the issue of contamination and breakage, the decreasing pressure head during use results in a decrease in flow rate after several hours of use and the need for frequent refilling. As an indication, an illustration of flow rate as a function of hydraulic head during operation of ceramic disc filters is shown in Figure 2. A significant increase in flow rate is achieved with an increase in hydraulic pressure. The impacts of hydraulic head on flow rate are significant when comparing clay pot-designs to alternatives.

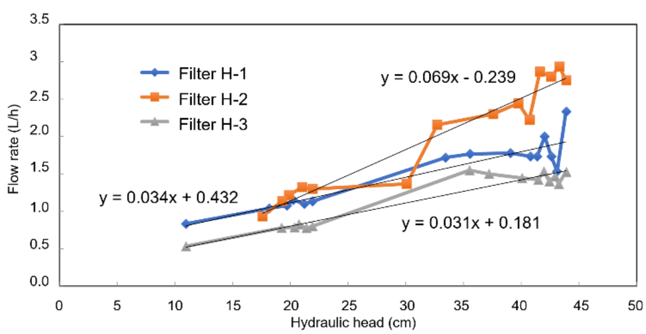

Figure 2. Flow rate (L/h) vs. hydraulic head (cm); ceramic disc filters (n = 3).

Other ceramic water filter designs have been proposed including the candle-shaped filter (Franz, 2005) and column or bottle-shaped filters (Brown et al., 2019; see Figure 3 as an example) placed at the bottom of a large pail. Use of a large raw water reservoir has significant advantages with regards to maintaining sufficient flow-through rates, enabling less frequent filling and higher hydraulic throughput due to depth of water in the pail. A major disadvantage of column and candle-shaped filters is the difficulty of cleaning and maintenance. To maintain acceptable flow rates, the exterior surface of the filter needs to be scrubbed once per week. A cylindrical design is difficult to clean effectively (particularly when submerged).

Other types of low-tech water treatment systems also exist including membrane filter systems (e.g. LifeStraw), chlorintion, and biosand filters (e.g. reviewed in Murphy et al., 2010c; Perez-Vidal et al., 2016). Some of the membrane filter systems are effective wherein a raw-water reservoir is at the top of the water treatment system, the membrane microfilter separating the top container from the bottom reservoir removes the sediments via filtration. As the membrane filter becomes clogged, provision is made to backwash the filter by pumping a portion of the treated water back up through the filter. However, these types of membrane filter technologies entail high costs (e.g. typically, considerably more than $100 USD) whereas the clay pot is distributed in Cambodia by Resource Development International for $8 USD (RDI, 2020). In other respects, ceramic pot filters are superior to biosand filters, chlorine and safe water storage, and coagulant chlorine technologies, particularly due to costs of purchase and continuing use. Hunter (2009) performed a comparative study between ceramic filters and alternatives (biosand filters, chlorination, solar water disinfection, and coagulation-chlorination) and found that after 12 months, ceramic filters were operational and effective while the alternatives were ineffective.

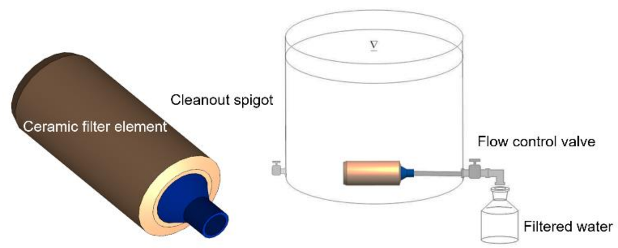

Figure 3. Ceramic column filter.

An important element of the Resource Development International — Cambodia (RDI) organization in Phnom Penh (RDI, 2020) is that the organization has a large hydraulic press which allows transformation of a large ball of clay mixed with rice into the shape of a clay pot, prior to sub-sequently being kiln-fired, then air-dried and made available for sale. While valuable, the provision of a large hydraulic press is infeasible at a village level due to economic constraints. Filter presses are typically 2,300 USD (not including labour and transport) (Henry et al., 2013). The full cost of initializing a filter production facility, with a hydraulic press, can range from 5,000 ~ 8,000 USD (Henry et al., 2013).

While the most common drinking water treatment solutions available in the developed/urban world include centralized treatment and distribution, there are limited options applicable to rural and remote communities that lack the infrastructure for water distribution systems, making POU technologies required. As apparent from the dimensions of technology described above, there are many options available for water filtration in the world today, but the number of affordable, applicable, effective, and long-lasting solutions are minimal for the impoverished, rural environment.

A major (and generally, the most important) issue with a POU technology is affordability. Many families still live on less than 1.90 USD/day (World Bank, 2020). Additionally, any POU at the household level needs to be easy to operate, have low maintenance (including ability to be easily cleaned), and avoid contamination of the filter element (hence limiting/avoiding human contact with the interior/clean-surface of the filter).

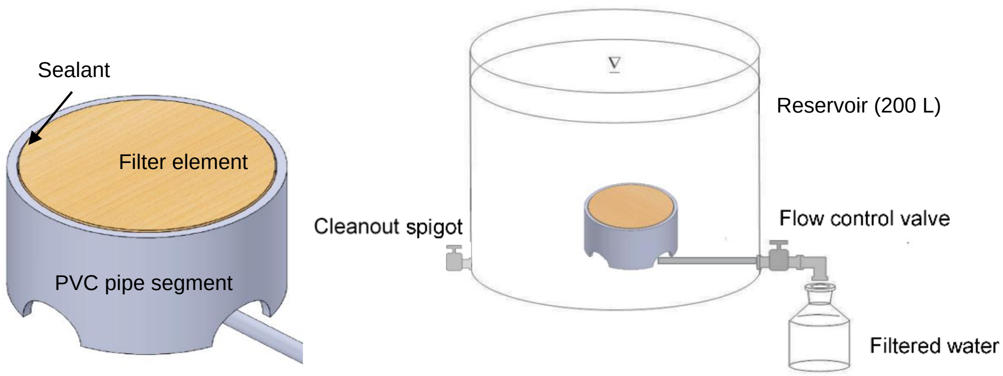

Figure 4. Ceramic disc filter: horizontal technology (HT).

3. Guelph Water Filter System

Stage 1 — Horizontal Technology (HT) Version of Guelph Water Filtration System

In response to the above-noted challenges, use of a 20 cm diameter clay disk sealed in a short length (8 cm long) of standard PVC pipe (horizontal technology or HT) has been proposed (McBean et al., 2019, see Figure 4). When the HT is placed at the bottom of a large pail, low frequency of refilling raw water as well as increased pressure head is achieved, in comparison to ceramic pot designs (as per Figure 1). Regarding the issue of the loss of hydraulic throughput due to clogging of the filter element, sediments within the raw water as well as fragments of the filter have been identified to be the primary causes of clogging. During periodic maintenance, the filter surface is brushed with a nylon brush resulting in particulate matter being released from the filter but a portion of this particulate matter settles into the pore structure of the filter, decreasing the hydraulic throughput, when utilizing the HT design.

Evaluation of ceramic disc filters (HT design) indicated a lifetime throughput volume of 7,300 L (throughput volume is defined as the volume of water treated prior to the flow rate dropping below 1 L/h and an expected filter life of 2.5 years (assuming a consumption rate of 2 L/person/day and a household of 4 people) (McBean et al., 2019).

With horizontal placement of the ceramic disk filters, both sources of sediments (raw water and fragments of the filter itself) tend to be entrained in the ceramic filter over time. Salvinelli et al. (2016) evaluated the flow-through rates of ceramic pot filters and found similar results (in regard to flow deterioration) to the horizontal disc filters. Suitable flow rates were maintained for 8,000 L of throughput volume with non-turbid influent sources during testing of ceramic pot filters (Salvinelli et al., 2016).

E.coli challenge tests at concentrations ranging from $5 \times 10^4 \sim 5 \times 10^5$ CFU/100mL have been conducted for the HT configuration. All samples were analyzed following EPA Method 1603 (Method 1603: *Escherichia coli* (*E. coli*) in water by membrane filtration using modified membrane-thermotolerant *E. coli* agar). Disc filters attain similar pathogen removal rates to alternative designs (including pot, candle, column, etc.) (e.g. Farrow et al., 2018; Brown et al., 2019; McBean et al., 2019). Analysis of the Guelph Water Filter system indicates *E. coli* removal of 3.5 ~ 4.5 LRV.

Stage 2 — Vertical Technology Version (VT) of Guelph Water Treatment System

To decrease the rate of filter clogging (thereby maintaining higher flow-through volumes), the novel Guelph Water Filter system utilizing vertical orientation of the filter element(s) was developed. Building from the performance of the single, HT configuration in Figure 4, a novel low-tech drinking water treatment device has been evaluated as depicted in Figure 5. The Guelph Water Filter Vertical Technology (VT) employs a dual filter design placed at the bottom of a large vessel (200 L). The VT is immersed in raw (i.e. untreated) water, and the treated water discharges out through the flow control valve into a collection vessel. The raw water reservoir only needs to be filled periodically (typically only 1 to 2 times per week), meaning less maintenance is required to maintain acceptable flow rates. The raw water reservoir (in the pail) can be periodically cleaned by occasionally removing accumulated sediments via a clean-out spigot.

The VT (see Figure 5) has two ceramic filters secured, one on each end of an 8 cm section of standard 20 cm diameter PVC pipe. Each of the ceramic filters is sealed around the edges of the vertical PVC element, and an exit drain is sealed into the interior of the PVC pipe, to allow the treated water to discharge into a 20 L plastic jug (see Figure 6).

Novel attributes of the Guelph Water Filter system include:

(a) The two vertically-aligned exterior ceramic filter portion of the treatment system reduces the potential for entrainment of suspended solids in the raw water, avoiding the particles becoming entrained into the two ceramic filters) and clogging of the filter;

(b) With two vertically-aligned filters, the production of treated water is twice as large, due to presence of two ceramic filters as part of the Guelph Water Filter system;

(c) The critical (interior) surfaces of the ceramic filters are protected from contact by the user, as they are the ‘internal’ surfaces within the PVC section and hence will not be contaminated by the user touching them;

(d) The PVC is a commercially-available size and robust against damage. The robustness of the PVC pipe segment provides protection of the system from breakage.

(a) Filter Housing with Ceramic Filter (VT)

(b) Filter (VT) within 200 L Reservoir

Figure 5. Images of vertical technology (VT): (a) filter housing with ceramic filter, and (b) VT filter within 200 L reservoir.

Performance Testing of Guelph Water Filter

The Guelph Water Filter system in both the Horizontal Treatment (HT), and the Vertical Treatment (VT) configuration approaches were tested. Both water filter systems were placed in deionized water for 48 hours prior to testing to ensure the pores were fully saturated. Each water filter was flushed with deionized water for 48 hours to remove debris and air, to minimize interference with water permeating through the internal pore structure.

Flow rates were evaluated over a period of 40 ~ 60 days. The effects of brushing are clearly evident in the figures below, with their influence on the flow rate as evident by 'X' where the flow rate is that attained immediately following completion of the brushing. Brushing was completed approximately once every 5 days.

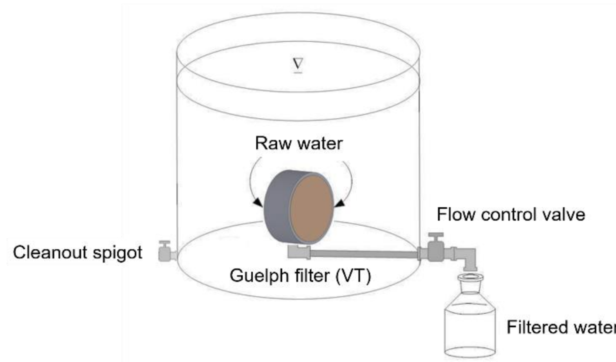

Figure 6. Guelph water filter: vertical technology.

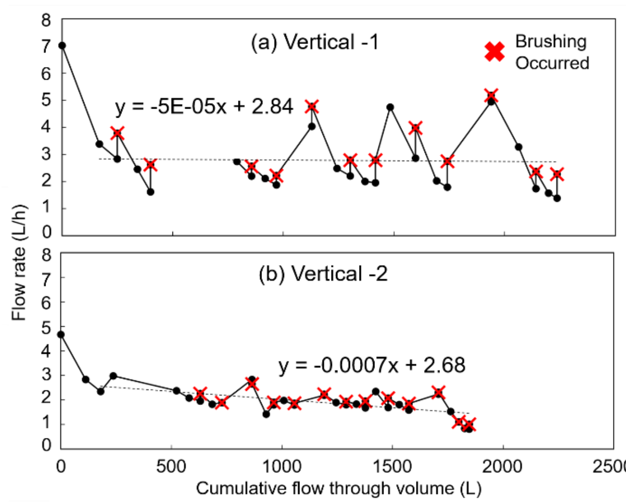

Figure 7. Hydraulic performance tests of vertical technology system: (a) Vertical-1, and (b) Vertical-2.

Figures 7(a) and (b) demonstrate performance of the Guelph Water Filter (VT) system.

A trend line through the data indicates a best-fit curve length of the plotted data. As there are two filters in the VT technology, the flow-through of the Guelph Water Filter system is the summation of the water production through two individual filters.

The filters for the purposes of this research were created using a simple disc form (approximately 20 cm in diameter and 3 cm in thickness) which could be easily manufactured at a community-level using simple materials. An average throughput volume of 19,630 L was observed. This correlates to an expected filter life of 6.7 years. As expected, variations of throughput occur due to the manufacturing process wherein a ensure results would be representative of the expected results in a small community/village.

As depicted in Figures 8(a) and (b), the vertical disc orientation is evidenced to achieve improvement in flow-through

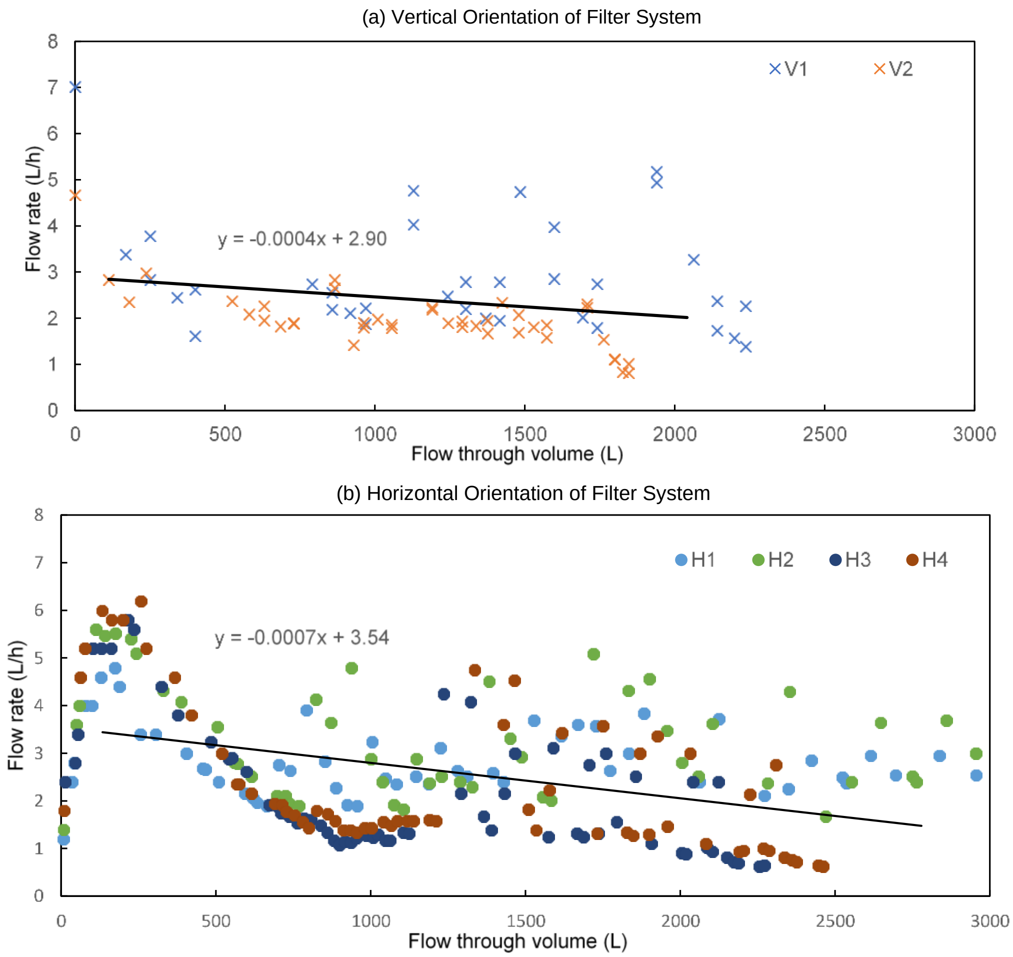

Figure 8. Comparison of flow deterioration: (a) vertical orientation of filter system (V) (n = 2) and (b) horizontal orientation of filter system (H) (n = 4) disc orientation (Horizontal disc data obtained from McBean et al., 2019).

volume due to the reduction in pore clogging during cleaning events. The comparison between vertical and horizontal filter elements was normalized based on available surface area for filtration.

4. Conclusions

Evidence of the need for improved systems for water treatment for the impoverished world populations is widely apparent. While an essential component of the Guelph Water Filtration system relies in part on the ceramic filter as an integral part of the water treatment, it is the components of the system, each responding to a particular aspect, that are keys which establish the Guelph Water Filtration system as a significant break-through for water treatment by improving the ability to provide safe water. The innovations now available with the novel system design include:

(i) A user of the vertical alignment of the ceramic filters prevents the touching of the discharge side of the filters, thereby preventing contamination of the treated water;

(ii) The PVC pipe minimizes breakage of the ceramic filter since it is enshrouded by a protective 'jacket' of commercially-available PVC pipe (20 cm diameter);

(iii) The removal of sediments from the filter is straightforward; a simple brushing of the exterior sides of the vertical alignment of the ceramic filters helps to minimize clogging of the filter from sediments and small particles from the filter itself. These sediments and particulates primarily fall to the bottom of the pail, as opposed to contributing to slowing the flow of water through the filter;

(iv) The Guelph Water Filter system prolongs the useful life for its intended purpose, namely water treatment. Occasionally, the large pail needs to be cleaned out which is easily accomplished, by having a small spigot at the bottom of the pail to allow cleaning of any accumulated sediments at the bottom of the pail;

(v) Tests of the performance of the device demonstrates that the drinking water reaches more than 3-log removal of *E. coli*, without chemical addition;

(vi) The fabrication of the ceramic filter element of the Guelph Water Filter is easily accomplished by firing the 20 cm diameter clay disks (80% clay, 20% rice husk at 850 °C), and hence is feasible at village level, providing the opportunity for local employment. Further, replacement of ceramic discs as needed is a straightforward repair process that is easily completed at the village level.

Acknowledgements. Research funding from NSERC Discovery Grant (RGPIN-2018-04623) and from the University of Guelph Research Leadership Chair funds are gratefully acknowledged. The participation of undergraduate students Justin Beauchamp and Leah Weller in the testing of ceramic filters is acknowledged.

References

Annan, E., Agyei-Tuffour, B., Bensah, Y.D., Konadu, D.S., Yaya, A., Onwona-Agyeman, B. and Nyankson, W. (2018). Application of clay ceramics and nanotechnology in water treatment: A review. *Cogen Engineering*. 5(1), 1-35. https://doi.10.1080/23311916.2018.1476017

Bielefeldt, A.R., Kowalski, K. and Summers, R.S. (2009). Bacterial treatment effectiveness of point-of-use ceramic water filters. *Water Research*. 43 (14), 3559-3565. https://doi.10.1016/j.watres.2009.04.047

Brown, D., Farrow, C., McBean, E.A., Gharabaghi, B. and Beauchamp, J. (2019). Advancing performance evaluation standards for household water treatment technologies. *Journal of Water and Health*. 17(2), 266-273. https://doi.10.2166/wh.2018.266

Brown, J. and Sobsey, M.D. (2010). Microbiological effectiveness of locally produced ceramic filters for drinking-water treatment in Cambodia. *Journal of Water and Health*. 8(1), 1-10. https://doi.10.2166/wh.2009.007

Farrow, C., McBean, E., Huang, G., Yang, A., Wu, Y.C., Liu, Z., Dai, Z. and Cawte, T. (2018). Ceramic water filters: a point-of-use water treatment technology to remove bacteria from drinking water in Longhai city, Fujian province, China. *Journal of Environmental Informatics*. 32(2), 63-68. https://doi.10.3808/jei.201800388

Farrow, C., McBean, E. and Salsali, H. (2014). Virus removal efficiency of ceramic water filters: effects of bentonite turbidity. *Water Science and Technology: Water Supply*. 14(2), 304-311. https://doi.10.2166/ws.2013.206

Franz, A. (2005). A performance study of ceramic candle filters in knya including tests for coliphage removal. *Master of Engineering Thesis: Massachusetts Institute of Technology*.

Henry, M., Maley, S. and Mehtam K. (2013). Designing a low-cost ceramic water filter press. *International Journal for Service Learning in Engineering*. 8(1), 62-77. https://doi.10.24908/ijsle.v8i1.4532

Hunter, P.R. (2009). Household water treatment in developing countries: comparing different intervention types using meta-regression. *Environmental Science and Technology*. 43(23), 8991-8997. https://doi.10.1021/es9028217

Lenton, R. (2020). Personal communication, chair of UN millennium project task force on water and sanitation.

McBean, E. (2019). Removal of emerging contaminants: the next water revolution. *Journal of Environmental Informatics Letters*. 1(1), 1-7. https://doi.10.3808/jeil.201900001

McBean, E. (2017). Water security, the nexus of water, food, population growth, and energy. *The Global Environmental Engineers Journal*. 3, 33-39. https://doi.10.15377/241 0-3624.2016.03.01.3

McBean, E., Farrow, C., Preston, T., Yang, A., Huiyan, C., Yichen, U., Zhen, L., Zhineng, D., Fu, H., Beauchamp, J., Beutel, R. and Huang, G. (2019). Investigation of maintenance impacts on flow rates in ceramic disc water filters. *Journal of Environmental Informatics Letters*. 1(2), 81-86. https://doi.10.3808/jeil.201900009

Mellor, J., Abebe, L., Ehdaie, B., Dillingham, R. and Smith, J. (2014). Modeling the sustainability of a ceramic water filter intervention. *Water Research*. 49, 286-299. https://doi.10.1016/j.watres.2013.11.035

Murphy, H., McBean, E. and Farahbakhsh. (2010). A critical evaluation of two point-of-use water treatment technologies: can they provide water that meets WHO drinking water guidelines? *Journal of Water and Health*. 8, 611-630. https://doi.org/10.2166/wh.2010.156

Murphy, H., McBean, E. and Farahbakhsh. (2010). Indicated microbial and chemical assessment of ceramic and biosand water filters in rural Cambodia. *Water, Science and Technology*. 10, 286-295. https://doi.org/10.2166/ws.2010.221

Murphy, H.M., McBean, E.A. and Farahbakhsh, K. (2010). Nitrification, denitrification and ammonification in point-of-use biosand filters in rural Cambodia. *Journal of Water and Health*. 8, 803-817. https://doi.10.2166/wh.2010.163

Pérez-Vidal, A., Diaz-Gómez, J., Castellanos-Rozo, J. and Usaquen-Perilla, O.L. (2016). Long-term evaluation of the performance of four point-of-use water filters. *Water Research*. 98, 176-182. https://doi.10.1016/j.watres.2016.04.016

Resource Development International – Cambodia (RDI). (2020). Cambodia website. https://www.info@rdic.org(accessed June 21, 2020).

Salvinelli, C., Elmore, A.C., Reidmeyer, M.R., Drake K.D. and Ahmad, K.I. (2016). Characterization of the relationship between ceramic pot filter water production and turbidity in source water. *Water Research.* 104, 28-33. https://doi. 10.1016/j.watres.2016.07.076

Simonis, J.J. and Basson, A.K. (2011). Evaluation of a low-cost ceramic micro-porous filter for elimination of common disease microorganisms. *Physics and Chemistry of the Earth.* 36 (14), 1129-1134. https://doi.10.1016/j.pce.2011.07.064

Halem, D.V., Heijman, S.G.J., Soppe, A.I.A., Dijk, J.C.V. and Amy, G.L. (2007). Ceramic silver-impregnated pot filters for household drinking water treatment in developing countries: material characterization and performance study. *Water Science and Technology: Water Supply.* 7(5-6), 9-17. https://doi.10.2166/ws.20 07.142

World Bank. (2018). *Decline of Global Extreme Poverty Continues but Has Slowed: World Bank*. https://www.worldbank.org/en/news/press-release/2018/09/19/decline-of-global-extreme-poverty-continues-but-has-slowed-world-bank (accessed June 24, 2020).

WHO/UNICEF. (2015). *Lack of sanitation for 2.4 billion people is undermining health improvements*. Final MDG progress report on water and sanitation released. Geneva/New York, USA.

WHO. (2017). *Water, Sanitation & Hygiene.* http://www.unwater.org/water-facts/water-sanitation-and-hygiene/

WHO. (2019). *Drinking-water Fact Sheet.* https://www.who.int/news-room/fact-sheets/detail/drinking-water