Delivering a low-cost, reliable drip irrigation filtration system for micro-irrigation in developing countries

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DELIVERING A LOW-COST, RELIABLE DRIP IRRIGATION FILTRATION SYSTEM FOR MICRO-IRRIGATION IN DEVELOPING COUNTRIES

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ABSTRACT

The cylindrical filters presently used in drip irrigation systems frequently clog, increasing pressure loss and lowering the flow rate through the filters. This work investigates alternative filtration strategies that increase the reliability of, and are compatible with, existing systems. To test different filtration strategies, a drip irrigation test setup was built to measure the pressure loss across different filters as particles accumulated. These experiments found that pleated cartridge filters, with high effective surface area, incurred the lowest pressure losses. More significantly, it was observed during these tests that the filtered out particles settled to the bottom of the filter housing when flow through the filter ceased. This inspired the redesign of the filter housing such that the housing extended far below the filter, providing a catch basin away from the filter for the particles to settle. Fixing the filter independently of the bottom casing significantly improves the overall performance of the filtration system and can be inexpensively manufactured via blow molding. This paper experimentally demonstrates that the cartridge filter inside the redesigned housing can filter out over 2 kg of sand while maintaining less than a .03 bar pressure drop across the filter at a flow rate of 25 l/s.

INTRODUCTION

Drip irrigation is an efficient way for subsistence farmers in developing countries to increase their crop yields. Drip irrigation systems inexpensively deliver water to the roots of plants via a series of plastic tubes (drip lines) with incrementally spaced holes or emitters, as shown in Figure 1. While drip irrigation delivers water to crops with efficiencies of up to 90% [1], surface irrigation, which has a much lower efficiency of 40-50%, is used in over 80% of the world's irrigated land [2]. Due to its low water consumption, drip irrigation may enable agriculture in dry areas and increase annual crop yields on existing farmland [3]. Despite its advantages, drip irrigation has not yet reached mainstream acceptance.

Historically, the high capital cost of drip irrigation systems has prevented wide-spread adoption, especially for small farmers in developing countries [4]. When compared to the simple labor costs of surface irrigation, the network of drip lines, thousands of emitters, and a pressure source (either a plastic tank for gravity-fed systems or an externally powered pump) necessary for drip irrigation can prove to be prohibitively expensive. Organizations such as iDE have developed low-cost drip irrigation systems targeted for small-plot subsistence farmers; however, sustaining adoption of low-cost drip irrigation kits in areas like Zambia continues to be challenging as some evaluations have shown that the majority of farmers abandoned the use of their drip kits [5].

FIGURE 1: A drip irrigation kit in use in Zambia. The elevated tank provides the pressure for water to flow through the main line to the drip lines, shown here horizontally. Photo from Tuabu, 2012 [5].

The primary cause of abandoned drip irrigation systems is unreliability and laborious maintenance that stem from frequent clogging of the irrigation lines due to particles in the source water. Although an inline mesh filter is typically installed between the water reservoir and the drip lines to prevent particles from reaching the drip lines and emitters, this filter clogs over time and requires cleaning and maintenance. In many cases, farmers remove the filter from the drip irrigation system altogether to eliminate the pressure loss created by a clogged filter [6]. This inevitably leads to emitters clogging downstream. Although a variety of filters are already available for drip irrigation, they do not meet the requirements of low-power, low-cost irrigation to serve the subsistence farmer.

A reliable, low-maintenance, inexpensive drip irrigation filter could have resounding impact on the agriculture in water deficit areas, particularly in countries like Zambia [7]. Zambia, for instance, has only reached 30% of its economic irrigation potential, and irrigation practices within the country have been shown to increase yields by two to four times that of rainfed agriculture [8]. Despite the need for efficient irrigation systems, only 10% of irrigated land in Zambia is drip irrigated [8]. Rainfed agriculture is unreliable, and droughts lead to food insecurity which threaten 80% of the population [8]. As farming accounts for 20% of Zambia's gross domestic product [9] and most of the country's bottom-of-the-pyramid citizens are farmers [10], agriculture continues to be the leading sector affecting food security, economic growth, and poverty reduction [11].

A reliable low-maintenance, low-cost filter for drip irrigation that maintains a minimal pressure loss throughout significant particle accummulation is needed. The proposed filter system must be compatible with low-cost drip irrigation systems that serve 1000 m^2 farm plots requiring 6200 liters of water per day, cost $200, and use a 0.2 bar pressure source [6]. Given the existing system, the filter must consistently deliver less than 0.1 bar in pressure loss and must cost less than $30. Additionally, the filter must have a 5-year product lifespan given the need for reliability and the variability in equipment supply. Finally, given the Zambian context, the filter must be able to remove particles ranging from "very fine" sand (50 µm) to "medium' sand (250 µm), which is representative of Zambian soil profiles that clog the emitters.

This paper describes and adapts existing cartridge filtration systems for the maintenance and cost challenges of the developing world. The proposed design enables minimal pressure drop across the filter while reducing the filter systems' potential to clog. This inexpensive design delivers the functionality and reliability of an off-the-shelf filter for a fraction of the price. This work hopes to address the reliability issues of drip irrigation to increase the adoption of sustainable irrigation practices.

SEPARATION STRATEGY

To design a reliable, low-cost, low-power filter, different filtration practices were investigated. Techniques for filtering inorganic particles from water differentiate based on the particle size and the scale of operations. In the case of drip irrigation systems, cost and power constraints prevent complex designs or the use of chemical additives like surfactants. The feasibility of three methods was considered: (1) separation via centrifugal action, (2) settling due to gravitational forces, and (3) physical separation using a screen or porous media. The physics that govern these options are illustrated in Figure 2.

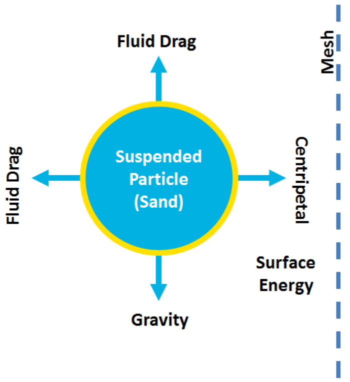

FIGURE 1: Body forces and mechanical barriers used to separate suspended particles from water.

Centrifugal filtration operates by flowing unfiltered water around a central axis during which centripetal forces move dense particles outward to the edges of the container. These particles can be collected in a sand trap and removed from the water body. Although well-established, this method generally requires input work and is very sensitive to flow rates and geometries. Creating a drip irrigation adaptation of this filtration strategy was therefore not pursued.

Settling tanks allow dense particles to gravitationally settle in a stagnate tank. The particles are then collected in a catch basin and the flow is sourced from the top of the tank. To be effective, this technique requires stagnant or very slow moving laminar fluid which is well-suited for large scale operations. Unfortunately, large settling tanks for drip irrigation can cost over 1000 USD and are therefore prohibitively expensive.

Filtration through a porous media or mesh screen geometrically separates particles from the flowing fluid in a drip irrigation system. As the flow passes through the screen, all particles above a critical size are physically blocked by the screen and removed from the flow.

Pressure drop across a porous media is governed by Darcy's Law in which the change in pressure ΔP (Pa) across the porous media can be expressed as

$$\Delta P = \frac{\dot{Q}\mu L}{kA} \tag{1}$$

where $\dot{Q}$ is the volumetric flow rate (m^3/s), A is effective cross-sectional area (m^2) of the porous media, μ is the viscosity (Pa·s) of the fluid through the medium, L is the thickness (m) of the medium, and k is the permeability (m^2) of the porous medium. Hydraulic resistance across a mesh filter increases via two mechanisms.

First, accumulated particles on the filter surface create additional barriers through which the fluid flows and therefore reduce the effective permeability of the surface (k/L). Assuming the accumulated particles coat the filter evenly, the effective permeability of a cylindrical filtration system can be found by:

$$\frac{k}{L} = \frac{k_o}{L_0} + \frac{k_{acc}}{L_{acc}} = \frac{k_o}{L_0} + \frac{k_{acc}A}{V_{acc}} \tag{2}$$

where k_o is the original permeability of the filter paper, L_o is the thickness of the filter paper, k_{acc} is the permeability of the filtered media, L_{acc} is the thickness of the accumulated layer, and V_{acc} is the volume of accumulated filtered media.

The second mechanism for reducing the flow across a mesh filter occurs when the filtered particles that fall away from the filter surface volumetrically fill the space between the filter and its housing. This accumulated material is significantly less permeable and therefore reduces the effective available surface area of the filter (A). This mechanism asymptotically decreases flow as particulate matter accumulates until the filter is volumetrically filled and thus clogged. The reduction of effective cross-sectional area in a typical cylindrical mesh filter is simply found by

$$A = \frac{V_{acc}A_o}{V_{filter}} = \frac{V_{acc}A_o}{\pi w\left(D_{housing} - D_{filter}\right)} \tag{3}$$

where A_o is the original effective cross-sectional area of the filter, V_{filter} is the available capacity or volume between the housing and the filter to contain filtered particles, w is the length of the filter/housing, $D_{housing}$ is the diameter of the housing, and D_{filter} is the effective diameter of the filter. These two mechanisms for increasing the hydraulic resistance of the filter are found in Figure 3.

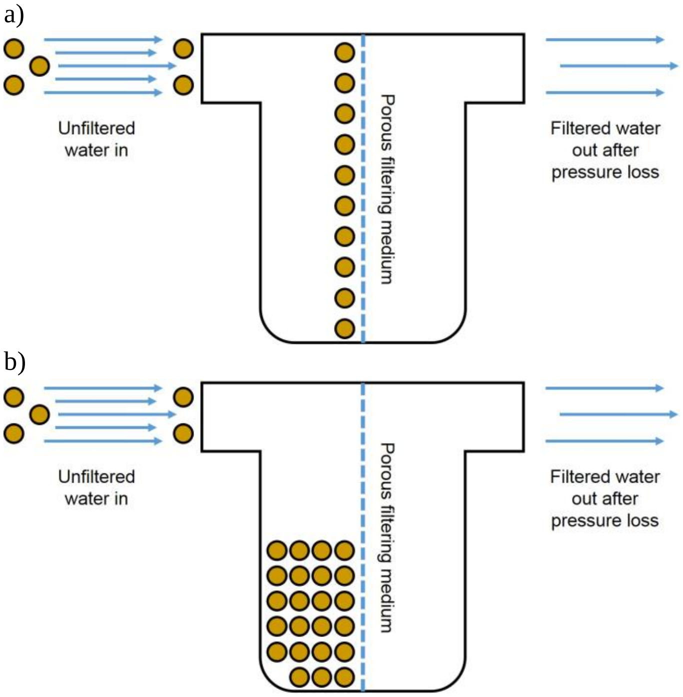

FIGURE 3: The two mechanisms that can create hydraulic resistance. a) In mechanism 1, particles evenly coat the filter surface, creating a thicker, less permeable medium. b) In mechanism 2, particles settle in the filter housing, reducing the effective filter area that is exposed to flow.

Simple cylindrical mesh filters are presently used in drip irrigation systems, as shown in Figure 4. Although this filtration strategy seems well suited for small-scale filtration systems, particle buildup and clogging by the aforementioned mechanisms readily occur because of the high levels of particulate matter typical in the source water of Zambia. These filters' low capacity for filtered particulates inherently requires an unrealistically high level of maintenance for the given source waters available to developing world drip irrigation systems. Ergo it is necessary to reduce the resistance to flow through the filter while also increasing the available volume for particles to settle.

FIGURE 4: A typical mesh filter currently used in drip irrigation systems.

A pleated cartridge filter, as shown in Figure 5, improves both. Firstly the increased surface area of the folded pleats reduce the pressure drop across the filter as governed by equation 1. Secondly the additional available volume within the pleats enables more particulates to deposit away from the walls of the filter.

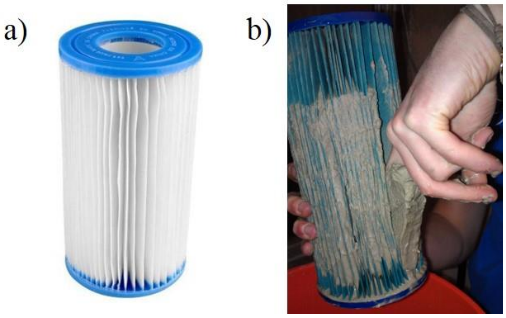

FIGURE 5: Example of pleated cartridge filters. a) A typical cartridge filter used for high volume flows. b) The folded pleats create additional space in which particulates can settle.

For these benefits, pleated cartridge filters are already used in industrial water treatment and in both residential and commercial swimming pools. With advertised lifetimes of 2-8 years [12], cartridge filters are already available for the desired flow rates for a 1000 m^2 drip irrigation system (≈ 25 L/min) with an acceptable pressure loss (<0.05 bar). This work will now characterize the advantage of a pleated cartridge filter over the conventional cylindrical mesh filter and improve upon the clogging mechanisms inherent to both systems.

EXPERIMENTAL SETUP

To measure filter performance in the context of a drip irrigation system, a scale test setup was constructed as shown in Figure 6a. The apparatus consisted of a 15 gallon tank that was elevated to 2 m and connected to a 1” flexible hose serving as the main line. The main line was connected to the inlet side of the filter housing and the outlet of the housing connected to a reservoir tank containing a sump-pump which sent water through the pump line back to the elevated tank. An off-the-shelf 50 µm, high-capacity polyester cartridge filter with a height of 10” was used (McMaster-Carr product #6657T25).

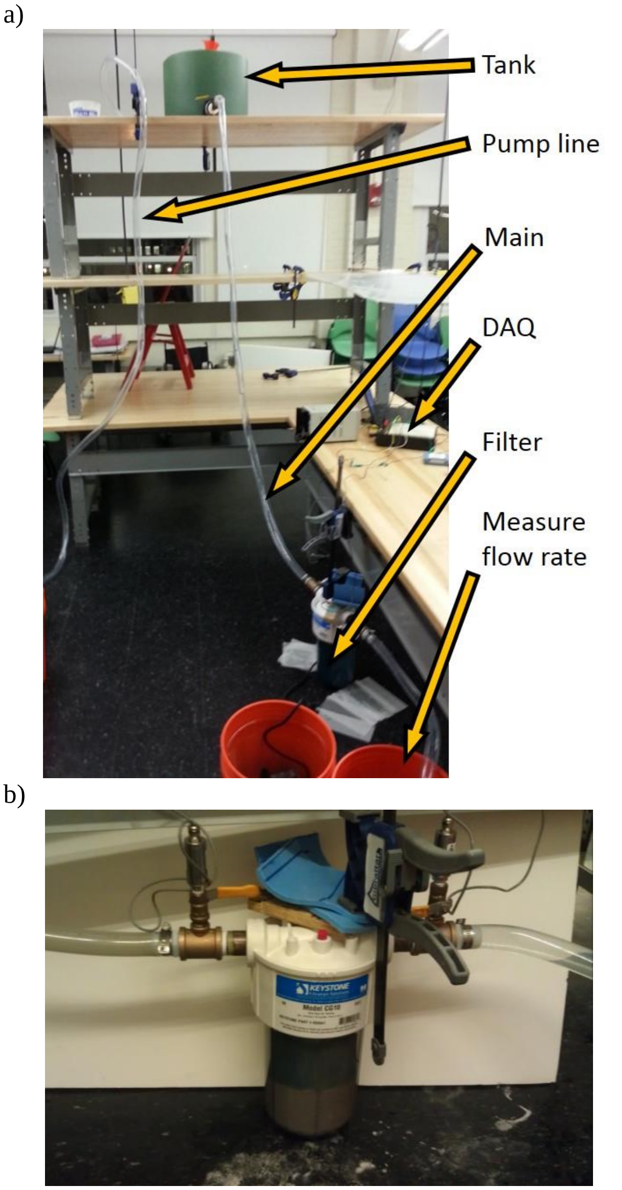

FIGURE 6: a) Experimental drip irrigation setup. b) Experimental filter assembly with dual pressure transducers. Unfiltered water flowed from the left, and the pressure transducers measure pressure before and after the filter.

As shown in Figure 6b, the pressure drop across the filter was measured using two Omega PX309-015G5V transducers which have a range of 0-15 psi and an accuracy of 0.25% [13]. The data was recorded using a Measurement Computing USB-201 DAQ at a sampling rate of 5 Hz. Flow rate was measured by timing how long it takes for 12L of water to flow out of the system.

TEST PROCEDURE

To simulate the filter's performance with Zambian source water, fine sand (50-250 µm) consistent with Zambian soil was added incrementally into the test setup's source water. This media was added while maintaining the flow across the filter. The pressure drop across the filter and system flow rate was then measured under two different conditions. The first measurement was taken while the flow was maintained across the filter after the particulates were added to the source water. The second measurement was taken after the flow has been stopped for several minutes and then restarted. This is representative of Zambian subsistence farmers finishing the irrigation of their crops for the day and then activating the system the following day. In each case, the pressure drop measurement was averaged over a 1 minute period. The increments of sand were added until the pressure drop exceeded an acceptable level (0.9-1.0 bar).

The flow rate through the system was initially 24-25 L/min which is consistent with the required flow rate for a 1000 m^2 field requiring 6200 L per day operating for 4 hours a day. As the pressure drop across filter increased, the flow rate decreased.

The procedure was run for three filter configurations: (1) the cartridge filter was used in the conventional configuration (Figure 7a), (2) the cartridge filter was wrapped with a 50 µm polyester filter paper sheet such that the filter became a pure cylinder similar to the current filter technology (Figure 7b), and (3) the cartridge filter was placed into an oversized housing such that the lower half of the housing was empty (Figure 7c).

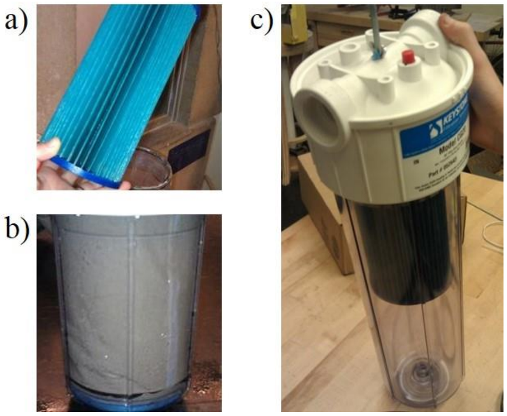

FIGURE 7: a) Conventional pleated filter configuration. b) Cylindrical, non-pleated configuration inside housing. c) Conventional pleated configuration in an extended housing.

PRESSURE LOSS BEHAVIORS

After each incremental sand loading for the first two filter configurations (Figures 7a and 7b), the head loss across the filter increased by the mechanisms described in equations 2 and 3. As shown in the time elapsed images in Figure 8, sand particles pressed on to the surface of the filter while there was still flow through the filter. As a result, the effective permeability of the filter surface decreased as described by equation 2. When the flow ceased, the force holding the particles to the surface abated and the filtered particles settled to the bottom of the housing due to gravity. When the flow was restarted, the system exhibited a post-settling behavior in which the pressure loss across the filter was reduced as compared to the prior continuous operation, as described by equation 3.

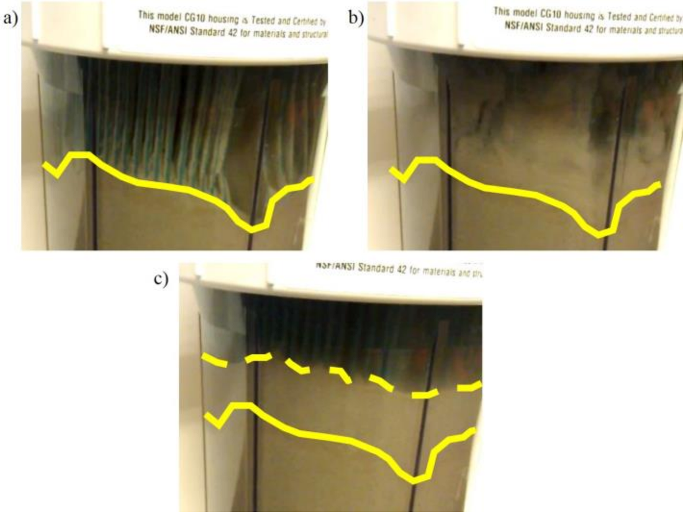

FIGURE 8: Time lapse of settling behavior within filter housing. a) As water flows through the filter, particulates coat the available surface area on the pleats. Solid line outlines initial level of particulate settling. b) Representative of farmers turning off their drip irrigation system for the day, the flow is sopped and the particles release from the pleats and begin to settle. c) Dotted line indicates new level of settled particulates.

This behavior of filtered particles coating the filter and then settling to the bottom of the housing are well seen in the zigzag pressure data of Figure 9. In this data, the peaks of each filter curve correspond to when the particles were introduced into the filter but the flow had not stopped. The drops or troughs in the data correspond to when the flow ceased, the particles settled to the bottom of the housing, and then flow recommenced.

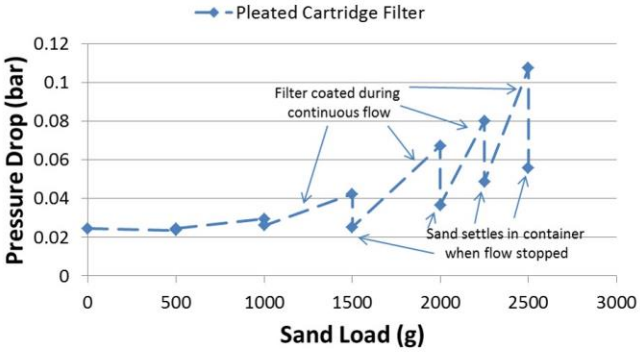

FIGURE 9: Pressure data visualization of pressure loss behavior during continuous flow and discontinued flow.

EXTENDED HOUSING

A pleated cartridge filter system could avoid the asymptotic pressure rise described by equation 3 if the filtered particles could settle away from the filter when the flow ceased. A simple way to do this would be to extend the housing below the filter. This approach is not possible with the existing filter housing, which not only collects the settled particles, but also fixtures and seals the filter by making contact with and pressing the filter's o-rings. Therefore, a new external housing and support structure for the cartridge filter was designed. This concept supported and sealed the cartridge filter with a central rod and rubber plug suspended from the top housing. As shown in Figure 10, this plug could be tightened against the filter with a wing nut. This simple mechanism allowed the bottom casing to be extended below the base of the filter as shown in Figure 7c.

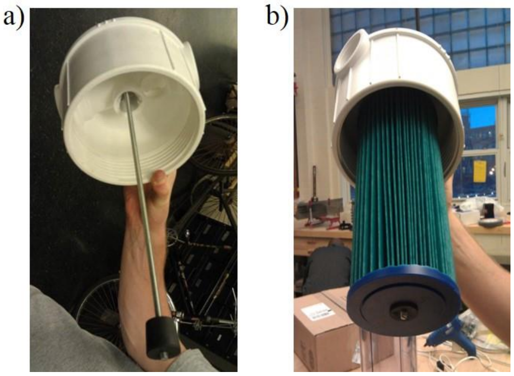

FIGURE 10: a) Internal threaded rod and plug assembly for supporting the cartridge filter b) newly supported cartridge filter with extended housing

The behavior of filtered particle with this housing modification was as expected--accumulated sand in the filter settled to the bottom of the tank.

EXPERIMENTAL RESULTS

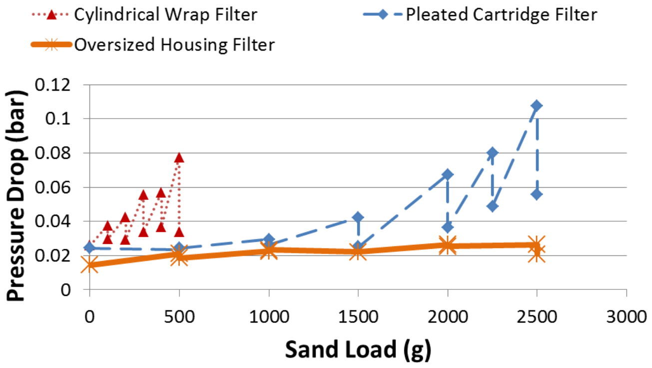

FIGURE 11: Measured pressure drop across the filters as sand was accumulated as measured by the dual pressure transducers.

The results in Figure 11 confirm three important concepts. First, the pressure drop across the pleated cartridge filter resulting from the effective permeability of the coated particles (mechanism 1) was lower than that of the cylindrical wrap filter for a given amount of accumulated particles. The pressure loss of the pleated filter only began to approach that of the cylindrical wrap filter after over 1500 grams of sand was loaded.

Second, the increase in pressure drop exhibited by the cylindrical wrap filter occurred much faster relative to the amount of particles that had been added to the filter (mechanism 2). This was the result of the available volume within the housing in which the sand could settle. With 500 grams of particles loaded around the cylindrical wrap filter, the sand level nearly reached the top of the housing, effectively blocking the usable filter area. In the case of the cartridge filter, the sand was able to accumulate within the pleats of the filter enabling much more sand to build up in the housing without covering the entire filter surface. 2500 g of filtered particles were needed to fill the housing

Third, the extended housing configuration described in Figure 7c allowed filtered particles to settle below the filter and therefore not cover the filter. Without sand accumulating around the filter, the comparatively low pressure loss across the filter in the extended housing was maintained at its initial level throughout successive sand loading (Figure 11).

LOW-COST PROTOTYPE

Decoupling the support and sealing of the cartridge filter from the external housing not only displayed the performance required of a low-pressure filter but also provided an additional opportunity to reduce the cost of the filter for rural drip irrigation systems. The off-the-shelf cartridge filter housing is a quarter inch thick, complex, plastic injection molded piece seals to the top housing via large structural threads and an O-ring.

Because the housing no longer has to serve as a structural element when the filter is supported by a central rod, the bottom housing can be both reduced in size and complexity and manufactured using less expensive processes. As shown in Figure 12a, the external housing can be redesigned to be a simple, thin blow-molded container that is comparable to a plastic bottle. This container can be supported by the already existing threaded rod that now supports the cartridge filter (Figure 10b). As shown in the CAD model (Figure 12a), the tensioned threaded rod can compress the external housing against the top structure and gasket and therefore eliminate the need for the complex threaded injected molding piece.

To test the proposed design, a low-cost prototype was constructed using a 2 L plastic bottle instead of the standard enclosure and a perforated 500 mL plastic bottle wrapped in filter paper to represent the cartridge filter (Figure 12b). When the low-cost plastic bottle prototype was loaded with sand, particle behaviors for continuous operation and settling were qualitatively similar to those observed in the aforementioned characterization. With the thin-walled, plastic bottle demonstration maintaining its seal and structure during filtration, it may be viable to explore thin enclosure materials and manufacturing options such as blow-molding to reduce costs while maximizing performance.

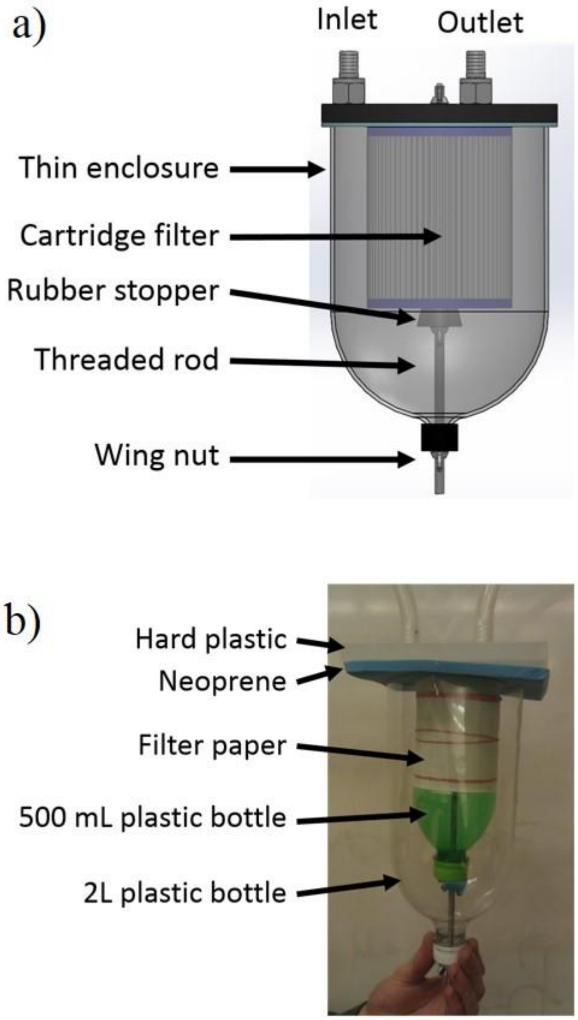

FIGURE 12: a) The CAD and b) concept prototype for an alternative housing geometry that fixtures and seals both the filter and external housing via a center mounted threaded rod.

CONCLUSION

To increase the reliability and usability of a drip irrigation system, clogging was investigated and an alternative low-cost, robust alternative filtration system was proposed. To reduce the pressure drop across the filter, the typical cylinder filter was abandoned for a pleated cartridge filter which exhibits more effective surface area and more volume for filtered particles to settle. The experimental setup showed that the pleated cartridge filter both had a lower starting resistance to flow and could hold more sand before clogging.

An alternative filter housing design is proposed that allows for the settling sand to reside away from the cartridge filter so as to prevent clogging. This design sealed and supported the cartridge filter via a threaded rod and rubber plug supported from the top housing. With this simple apparatus, the housing could be extended beyond the base of the cartridge filter to extend the maintenance life of the system.

The rod supported cartridge filter design further enabled a lower cost filtration system. The present off-the-shelf external housing is a large structural piece that becomes irrelevant given the support of the rod/plug assembly. Ergo, a low-cost alternative housing that is made via blow molding was designed in CAD, and a first prototype was made from 2 liter plastic bottles. This concept prototype demonstrated that an inexpensive housing along with a cartridge filter could yield a low-cost and reliable drip irrigation filtration system.

Further work is needed to implement the discussed work in the field. First, this paper recommends that the CAD design be further developed with input from iDE and other players in the space. Second, it is necessary to find appropriate gasket material that can endure the 5-10 years of system life. Third, the lifespan of off-the-shelf cartridge filters should be tested with site-specific water sources to ensure their performance is consistent with lab performance. Finally, this paper calls for further investigation on the ability of diatomaceous earth to prevent clogging of organic matter in cartridge filter systems.

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