Optimizing Flow Rate and Bacterial Removal Performance of Ceramic Pot Filters in Tamale, Ghana

by

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Abstract

Pure Home Water (PHW) is an organization that seeks to improve the drinking water quality for those who do not have access to clean water in Northern Ghana. This study focuses on the further optimization of ceramic pot filters, which is a promising low-cost household water treatment and the main product manufactured by Pure Home Water, by investigating the relationship between manufacturing parameters and filter performance. The manufacturing parameters researched in this thesis includes rice husk size and the mixing process, and the performance variables includes flow rate and bacterial removal. Through this research, the author determined the positive exponential relationship between rice husk size and flow rate, and the negative step-function relationship between rice husk size and bacterial removal, as well as between flow rate and bacterial removal. In addition, pugmill proved to work better in mixing water, rice husk and clay powder since the filters made from the mixture mixed by pugmill had higher total coliform bacterial removal than those mixed by hand. Besides the investigation of the relationship, the author applied the study to full-sized filters, finding that full-sized filters had the same trends as sample ceramic disks and very similar results in bacterial removal with disks when the rice husk size is smaller than 1080 μm.

Thesis Supervisor: Susan Murcott

Title: Research Scientist, Department of Urban Studies and Planning

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I want to thank all the staff at the Pure Home Water factory for helping me make filters and finish the tests in Ghana!

I want to thank Steve Rudolph for his help on using the sieves and the sieve shaker, as well as making it possible to saw the disks out of the plates! And I also want to thank Mike Tarkanian for helping me to fire the plates at MIT using his kiln even when his schedule was very tight.

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Acronyms

CPF	Ceramic Pot Filter
E. coli	*Escherichia coli*
Group M	The group of sample ceramic disks made at MIT
Group T_F	The group of sample ceramic disks cut from full-sized filters at the PHW factory in Tamale, Ghana
Group T_P	The group of sample ceramic disks cut from the plates made in Tamale
HWTS	Household water treatment and safe storage
LRV	Logarithmic removal value
MIT	Massachusetts Institute of Technology
MPN	Most probable number
PBS	Phosphate buffered saline
PHW	Pure Home Water
RHS	Rice husk size
USAID	United States Agency for International Development
UNICEF	United Nations Children's Fund
WHO	World Health Organization

1 Introduction

1.1 Background

1.1.1 Safe Drinking Water

In the World Health Organization's *Guidelines for Drinking-Water Quality*, "safe drinking water" is defined as water that "does not represent any significant risk to health over a lifetime of consumption, including different sensitivities that may occur between life stages" (WHO, 2011). It is a basic human need and is of great importance. However, more than 780 million people around the world have no access to safe drinking water sources, of which 84% live in rural areas (WHO, UNICEF, 2014). According to WHO/UNICEF *Joint Monitoring Report 2012*, access to safe drinking water is measured by "the percentage of population that use improved drinking water sources" (WHO, UNICEF, 2014). An "improved drinking water source" means infrastructure constructions that can prevent water from being contaminated by outside contaminants, including: protected dug wells, protected springs, piped household water connection, and rainwater collection. In contrast, unimproved drinking water includes unprotected dug wells, unprotected springs, and surface water. Figure 1-1 shows the access to piped water, other improved supplies and unimproved supplies including surface water among regions from 1990 to 2010.

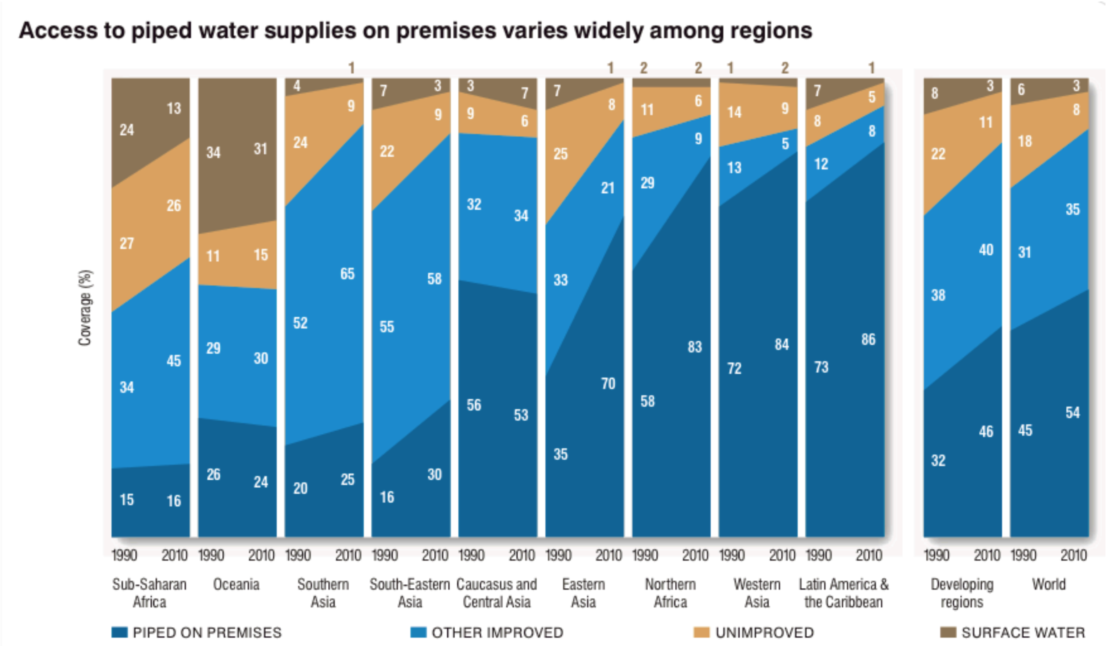

Figure 1-1 Drinking water coverage trends by developing regions, 1990-2010 (WHO, UNICEF, 2014)[1]

This water safety problem is particularly serious in the developing world. As shown in Figure 1-2, Africa is the region that has the lowest improved drinking water coverage. The drinking water coverage is below 50 % in some regions in Africa.

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[1] WHO, UNICEF, Progress on drinking water and sanitation: Joint Monitoring Programme update 2014,

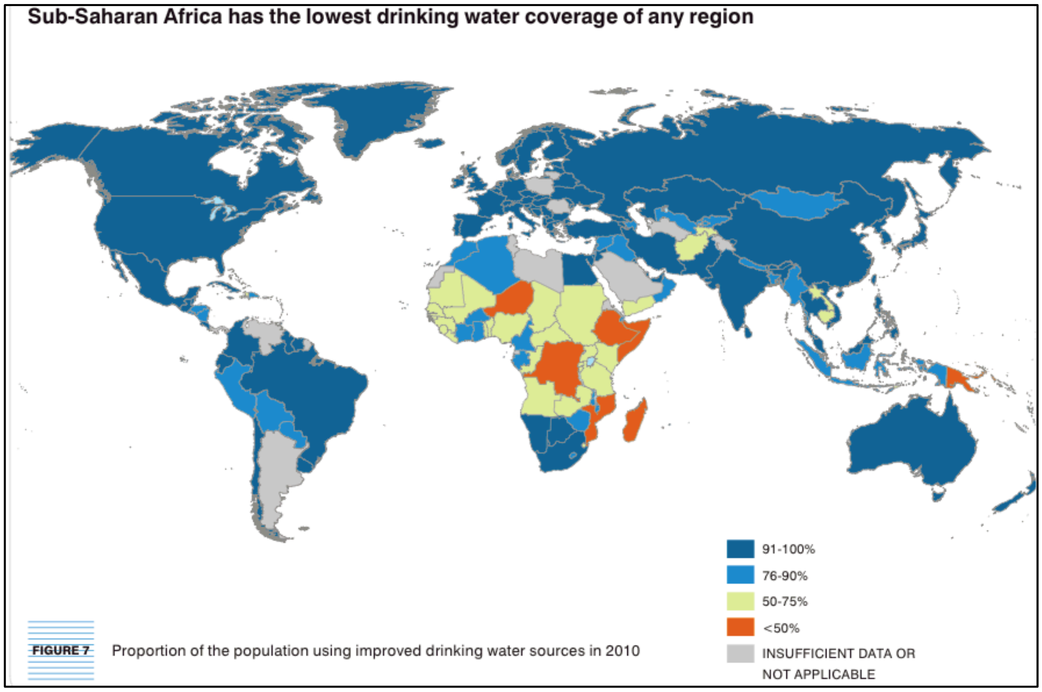

Figure 1-2 Proportion of the population using drinking water sources in 2010 (WHO, UNICEF, 2014)[2]

Ghana is one of the countries in West Africa with serious challenges related to safe drinking water, basic sanitation and hygiene. The northern part of Ghana is especially deprived, with one in ten children dying before age of five years (Water Aid America, 2014).

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[2] WHO, UNICEF, Progress on drinking water and sanitation -- Joint Monitoring Programme update 2014, page 09 http://apps.who.int/iris/bitstream/10665/112727/1/9789241507240_eng.pdf?ua=1

Figure 1-3 Joanna Manu collects drinking water from a River in Western Ghana

Figure 1-4 Surface water polluted with turbidity, bacteria, etc. used as drinking water in Ghana

1.1.2 Pure Home Water

Faced with such a drinking water and sanitation crisis, one of the feasible solutions to this problem is to develop a low-cost, simple and practicable household drinking water treatment and safe storage (HWTS) products. In order to contribute to this effort, Susan Murcott founded Pure Home Water (PHW) in 2005. PHW is a non-profit organization located in Tamale, Ghana. Its goal is to provide safe drinking water in northern Ghana by selling low-cost household treatment products, as well as become financially and locally self-sustaining[3]. Over the last several years, PHW has produced and distributed Ceramic Pot Filters (CPFs), which are locally branded as "AfriClay Filters", to more than 100,000 people, improving both health and quality of life in local communities.

Figure 1-5 Pure Home Water factory

Figure 1-6 Drinking water before and after treatment by CPFs

1.1.3 Ceramic Pot Filters

In 1981, the CPF was invented by Fernando Mazariegos in Guatemala. Since 1998, the CPFs has been promoted by several NGOs, including Potters for Peace, Potters without Borders, First Aid, Eco Filter, among others, to many other countries. Currently, there are 52 factories in 31 countries around the world (Murcott, 2013).

Many studies about the CPFs have been conducted in the past years, including filter's performance both in the lab scale and in the field, health impact and user acceptance. Donachy's *Summaries of Reports and Studies of the Ceramic Water Purifier* (2011) gave a fairly complete discussion of them. In 2001, Susan Murcott supervised the first MIT student team to independently evaluate the optimization and performance of the CPFs.

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[3] http://web.mit.edu/watsan/meng_ghana.html

The general process of manufacturing the CPFs involves mixing, molding, drying, firing, cooling, and painting colloidal silver, which acts as a disinfectant. The CPF is made from a mixture of rice husk (or sawdust), clay powder and water, and can be formed into at least three different shapes of pots: flowerpot shape, parabolic shape, and hemisphere shape. Pure Home Water currently produces hemisphere shape pots. Rice husk and sawdust incinerates when the CPF is fired, which leaves small pores so that the CPF can filter water through it. The schematic of the CPF is shown in Figure 1-7.

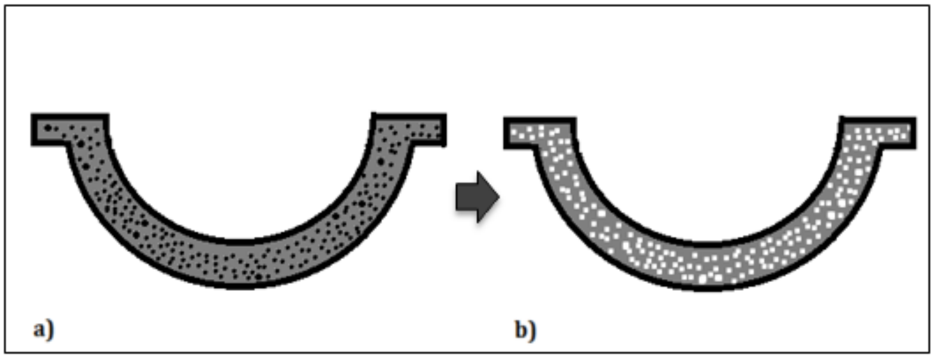


Figure 1-7 Schematic of the CPF Before (a) and after (b) firing. The black dots represent rice husk or sawdust particles. The white dots represent pores

The ceramic pot itself is placed in a bucket with lid and spigot included. The bucket can provide a safe-storage container for holding the filtered water. The figure of a complete CPF filter system is shown in Figure 1-8.

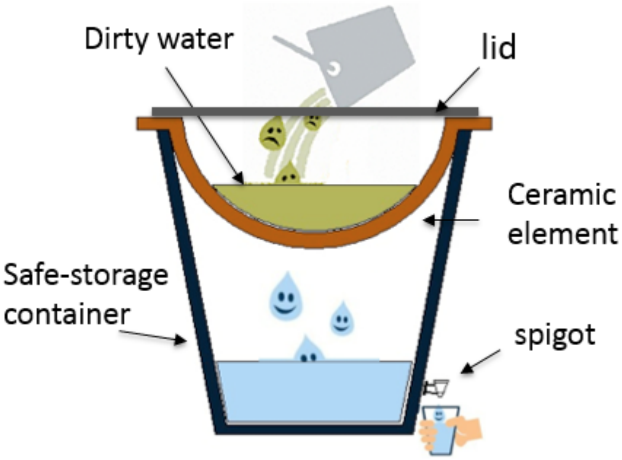


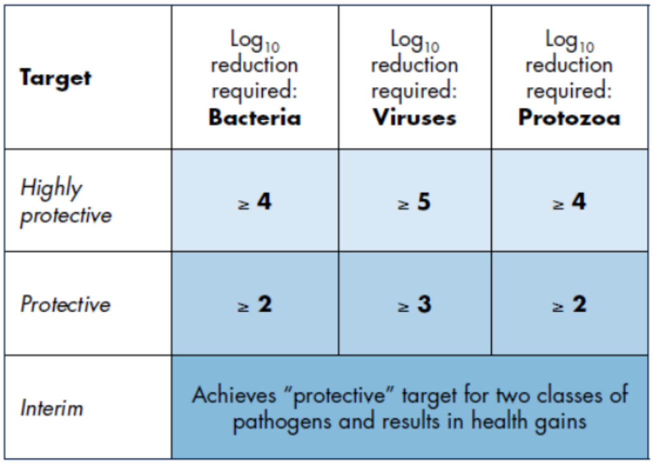
Figure 1-8 Schematic of the assembled CPF

Ideally, the CPFs should remove a variety of pathogens, including bacteria and protozoa. In Brown's PhD dissertation, he found that the CPF has reduced diarrheal diseases by 40% in areas where it was used in Cambodia (Brown, 2007). In Hunter's study in 2009, he found that "with the currently available evidence, ceramic water filters are the most effective form of household water treatment in the long term" (Hunter, 2009).

This study focuses on the further optimization of ceramic pot filters, which is a promising low-cost household water treatment and the main product manufactured by Pure Home Water, by investigating the relationship between manufacturing parameters and filter performance following on the research by Amelia Servi in 2013. This thesis focuses on two manufacturing factors: **rice husk size** and the **mixing process** of mixing by hand and by pugmill, and two performance metrics: **flow rate** and **bacteria removal**.

Flow rate was studied because a common complaint from users in Ghana of CPFs is that the flow rate is too slow. The CPF factories around the world have standardized on different flow rates. The flow rate range is generally between 1L/hr to 5L/hr (The Ceramics Manufacturing Working Group, 2011). Yet some factories do have a fast flow rate of 7L/hr (Servi, 2013). However, normally a high flow rate has a relative low bacterial removal. Hence, it's meaningful to determine a higher flow rate that is possible without significant bacterial removal reduction.

Household Water Treatment microbiological performance targets established by World Health Organization is shown in Figure 1-9. CPFs typically achieve interim or protective levels of bacteria and protozoa reduction.



Target	Log_{10} reduction required: **Bacteria**	Log_{10} reduction required: **Viruses**	Log_{10} reduction required: **Protozoa**
Highly protective	≥ **4**	≥ **5**	≥ **4**
Protective	≥ **2**	≥ **3**	≥ **2**
Interim	Achieves "protective" target for two classes of pathogens and results in health gains		

Figure 1-9 WHO drinking water guideline expressed as log reduction values (WHO, 2011)

1.2 Research Goal and Objectives

Although CPF is a promising option for household water treatment, manufacturers and users still strive for better performance. As follow-on research to Servi's Master thesis (2013), the goal of this thesis is to confirm the relationships discovered by Servi, which are the relationship between rice husk size and flow rate and the relationship between rice husk size and bacterial removal. Another goal is to extend the research from disks to full-sized filters. By doing this, the author hopes to provide factories a deeper understanding of the effects of two specific manufacturing factors, which are rice husk size and mixing process, on filter performance so as to help more people in developing countries to gain access to safe drinking water.

To achieve this goal, this thesis has these specific objectives:

1) Determine the relationship between rice husk size and hydraulic conductivity using sample ceramic disks;

2) Determine the relationship between flow rate and bacterial removal using sample ceramic disks, which was proposed by Servi (2013) in her recommendation for future research. This relationship is worth studying since it hasn't been clearly researched;

3) Determine the relationship between hydraulic conductivity and bacterial removal using

ceramic disks. This relationship is worth studying because the geometries of filters are different from factory to factory, which will affect their flow rate. Thus, it is not appropriate to compare flow rate directly across factories. What can be compared is actually the hydraulic conductivity.

4) Determine the relationship between rice husk size and bacterial removal using sample ceramic disks and full-sized filters;

5) Determine the relationship between mixing processes (by hands and by pugmill) and bacterial removal using full-sized filters, since currently the mixture of water, rice husks and clay powder at PHW are sometimes mixed by hand and sometimes mixed by pugmill;

6) Compare the results in 4) to find out the feasibility of applying the results gained from sample ceramic disks to full-sized filters, and then make recommendations of manufacturing variables to the PHW factory stuff and propose future research using the the results from Objectives 1) to 5).

2 Literature Review

Various previous studies, including Lantagne (2009), Plappally (2010), Miller (2010), Gensburger (2011), Miller (2012), Rayner (2012), Kelly (2013), and Servi et al (2013), have shown that the performance of Ceramic Pot Filters (including flow rate, bacterial removal rate, and strength) is most probably related to four manufacturing parameters: percentage of rice husk, rice husk size, wall thickness and filter shape. Some of these relationships have already been well investigated, such as the relationship between percentage rice husk and filter performance; while others are not well understood, such as the relationship between rice husk size and filter performance.

Table 2-1 shows a matrix summarizing the manufacturing parameters and performance metrics related to this study. This matrix is adapted from the parameter/performance matrix in Servi's thesis (Servi, 2013) and reorganized by the author of this thesis. This literature review will only focus on the variables pertaining to this study, which are the five areas highlighted by the oval circles in Table 2-1.

It should be noted that this study and Servi's study both focus on filters produced with rice husk as combustible, but Plappally (2010) and Lantagne's (2009) studies using sawdust are also considered relevant. In addition, the CPFs tested in this study were not covered with silver, but the flow rate results from Lantagne (2009) and Miller (2010) who analyzed filters with silver, are still included in this matrix. What's more, this study tested bacterial removal using *E.coli*, but Miller's (2012) results using used total coliform are also included.

Table 2-1 Parameter/performance matrix filled with data from the literature

	Flow Rate	Bacterial Removal	Strength
Percentage Rice Husk	Miller (2012): positive linear	Miller (2012): no correlation	Plappally (2010): negative correlation
	Rayner (2012): positive correlation	Gensburger (2011): no correlation	Watters (2010): negative correlation
	Gensburger (2011): positive linear		
	Plappally (2010): positive correlation		
	Miller (2010): positive correlation		
	Lantagne (2009): positive correlation		
Wall Thickness	Servi (2013): inversely proportional	Servi (2013): positive linear	Watters (2010): power relationship
		Rayner (2012): positive correlation	Watters (2010): quadratic
Rice Husk Size	Servi (2013): exponential or positive step	Servi (2013): negative linear or negative step	
	Klarman (2009): no correlation	Rayner (2012): negative correlation	
		Gensburger (2011): negative correlation	
Flow Rate	N/A	Rayner (2012): no corelation	____
		Bloem (2009): no correlation	
		Klarman (2009): negative correlation	
Hydraulic Conductivity	____		____
Mixing Process	____		____

2.1 Effect of Rice Husk Size on Flow Rate

Servi (2013) showed a positive correlation between flow rate and rice husk size, which confirmed the results of Gensburger (2011). But about the relationship, Servi gave two possible interpretations: one is a positive exponential relationship; the other is a positive step function relationship. The step function relationship is that there are two regimes for flow rate, one relatively low (approximately 0.003mL/s in her study) and the other relatively high (approximately 0.43mL/s in her study) with a transition occurring at a rice husk size of about 650µm. Using the experimental data she gained, Servi formulated an equation to approximate the flow rate (Q) of the PHW CPF:

$$\boldsymbol{Q = \left\{ \begin{matrix} 8\frac{(P-0.1)}{L},\ D \leq 650\ mm \\ 800\frac{(P-0.1)}{L},\ D > 650\ mm \end{matrix} \right\}} \qquad \textbf{Equation 1}$$

D is the rice husk size, and L is the wall thickness of CPF.

In contrast, Klarman (2009) found that using a larger mesh size of 0.45µm to sieve the sawdust had no significant impact on CPF's flow rates then using a mesh size of 0.3µm. (Note that Servi and Gensburger used rice husk as their combustible whereas Klarman mainly used sawdust plus one set each with coffee husks or rice husk respectively (Klarman, 2009).)

2.2 Effect of Rice Husk Size on Bacterial Removal

Servi (2013) found a negative correlation between bacterial removal and rice husk size also with two possible interpretations: negative linear relationship or negative step function relationship. The step function relationship is that bacteria removal switches from a zone of high removal (approximately 2.6 LRV in her study) to a zone of low removal (approximately 0.75 LRV in her study) at a rice husks size of approximately 650µm. Servi also formulated an equation to approximate the bacterial removal (B) of the PHW CPF:

$$\boldsymbol{B} = \begin{Bmatrix} \mathbf{0.15}\times(\boldsymbol{L}-\mathbf{2.8}),\ \boldsymbol{D} \leq \mathbf{650}\ \boldsymbol{mm} \\ \mathbf{0.04}\times(\boldsymbol{L}-\mathbf{2.8}),\ \boldsymbol{D} > \mathbf{650}\ \boldsymbol{mm} \end{Bmatrix} \qquad \textbf{Equation 2}$$

Equation 1 and 2 are valid for 20%<P<35%, 400µm<D<925µm, 10mm<L<20mm, where P is the percentage rice husk, L is the wall thickness. Servi stated that while these equations could only be applied to current PHW CPFs, the shapes of the curves should be widely applicable.

Rayner (2012) discovered that the filters' advection coefficient and bacterial deactivation performance had a negative correlation, which implied that pore size might have a negative correlation with bacterial removal performance. Gensburger (2011) also found a negative effect of pore size on the bacterial removal effectiveness.

2.3 Effect of Flow Rate on CPFs Performance

There are several possible mechanisms that exist for the bacterial removal of ceramic pot filters: mechanical screening, sedimentation, adsorption, chemical activity, and biological activity (Halem, 2006). Mechanical screening removes contaminants when the water passes through pores in the filter that are created by the incineration of the combustible material. Because of the heterogeneous nature of the filter material, it is still possible to screen out bacteria even if the characteristic pore length is larger than the diameter of the bacteria (Servi, 2013). Adsorption removes bacteria when they collide with the pore walls when the water passes through the filter. Biological activity occurs through the reaction between the bacteria in the water and the microorganisms living in the filter. Sedimentation occurs because of the density difference between the contaminant and the fluid. It is a dominant removal mechanism in most biological filtration systems, thus is widely considered as the possible mechanism of ceramic pot filter (Servi, 2013). If sedimentation is the mechanism of bacterial removal, then increased flow rates will decrease the bacterial removal. Thus, studying the influence of flow rate on bacterial removal will help to elucidate the CPF's bacterial removal mechanism.

There are a number of studies measuring filters' bacterial removal with increased flow rates. One research result is that flow rate and bacterial removal are not correlated strongly (Rayner, 2012). Some disk sets with higher flow rates in her study outperformed disk sets with lower flow rates in terms of bacterial removal. In Bloem's study (2009), she increased the flow rate up to 10 L/h, and found out that two kinds of filters with lower and higher flow rates respectively performed equally well on *E.coli* removal. However, Klarman (2009) found that the percentage microbiological removal began to decrease below 99% when the flow rate is higher than 1.7 l/hr. It should be noted that these previous studies changed flow rate by changing percentage rice husk or rice husk size, but in this study, the author changed the flow rate by changing water head, which was accomplished by utilizing a syringe pump. This will be discussed in Section 3.5 where we discuss test methods.

3 Methods

3.1 Test Set Up

In this research, four different groups of sample ceramic disks were produced and tested:

- Group M was the group of sample ceramic disks made at MIT;
- Group T_F was the group of sample ceramic disks cut from full-sized filters at the PHW factory in Tamale, Ghana;
- Group T_P was the group of sample ceramic disks cut from the plates made at the PHW factory in Tamale, Ghana;
- Full-sized filters are complete CPF filters made at the factory in Tamale, Ghana.

The differences in their recipes, manufacturing process, and rice husk size range can be seen in Table 3-1. The reason why these groups of sample ceramic disks and filters were made will be explained in Section 3.2.

Table 3-1 Comparison of different disks or filters in terms of their recipes (mass ratios), manufacturing process, and rice husk size range

	Mass Ratio*	Cut From	Mix Process	Press Process	Rice husk size range(μm)
Group M	12:4:4	Plates	Hand	Author	350-420, 420-600, 600-710, 710-850, 850-1000
Group T_F	10:4:4	Filters	Machine	Women in factory	1180-1660, 980-1180, 230-980**
Group T_P	10:4:4	Plates	Hand	Author	
Full-sized filter	10:4:4	N/A	Machine	Women in factory	

Normal Full –sized filter	10:4:4	N/A	Machine	Women in factory / pugmill	0-1660

[*] The mass ratio is the mass of Gbalahi Clay: Wayamba Clay: Rice Husk

[**] All three rice husk size ranges were produced for the three group types: T_F, T_P and Full-sized filters.

In this thesis, rice husk size for a filter or a sample ceramic disk is reported as a range between the courser and finer mesh diameters as (Table 3-1). It is also sometimes expressed as the average of its courser and finer mesh diameters. The original unsieved rice husk typically has a diameter of 0-2000μm.

Five tests were conduced in this study.

Rice husk size & hydraulic conductivity test is for determining the hydraulic conductivity of disks of different rice husk sizes. Group M, T_F and T_P were tested using the Bucket Setup and the full-sized filters were tested using the Full-sized Filter Setup. These setups will be introduced in Section 3.5.2 and Section 3.5.4. The water head used for full-sized filter tests was the same as that used for Group T_F & T_P.

Flow rate & bacterial removal test is for determining the relationship between flow rate and bacterial removal when the rice husk size is fixed using a syringe pump.

Hydraulic conductivity & bacterial removal test is for determining the relationship between hydraulic conductivity and bacterial removal. Hydraulic conductivity was investigated because for the filters produced by different factories, the geometries of filters are different, which will affect their flow rate. Thus, it is not appropriate to compare flow rate directly across factories. What should be compared is actually the hydraulic conductivity.

Rice husk size & bacterial removal test is for determining the relationship between rice husk size and bacterial removal. The test for Group T_F & T_P was conducted at the same time as the rice husk size & flow rate test for Group T_F & T_P. The test for full-sized filters was also conducted at the same time as the rice husk size and flow rate test for full-sized filters.

Mixing process & bacterial removal test is for comparing the bacterial removal performance between hand-mixed filters and pugmill-mixed filters. The filters used in this test were normal full-sized filters produced in PHW before the author arrived at the factory. Because of the huge amount of *E.coli* solution needed in this test, the author did not use *E.coli* solution, which was used in all the other tests. Instead, dugout water, which is the local surface water supply that has been the main local water supply source was used as the influent for the normal full-sized filter tests.

Table 3-2 shows the list of experiments that have been conducted in this study:

Table 3-2 Tests conducted in this study

Tests	Group M	Group T_F & T_P	Full-sized filters	Normal full-sized filters
Rice husk size & hydraulic conductivity	Constant water head Bucket Setup	Constant water head Bucket Setup	Constant water head Full-sized Filter Setup	--
Flow rate & bacterial removal	Constant Rice husk size Syringe pump	--	--	--
Rice husk size & bacterial removal	Constant flow rate Syringe pump	Constant water head Bucket Setup	Constant water head Full-sized Filter Setup	--
Hydraulic conductivity & bacterial removal	Combine the data of hydraulic conductivity and bacterial removal of all the disks		--	--
Mixing process & bacterial removal	--	--	--	Hand mixing vs. pugmill mixing Influent is dugout water

3.2 Sample Making Method

3.2.1 Group M Samples-Making Method

Group M stands for the group of sample ceramic disks made at MIT during fall term 2013. The plates were made from a mixture of Gbalahi Clay, Wayamba Clay – which are the two main clay types used at PHW – rice husk, and water. The rice husk used was imported from the Cambodia factory while the clay used was from Tamale, Ghana. In imitation of the real process of making a full-sized filter at a factory, the mixture of clay powder, rice husk and water is formed into a ball first. Then instead of pressing in a hydraulic press, which is used in the PHW factory to produce actual full-sized filters, the ball was pressed into a plate shape by hand using a flat-bottom bread pan, as is shown in Figure 3-1b. The plates were fired in a Nabertherm N200 kiln at the MIT Department of Material Science and Engineering foundry, which is managed by Mike Tarkanian. The maximum temperature of the kiln is 1300°C, heated from five sides. Its inner dimensions are 50 x 53 x 59(cm).

After firing, four filter samples of the same rice husk size were sawed from a single plate. The recipe (mass ratio and rice husk range) for Group M is shown in Table 3-1.

The sample ceramic disk make-up procedure is presented as follows.

1) Sieve the rice husk into five different sizes (350-420μm, 420-600μm, 600-710μm, 710-850μm, 850-1000μm) using the W.S. Tyler Ro-Tap sieve shaker at the MIT Department of Civil and Environmental Engineering concrete room (1-071), as is shown in Figure 3-1a. The sizes of rice husks were chosen according to the sizes of rice husks used in Servi's Master's thesis (Servi, 2013).

2) Mix the rice husks with clay and water and form the mixture into a ball shape. Then press the ball into a plate shape by hand using a flat-bottom bread pan, as is shown in Figure 3-1b.

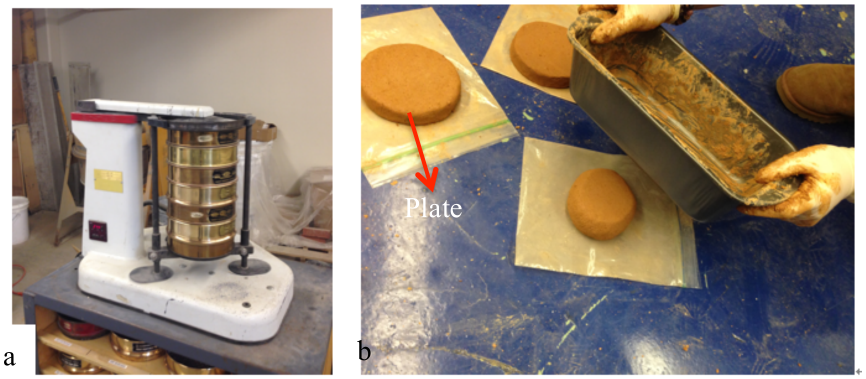


Figure 3-1 (a) Process of sieving using sieve shaker (b) Process of pressing

3) Fire the plates in the kiln at MIT, as is shown in Figure 3-2a. Heat the plates in the kiln to 830℃ for 11 hours and then cool them down gradually to 30°C for 16 hours. The firing profile can be found in Appendix A. This firing profile is the same as what was used in Servi's Master's thesis (2013).

4) Cut four sample ceramic disks from each plate (three are for bacterial removal testing and one backup), as is shown in Figure 3-2b and c. The average diameter of the disks was 27mm, and the average thickness of the disks was 18mm.

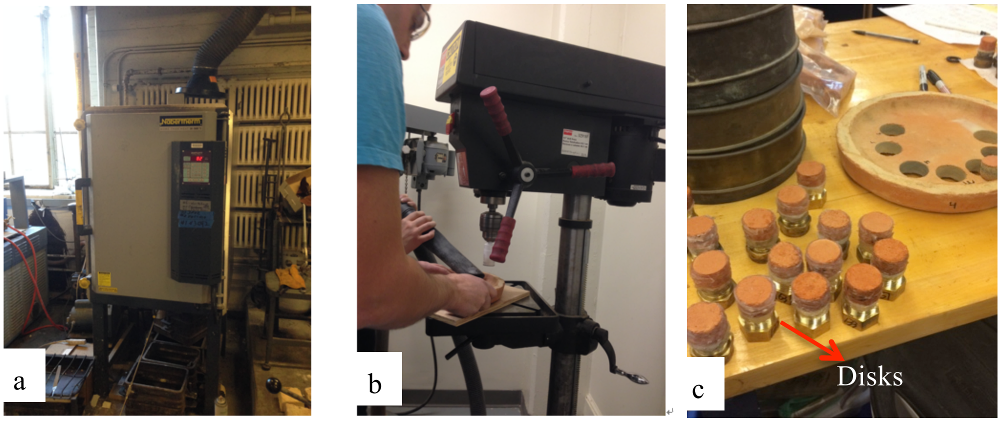


Figure 3-2 (a) The kiln, (b) the process of sawing, (c) the disks and plate after cutting

5) After cutting from the plates, small sample ceramic disks were cemented with PC-11 epoxy paste to brass fittings (Figure 3-3) and then their side faces were covered with two coats of clear marine silicone sealant to prevent leakage (Figure 3-4).

Figure 3-3 Group T_F with glue attaches sample ceramic disks to brass fittings but without silicon glue on side faces

Figure 3-4 Group T_F with silicon glue on side faces

3.2.2 Group T_F Samples Making Method

Group T_F stands for the group of sample ceramic disks cut from full-sized filters at the PHW factory in Tamale, Ghana. In order to evaluate the full-sized filters, Group T_F were created to investigate the relationship between rice husk size and bacterial removal, as well as the relationship between rice husk size and flow rate, when the water head is held constant. The procedure is to cut samples disks from full-sized filters using a drilling machine, as is shown in

Figure 3-5. The full-sized filters were made from a mixture of Gbalahi Clay, Wayamba Clay, and rice husk with a mass ratio of 10:4:4, which was different from the mass ratio used in Group M but the same as what was applied in the PHW factory.

Figure 3-5 The drilling process using a drill press

Figure 3-6 Sets of mesh screens used at the PHW

Figure 3-7 Sets of sieves used for Group M

The rice husks were sieved by a set of manufacturing production sized mesh screens into three sizes: 234-980μm, 980-1180μm, 1180-1660μm (used at the PHW Figure 3-7). These rice husk sizes are different from those of Group M because the sieves used to sieve rice husks for Group M were too small and could not be used to sieve rice husks for full-sized filters as it would take days to obtain sufficient quantities of rice husk (see figure 3-7). Thus, four big screens of different sizes were used to sieve rice husks for full-sized filters and Group T_F. The detailed manufacturing process of full-sized filters will be discussed in Section 3.3.

The process after cutting disks were the same as Group M.

3.2.3 Group T_p Samples Making Method

Group T_P stands for the group of sample ceramic disks cut from the plates made in Tamale. Because the recipes used in the Group M and Group T_F were different as explained in Section 3.2.2 above, in order to compare the sample ceramic disks cut from filters and those cut from handmade plates under the same recipe, Group T_p were created using the same recipe as Group T_F. The make-up procedure for Group T_P is generally the same as the make-up for Group M but with these few differences:

1) The rice husk size ranges for Group T_P were the same as Group T_F, but not Group M: 234-980μm, 980-1180μm, 1180-1660μ.

2) The plates were fired in the kiln at PHW factory together with the full-sized filters after the drying process, as shown in Figure 3-8 and Figure 3-9.

The purpose of making Group T_P was to verify the feasibility of conducting experiments using plates instead of filters.

Figure 3-8 The kiln in PHW

Figure 3-9 Drying process of plates

3.3 Filter Manufacturing Method

This chapter focuses on how the author made the filters at the PHW factory. The factory at PHW has been in existence and producing filters first for research and de since 2010 and later for sales since 2013. Its original methods of production were well documented in *Pure Home Water Ceramic Filter Manufacturing Manual* (Miller & Watters, 2010). The method currently used for manufacturing CPFs at PHW in 2014 is illustrated in this chapter and briefly described below.

3.3.1 Preparation of the clay

After drying and breaking the clay clods dug from the ground, the clay is pounded using a mortar and pestle as shown in Figure 3-10. After pounding, the clay is sieved using a sieve that has an opening size of 1.12mm to ensure that the particle size of the powder is less than that sieve opening (Miller & Watters, 2010).

Figure 3-10 The clay is pounded by local women

3.3.2 Preparation of rice husks at PHW factory

Typically one or two women sieve the rice husks at the PHW factory using a mesh screen that has an opening size of 1680µm, as is shown in Figure 3-11. The size of rice husks used to manufacture real full-sized filters at the factory is 0-1680µm.

Figure 3-11 Sieving process at PHW factory

3.3.3 Preparation of rice husks by the author for research

As was mentioned in Section 3.2.2, the author prepared three different sizes of rice husks using a set of four mesh screens. The set of mesh screens used are listed in Table 3-3.

Table 3-3 Parameters of the sets of mesh screens used

Name	Mesh Number	Wire diameter (inch)	Opening size (μm)
“USA new”	12	0.018	1660
“Nigeria”	16	0.016	1180
“Medium”	18	0.017	980
“Small”	60	0.0075	234

Thus, the three different rice husk sizes are: 1180-1660μm, 980-1180μm, 234-980μm , the sizes that get trapped between each level of mesh screen.

There are several steps to get the rice husks:

1. Place the mesh screens in sequence as shown in Figure 3-6 and Figure 3-12. “USA new” goes on the top of the whole set, “Nigeria” goes in the middle, and “Medium” goes on the bottom.
2. Place the rice husks on top of the “USA new” screen, as can be seen in Figure 3-13. And then sieve the rice husks by hand, as shown in Figure 3-14. After about 5 minutes’ sieving process,

remove the "USA new" screen and collect the rice husks on the top of "Nigeria" screen. Thus, the rice husks collected have the size between 1180-1660μm.

3. Repeat the above steps until enough rice husks for each of the three different sizes are collected.

Figure 3-12 Sets of mesh screens

Figure 3-13 Put rice husks on top of mesh screens

Figure 3-14 Sieve the rice husks by hand

Figure 3-15 Rice husks after sieving

3.3.4 Method of Mixing Materials

After the preparation of materials, the appropriate amount of clay, rice husks, and water is weighed according to the intended composition. A mix of 10kg of Gbalahi Clay, 4kg of Wayamba Clay, and 4kg of rice husks could make 3 full-sized filters.

After the materials are prepared, put the two kinds of clay powder and rice husks into the mixer shown in Figure 3-16 in order to make them uniformly mixed. And then place the mixed materials on a tarp in order to prevent extra contaminants; add water to the mixture and continue to mix by hand until it becomes cohesive enough to press. Figure 3-17 shows the mixing process with water being added by the standing woman holding the watering can.

Figure 3-16 The mixer

Figure 3-17 Adding water to the mix

3.3.5 Method of Pressing

There are two parts of the hydraulic press mold. On the top is the Female Mold and on the bottom is the Male Mold, as can be seen in Figure 3-18 and Figure 3-19.

Figure 3-18 The Hydraulic Press showing Male & Female Molds

Figure 3-19 Putting the clay/rice husk mixture on the Male Mold

Figure 3-20 Filter after pressing

First, put plastic bags over the Male and Female Molds as shown in Figure 3-18. Then, with the drawer, which holds the Male Mold, pulled out, place the wet clay mix on top of the Male Mold, and pat it down to roughly match the shape of the top portion of the Male Mold, as can be seen in Figure 3-18. Slide the drawer back in position so that the Male Mold is under the Female Mold. And then use the hand crank to lower the Female Mold on top of the Male Mold; release the hand crank so that the filter is formed (Miller & Watters, 2010), which can be seen in Figure 3-20. Lastly, use water and a hand tool to make the surface more finished.

3.3.6 Method of Drying Filters

After the filters have been pressed and formed into a hemisphere shape, they must be dried before they can be fired. This is in order to prevent them from undergoing a shape change in the firing process, which will cause cracking. Filters also should be carefully monitored during this step so as to avoid cracking in the drying process.

As can be seen in Figure 3-21, place the filters up-side-down on the shelf in a shaded area and let them dry for one week during the 9-month dry season.

Figure 3-21 Drying Filters

3.3.7 Method of Firing Filters

After one week’s drying process, the firing process begins. CPFs are stacked in the largest kiln at the PHW factory. The kiln can be seen in Figure 3-22. They are fired for approximately 10 hours with a maximum temperature of around 850 degrees centigrade. After firing, let the CPFs cool down, brush off the ash from their surface, and then stack them on the shelf (as shown in Figure 3-23).

Figure 3-22 The kiln in PHW

Figure 3-23 Finished filters after firing

3.4 Normal Full-Sized Filters for Mixing Process Testing

When mixing water with rice husk and clay powder, there have been several methods to mix them. The first is the hand-mixing process as described in Section 3.3.4, and the second is the pugmill-mixing process. The hand-mixing process is the simplest and is what has been used since PHW first began producing filters for research. The pugmill mixing process is putting the mixture into the pugmill and then adding water. PHW acquired electricity in early 2013 and acquired a pugmill in November 2013. And pugmill-mixed filters were produced for the first time in December 2013, just one month before the author's field research there.

The filters used in this test were normal filters that the factory produced before the author came to Tamale with a mass ratio of 10:4:4 and a rice husk size range of 0-1660μm.

3.5 Lab Setting in Tamale

In January 2014, the Pure Home Water (PHW) lab was located at the Pure Home Water office in Tamale, not at the factory in Taha (in summer 2014, the lab was moved to the factory, but this was not the case during the research for this thesis). Every experiment related to bacterial removal and flow rate was conducted in this lab, which contained an incubator, an oven, a refrigerator, a Quanti-Tray Sealer, and a water distiller, as shown in Figure 3-24.

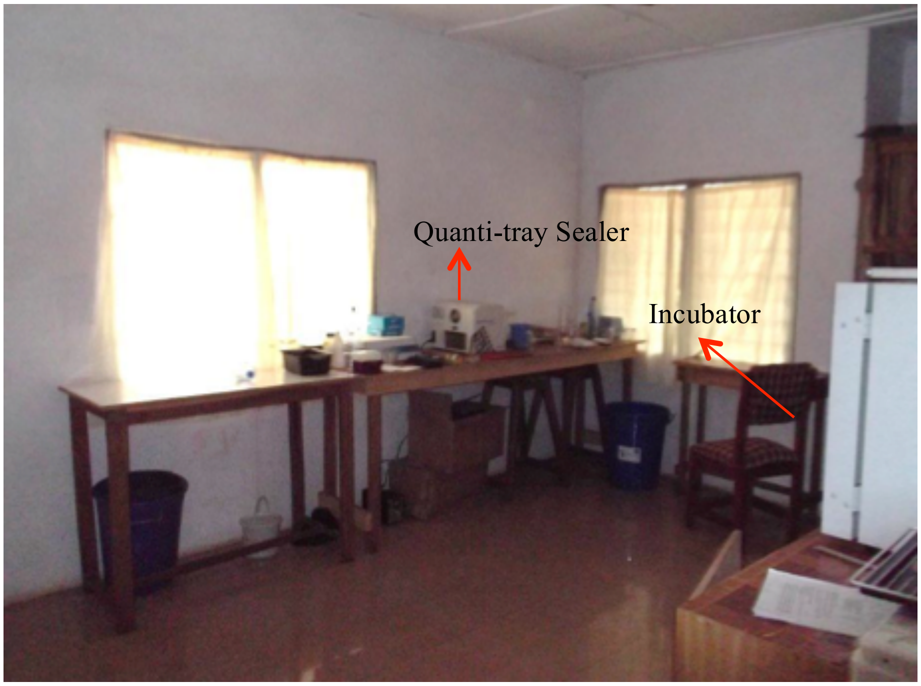


Figure 3-24 The Pure Home Water Lab in Tamale, Ghana

3.5.1 Group M Test Method

As mentioned in Section 3.2.1, Group M are the sample ceramic disks cut from the hand-mixed and hand-pressed plates at MIT, with a mass ratio of Gbalahi Clay, Wayamba Clay, and Rice Husks of 12:4:4. These disks were made at MIT, brought to Ghana and tested in the PHW Lab in Tamale.

The bacterial removal rate of Group M was tested using a syringe pump (Figure 3-25). The specific procedure of this test is as follows:

First, the *E.coli* solution was prepared which would be used as the influent. The author used *Escherichia coli* K12, which was bought from ATCC, a global nonprofit bioresource center[4]. The *E. coli* was prepared in Luria Broth (LB), which is the most widely used medium for the growth of bacteria, to produce a slurry containing a high concentration. The slurry was then diluted in a blend of phosphate buffered saline solution (PBS) and deionized water (with a volume ratio of

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[4] http://www.atcc.org/

1:4) to 10^5 MPN/mL to be used as the influent in the experiments. The detailed procedure for making up the *E.coli* solution is given in Appendix B.

Second, the bacterial removal rates of samples with different rice husk sizes were tested under the same flow rate, in order to investigate the relationship between bacterial removal and rice husk size. The flow rate was controlled using a syringe pump[5]. As is shown in Figure 3-25, two syringes were connected with the disks using tube and brass fittings. Once the velocity of the syringe pump for pushing the syringes was set up, the prepared influent that was in the syringes went through the disks at the fixed flow rate. The author started to collect the effluent using sterilized bottles after the first 10 mL effluent came out (i.e. once it had stabilized). Then the author extracted 1 mL effluent using a sterile pipette to test its most probable number using IDEXX QuantiTray/2000.

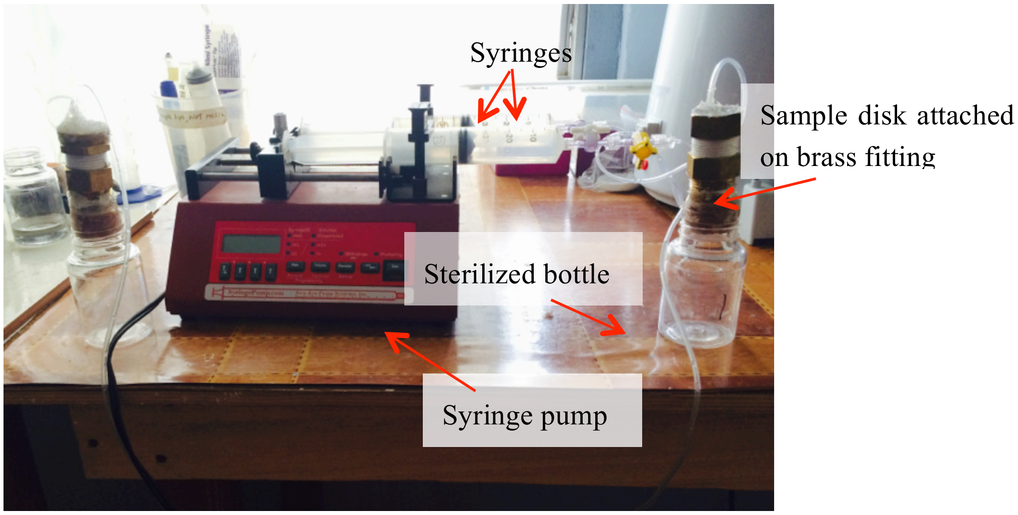

Figure 3-25 Setup of Group M Testing

Third, for each rice husk size, the bacterial removal of disks using different flow rates was tested, in order to investigate the relationship between bacterial removal and flow rate. The author chose four different flow rates: 0.1mL/min, 0.5mL/min, 1.0mL/min, and 1.5mL/min. The four respective flow rates were set using the syringe pump. The diameter of the syringe and the flow rate were inputted into the syringe pump so that it was given a pressure which automatically made

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[5] www.syringepump.com. Model: NE-4000.

the piston move at a uniform rate, then the effluent came out at a constant velocity.

3.5.2 Group Tp Test Method

As mentioned in Section 3.2.3, Group T_P is the group of sample ceramic disks cut from the hand-mixed and hand-pressed plates made in Tamale, with a mass ratio of Gbalahi Clay, Wayamba Clay, and rice husk of 10:4:4.

Group T_P was tested in Tamale using the Bucket Setup, which is shown in Figure 3-26a and b. This method has been previously described by Servi (2013). The bucket has a hole at the bottom, through which the bucket and the four-prong fitting can be connected. Brass fittings can be installed onto the four-port fitting, so that the influent contained in the bucket can be filtered through the sample ceramic disks. In order to ensure that each disk had the same water head, the sample ceramic disks were only installed on number 1 and 4 positions as shown in Figure 3-26b.

Figure 3-26 (a)The Bucket Setup for testing Group T_P and Group T_F (b)Close up showing 1 and 4 disk ports of the four-prong fitting

The hydraulic conductivities and bacterial removal rates of Group T_P can be tested at the same time. First, the *E.coli* slurry (10^8cfu/mL) was diluted in a blend of phosphate buffered saline solution (PBS) and deionized water (with a volume ratio of 1:4) to 10^4cfu/mL to be used as the influent in the experiments. The concentration of the influent used to test Group T_P was lower than the concentration used to test Group M (described in Section 3.5.1, using syringe pump) because after several trial tests, the author found out that the bacterial removal rate of Group T_P was lower than Group M by about 50%. This may be because that the rice husk used in Group M and Group T_P were from two places (Cambodia and Ghana), and that the mixing processes were different (by hand and by machine). When the influent was prepared, it was poured into the bucket to reach a fixed water head of 14cm. After 10 mL effluent came out, at which point the bacterial removal had become steady, the author collected the effluent using sterilized bottles and recorded the duration of time. The hydraulic conductivity can be calculated using the amount of collected water weighed on a scale and the recorded time. Then the author extracted 1 mL effluent using a sterilized pipette and tested its most probable number (MPN) using IDEXX QuantiTray/2000.

There were three disks for each size, that is, there were nine disks in total. Each disk was tested through the process described above.

3.5.3 Group T_F Test Method

As previously mentioned in Section 3.2.2, Group T_F is the group of sample ceramic disks cut from the hand-mixed and machine-pressed full-sized filters made in Tamale. The full-sized filters were made from a mixture of Gbalahi Clay, Wayamba Clay, and rice husk in a ratio of 10:4:4.

The testing process was the same as Group T_P using the bucket setup (Figure 3-26a and b).

3.5.4 Full-sized Filter Test Method

The full-sized filters were made at the Pure Home Water factory in Tamale from a mixture of Gbalahi Clay, Wayamba Clay, and rice husk as a ratio of 10:4:4 as was already mentioned in Section 3.1. The mixture was mixed by the workers at the factory by hand and pressed using the hydraulic press. The full-sized filters were made with four samples from three different rice husk sizes: Filter 1-1 to 1-5 set was made with rice husks bigger than 1660μm, but the rice husk size was too big so that these filters all collapsed; Filter 2-1 to Filter 2-5 set was made with a mean rice husk size of 1420μm; Filter 3-1 to Filter 3-5 set was made with a mean rice husk size of 1080μm; Filter 4-1 to Filter 4-5 set was made with a mean rice husk size of 607μm. After firing and soaking, only one of the Filter 2-1 to Filter 2-5 set was in good condition, all the others were broken. Thus, only one filter of set #2, #3 and #4 were tested.

Figure 3-27 Full-sized filters with Three Different Rice Husk Sizes (from left to right: 2-1, 3-3 and 4-5)

The full-sized filters were tested in the lab in Tamale using full-sized filter Setup as shown in Figure 3-28. The procedure of testing is as follows: first, the filters were soaked in distilled water for 24 hours, and then were rinsed by distilled water using a brush. This was done to make the filters saturated and as clean as possible. Making the filters saturated helps to stabilize the flow as soon as possible when testing.

Second, the *E.coli* slurry (10^8MPN/mL) was diluted in a blend of phosphate buffered saline (PBS) and deionized water (with a volume ratio of 1:4) to 10^3MPN/mL to be used as the influent in the experiments. The concentration of the influent was chosen because it was high enough get the bacterial removal results based on trial tests.

Finally, the ceramic filters were put on the top of a big bucket with a hole near the bottom so that a beaker could be put in to collect the effluent. Another big bucket with lid and spigot was put on the table over the filter. The influent was poured into the bucket on the table, so that the influent that flowed into the filter can be controlled using the spigot. Fill the filter with influent to 1cm below the edge of the filter with a water head of 14cm. The water head was always kept at 14cm by manually adjusting the spigot. After 10 mL effluent came out, started to collect the effluent using the sterilized beaker, so that the bacterial removal of that sample has become steady. Then extract 10 mL effluent using pipette and test its most probable number using IDEXX Quanti-Tray/2000.

Figure 3-28 The Full-sized Filter Setup at the PHW Lab in Tamale, Ghana

3.5.5 Normal Full-sized Filter Test Method

The normal full-sized filters produced in the factory were only tested for the mixing process and bacterial removal test. In this set of tests, we filled fifteen hand mixing filters and fifteen pugmill mixing filters with dugout water at the same water head in order to investigate which mixing method has higher total coliform removal. Because of the huge amount of influent needed in this test, dugout water was used. It is the local surface water supply that has been the main local water supply source and generally has 50-100MPN/100ml total coliform and 0-10MPN/100ml *E.coli*, based on the author's test results during January 2014 (dry season). Because the *E.coli* concentration is too low, total coliform removal was tested as the indicator of bacterial removal. Total coliform was only used in this test.

3.6 Bacterial removal Test Method

To determine the performance of each sample and filter in terms of bacterial removal, the IDEXX Quanti-Tray/2000[6] test was used.

This procedure involves four steps:

1) Dispose 1 mL effluent into a 100mL sterile Quanti-Tray bottle. Dilute the effluent using 99ml distilled water in Ghana (deionized water at MIT) to form a 100mL sample mixture in order to create a 1:100 dilution of the sample.
2) Add a packet of Colilert (W 200 I).
3) Put the 100mL solution into a 98-well Quanti-Tray. Put the Quanti-Tray into the Quanti-Tray Sealer. The Quanti-Tray® Sealer 2X automatically distributes the sample mixture into separate wells.
4) Put the sealed Quanti-Tray into the incubator at the temperature of 35℃. After 24-hr incubation, the number of positive wells can be converted to a most probable number (MPN), as shown in Figure 3-29. The total coliform can be counted from the number of wells that turned yellow; and the *E.coli* can be counted from the number of wells that fluoresce. This count can be used to determine the MPN using either the Thomas Equation[7] or the MPN tables provided by IDEXX with the product.

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[6] http://www.idexx.com/view/xhtml/en_us/water/products/quanti-tray.jsf

[7] Thomas provided an approximation equation that could be used to calculate MPN for any combination of tubes (equivalent to the "wells" in the Quanti-tray):

$$MPN/100ml = \frac{\#\ of\ positive\ tubes \times 10}{\sqrt{(\#of\ ml\ in\ negative\ tubes)\times(\#\ of\ ml\ in\ all\ tubes)}}$$

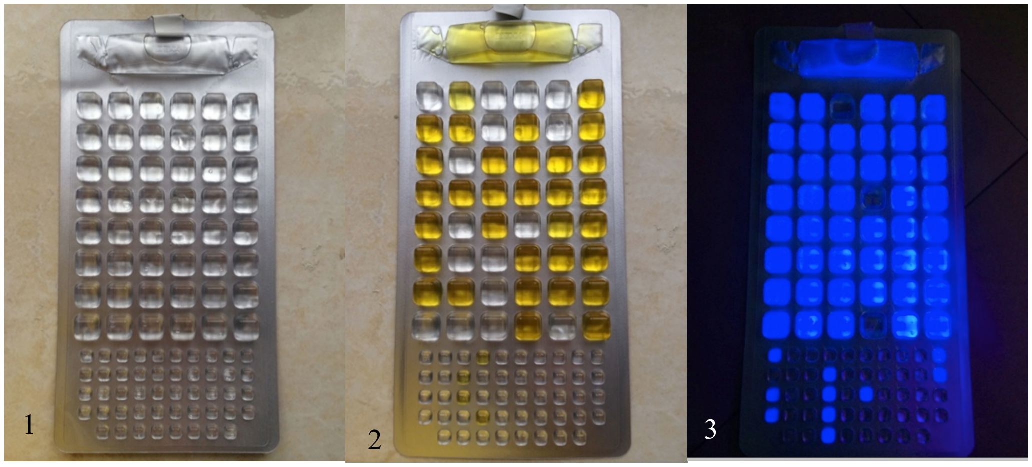

Figure 3-29 Quanti-Trays showing: 1) All negative results; 2) Yellow results showing positive for total coliform; 3) Fluorescent results showing positive for *E.coli*.

All bacteria tests were performed in triplicate and the median value was used for logarithmic removal value (LRV) calculation. In this thesis, the bacterial removal is expressed as LRV:

$$\boldsymbol{LRV = -log(\frac{MPN\ in\ influent}{MPN\ in\ effluent})} \qquad \textbf{Equation 3}$$

3.7 Statistical Methods

3.7.1 Unpaired Two-Sample Student's T-Test

Unpaired two-sample student's t-test was performed using Excel at a 95% confidence interval to analyze the differences between the log removal value (LRV) of two sets of disks. The presumption is that the statistics follow a normal distribution. Two-tailed distribution and two-sample equal variance were chosen for the method. The principle of how to calculate t-test is as follows:

$$\boldsymbol{t = \frac{\overline{X_1} - \overline{X_2}}{s_{X_1X_2} \cdot \sqrt{\frac{2}{n}}}} \qquad \textbf{Equation 4}$$

where $$S_{X_1X_2} = \sqrt{\frac{1}{2}(S_{X_1}^2 + S_{X_2}^2)}$$

Here $S_{X_1X_2}$ is the grand standard deviation (or pooled standard deviation), 1 = group one, 2 =

group two. $S_{X_1}^2$ and $S_{X_2}^2$ are the unbiased estimators of the variances of the two samples. The denominator of t is the standard error of the difference between two means. For significance testing, the degree of freedom for this test is $2n - 2$ where n is the number of samples in each group (Coladarci & Cobb, 2013).

After calculated by the t-test formula in Excel, if p-value > 0.05, the difference between the two sets of samples is not significant; when p-value < 0.05, the difference between the two sets of samples is significant.

3.7.2 Box Plots

Boxplots are well-known data analytic method that displays differences between samples without making any assumptions of the underlying statistical distribution: they are non-parametric. It is a convenient way of graphically depicting groups of numerical data through their five-number summaries. They include the smallest observation, known as the sample minimum, lower quartile (Q1), median (Q2), upper quartile (Q3) as well as the largest observation, known as the sample maximum. They also point out which observations, if any, might be considered outliers and are used to exhibit differences between samples.

4 Influencing Factors on CPFs Performance

4.1 Performance Criteria 1: Flow Rate

According to Servi (2013), the flow exiting the filter is laminar. Thus we can use Darcy's law for laminar flow through porous media given by:

$$\boldsymbol{Q = \frac{KAh}{L}} \qquad \textbf{Equation 5}$$

Where Q is the volumetric flow rate, K is the hydraulic conductivity, A is the cross-sectional area, h is the hydraulic head and L is the wall thickness. Darcy's law is used here to calculate the hydraulic conductivity to eliminate the influence of geometry (wall thickness and cross-sectional area) on the flow rate.

4.1.1 Rice Husk Size & Hydraulic Conductivity Test

The author investigated the relationship between flow rate and rice husk size because flow rate is relevant to bacteria removal, and the way to control flow rate in manufacturing process is by rice husk size at the PHW factory. Referring to Darcy's law, the hydraulic conductivity of each sample can be calculated based on flow rate, wall thickness, cross-sectional area and hydraulic head.

1) Disk Group M

The relationship between rice husk size and hydraulic conductivity is plotted in order to eliminate the effect of geometry, thus allowing a comparison between samples with different geometries.

According to Kozeny-Carman relationship[8], pressure gradient is proportional to the square of pore size, which means flow rate is proportional to the square of pore size. Figure 4-1 is the plot of the relationship between K and the square of rice husk size (RHS^2), with an R^2 of 0.89. It is in accordance with the Kozeny-Carman relationship.

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[8] Kozeny-Carman equation: $\frac{\Delta P}{L} = \frac{180\, V_0 \mu (1-\varepsilon)^2}{\varphi_S^2 D_P^2 \varepsilon^2}$

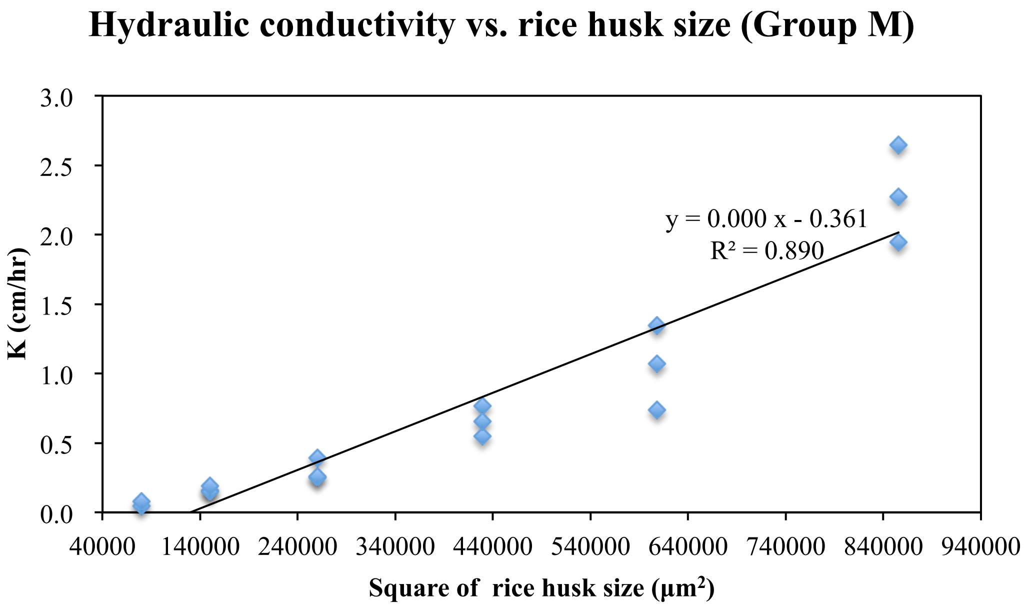

Figure 4-1 The relationship between RHS^2 and K for Group M

However, the author found that the exponential relationship works better for this study. Figure 4-2 shows that the R^2 of the exponential relationship is 0.96, which is higher than 0.89. It is in accordance with one of Servi's explanations for the relationship between hydraulic conductivity and rice husk size (Servi, 2013), but the mechanism behind this relationship hasn't been confirmed. The reason for an exponential relationship might be that rice husks will join together at times to form enormous pores, and this effect is amplified when the rice husk size is larger.

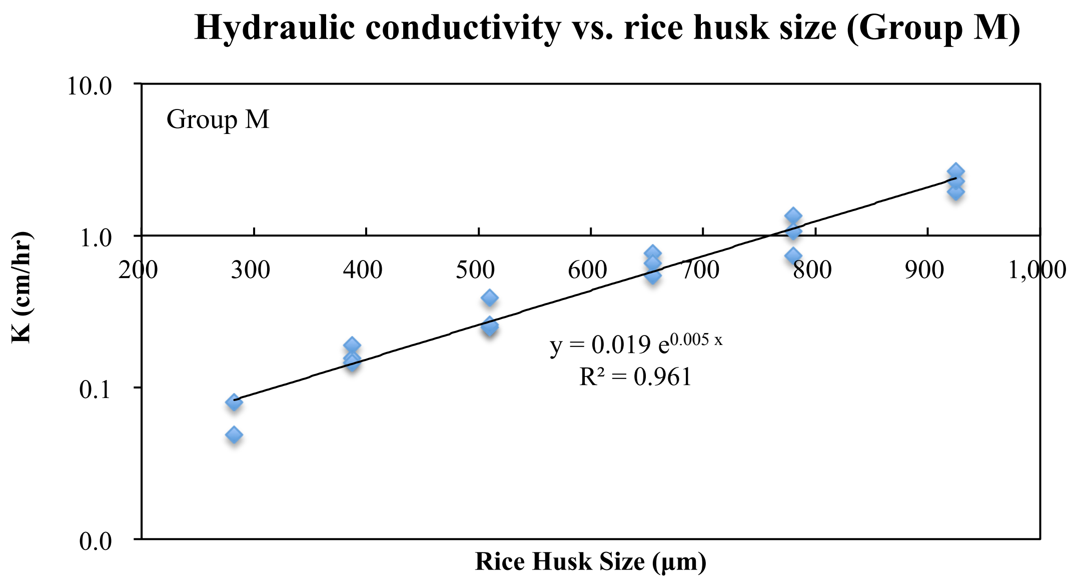

Figure 4-2 The semilogy plot of the relationship between RHS and K for Group M

2) Disk Group T_P & Disk Group T_F

The relationship between flow rate and rice husk size was studied and is depicted in the following figures. Figure 4-3 shows the relationship between hydraulic conductivity and the square of RHS, and Figure 4-4 is the semilogarithmic plot of K and RHS showing the exponential relationship.

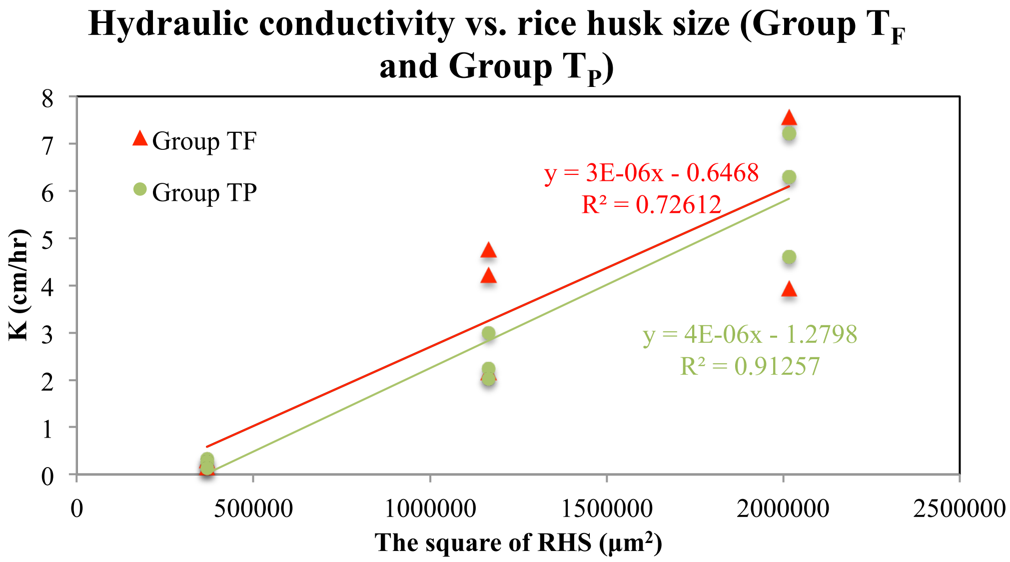

Figure 4-3 The relationship between RHS^2 and K for Group T_F and T_P

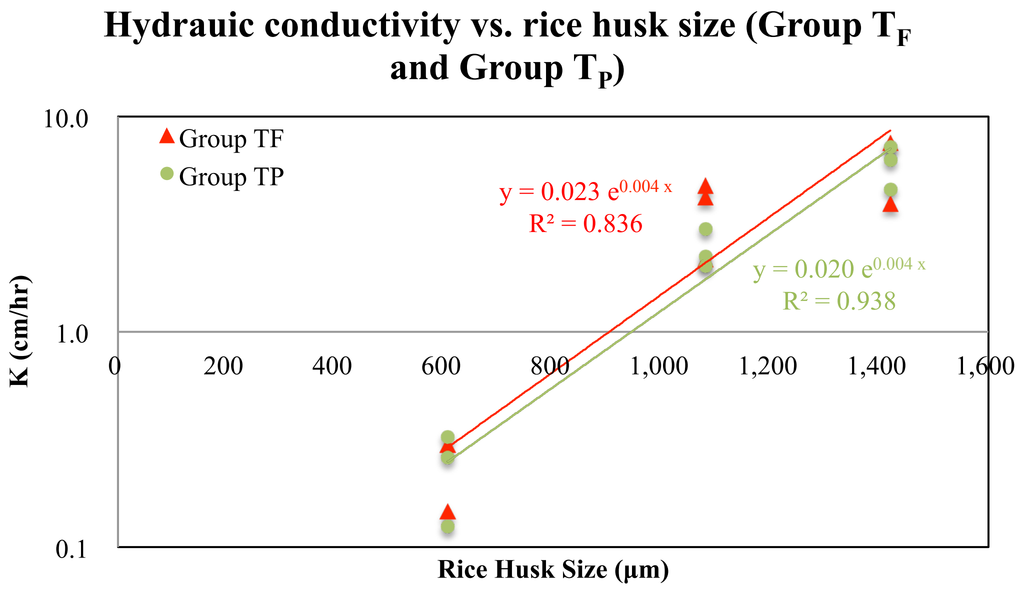

Figure 4-4 The semilogy plot of the relationship between rice husk size and K for Group T_P and T_F

As is shown in Figure 4-3, K is proportional to the square of RHS. But the same as Group M, Figure 4-4 shows that the exponential relationship works better for Group T_F and Group T_P. In addition, according to the data, the K values of Group T_P are more consistent and have a smaller variation in each data set than those of Group T_F, which means the disks in Group T_P performs more in accordance with each other.

4.2 Performance Criteria 2: Bacterial Removal Rate

4.2.1 Flow Rate & Bacterial Removal Test

1) Disk Group M

The relationship between bacterial removal and flow rate was investigated. This experiment was conducted as described in Section 3.5.1. All the disks were produced at MIT out of clay and rice husks from Cambodia (not Tamale Ghana) and consisted of 20 percent rice husks by mass. Each point in Figure 4-5 corresponds to a specific disk and is plotted at the x-value that represents the average rice husk size of the disk. The y-value represents the LRV of *E.coli.* All of the “LRV” on the y-axis in this thesis mean the LRV of *E.coli*. The LRV of total coliform will be identified separately in those charts.

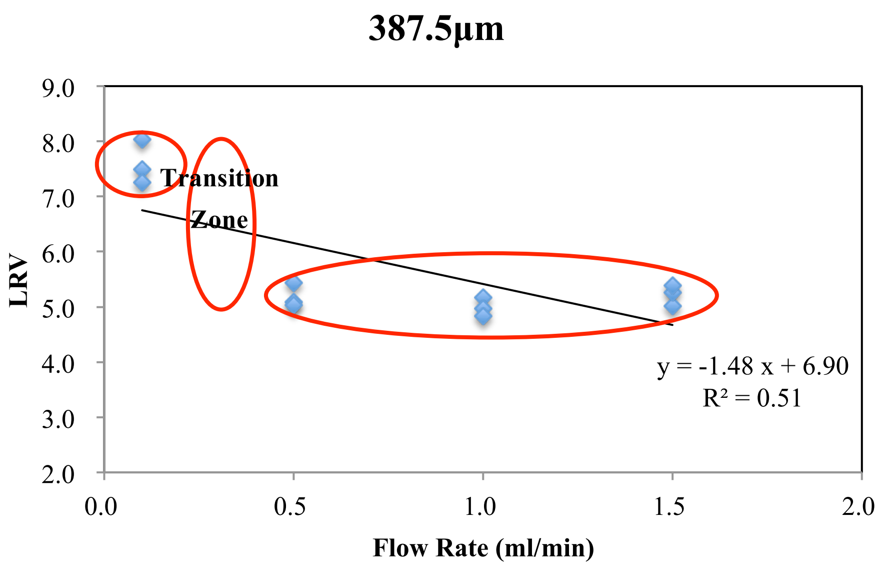

Figure 4-5 The relationship between flow rate and LRV (Group M, RHS=387µm)

In Figure 4-5, LRV is plotted at each of the four rice husk sizes in order to show the full range of the bacterial removals. The tendency line and the value of R^2 suggest that the relationship cannot be negative linear. It is possible that the data points are too few to show the linear tendency, but another possible explanation is that it is a negative step function relationship with two regimes (the two horizontal circles) for LRV, one relatively high (approximately 7.0) and the other relatively low (approximately 5.0), and a transition occurring at a flow rate in the range of 0.1 to 0.5 mL/min.

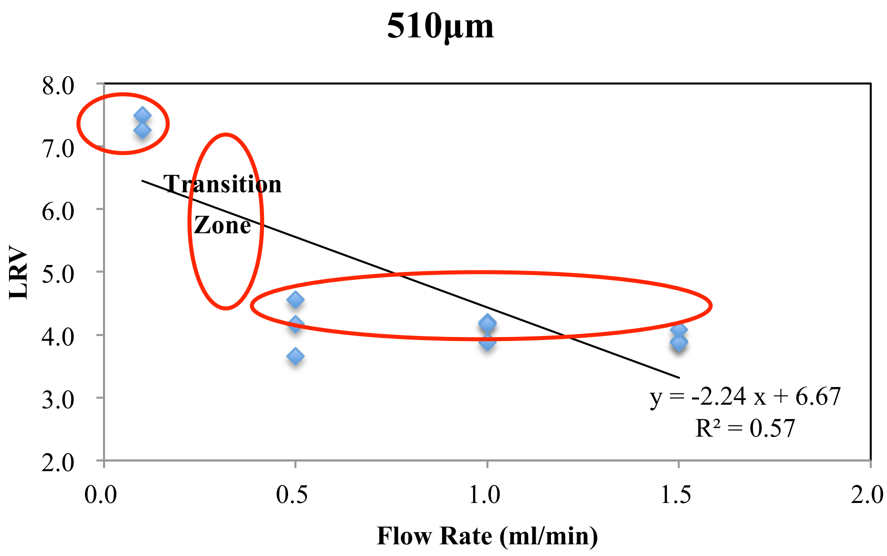

Figure 4-6 The relationship between flow rate and LRV (Group M, RHS=510µm)

The same as Figure 4-5, Figure 4-6 suggests that at a rice husk size of 510µm, the possible explanation is a negative step function relationship with two regimes (the horizontal circles) for LRV, one relatively high (approximately 5.2) and the other relatively low (approximately 4.0) and a transition (the vertical circle) occurring at a flow rate in the range of 0.1 to 0.5 mL/min.

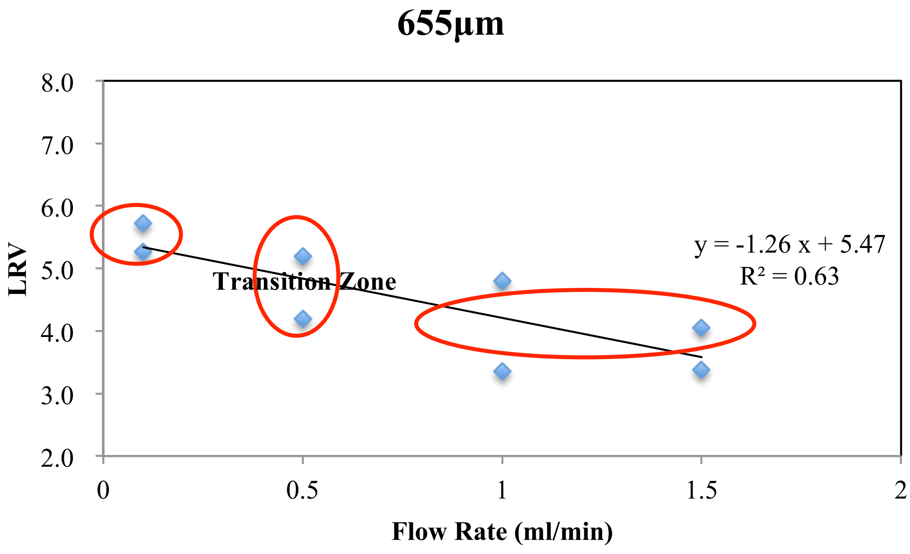

Figure 4-7 The relationship between flow rate and LRV (Group M, RHS=655µm)

Figure 4-7 may be interpreted in two ways: the first possibility is that at a rice husk size of 655µm, bacterial LRV and flow rate has a negative linear correlation; another possible explanation is that they has a negative step function relationship with two regimes (the horizontal circles) for LRV, one relatively high (approximately 5.0) and the other relatively low (approximately 3.5) and a transition (the vertical circle) occurring at a flow rate in the range of 0.1 to 1.0 mL/min.

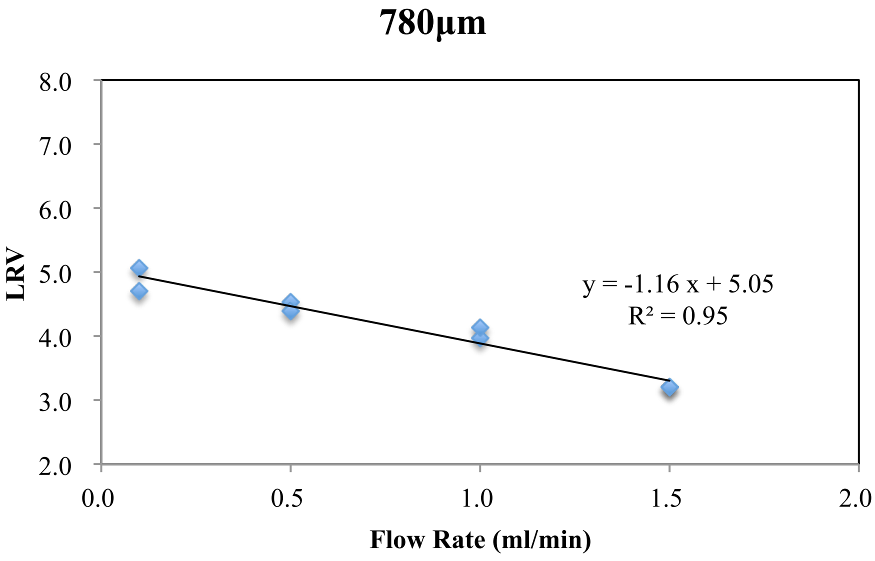

Figure 4-8 The relationship between flow rate and LRV (Group M, RHS=780µm)

Figure 4-8 suggests that at a rice husk size of 780µm, there is a negative linear correlation between bacterial LRV and flow rate.

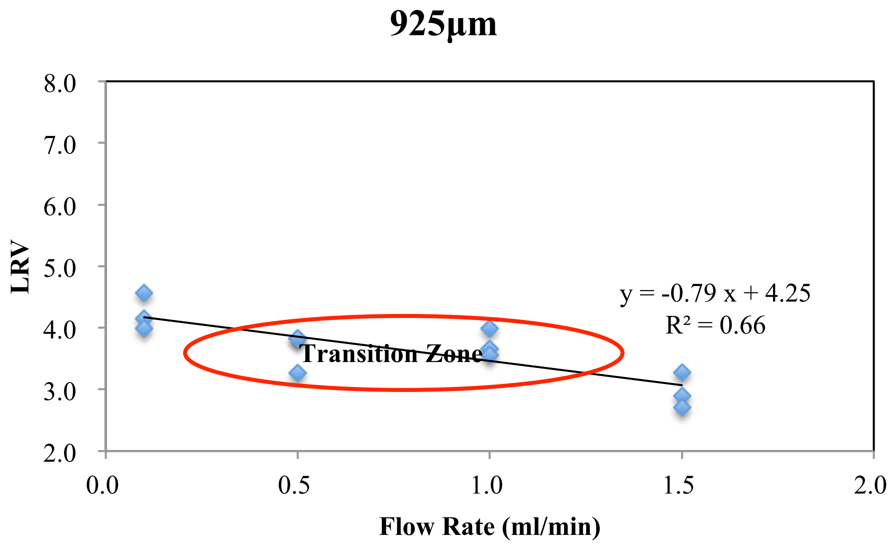

Figure 4-9 The relationship between flow rate and LRV (Group M, RHS=925µm)

Figure 4-9 also can be interpreted in two ways: the first explanation is that at a rice husk size of 925µm, bacterial LRV and flow rate has a negative linear correlation; another possible explanation is that they has a negative step function relationship with two regimes for LRV, one relatively high (approximately 4.5) and the other relatively low (approximately 3.0) and a transition (the horizontal circle) occurring at a flow rate in the range of 0.1 to 1.5 mL/min.

Then the author applied the t-test method. To do this, the author defined a set of data as the LRVs of the same rice husk size and flow rate, then applied the t-test method to each two sets of data, in order to determine whether they are significantly different from each other. The presumption is that the statistics (bacterial removal versus flow rate) follows a normal distribution. For example, for disks with rice husk size of 925µm, given two separate sets of independent and identically distributed samples (flow rate=1.5mL/min and flow rate=1.0mL/min), the t-test can be used to investigate whether the two sets of sample are significantly different from each other. In this case, the unpaired form of the t-test is used because the data sets are not paired data. The threshold chosen for statistical significance is α=0.05. Thus when p-value > 0.05, the difference between the two sets of samples is not significant; when p-value < 0.05, the difference between the two sets of samples is significant.

Table 4-1 The t-test under the rice husk sizes of 387.5, 510, 655, 780, 925µm (Group M)

Flow Rates	387.5µm		510µm		655µm		780µm		925µm	
t-test Pair	P	S/NS	P	S/NS	P	S/NS	P	S/NS	P	S/NS
1.5 / 1.0ml/min	0.327	NS	0.483	NS	0.620	NS	0.025	S	0.015	S
1.0 / 0.5ml/min	0.454	NS	0.903	NS	0.442	NS	0.091	NS	0.658	NS
0.5 / 0.1ml/min	0.001	S	0.437	NS	0.267	NS	0.230	NS	0.061	NS

*S represents "significant", and NS represents "not significant".

When P>0.05, the difference is "not significant"; when P<0.05, the difference is "significant".

Table 4-1 suggests that when rice husk size is 387.5µm, there is a significant difference if the flow rate is changed from 0.5ml/min to 0.1ml/min; when rice husk size is 510µm, there is no significant difference if the flow rate is changed from 1.5ml/min to 0.1ml/min; when rice husk size is 655µm, there is no significant difference if the flow rate is changed from 1.5ml/min to 0.1ml/min; when rice husk size is 780µm, there is a significant difference if the flow rate is changed from 1.5ml/min to 1.0 ml/min; when rice husk size is 925µm, there is a significant difference if the flow rate is changed from 1.5ml/min to 1.0 ml/min.

To summarize, when the mean rice husk size is relatively small (387.5µm), the low flow rate (0.5ml/min) would have a significant impact on the bacterial removal; when the mean rice husk size is medium (510-665µm), the flow rate would have very limited impact on the bacterial removal in the range of 0.1-1.5ml/min; when the mean rice husk size is relatively big (780-925µm), the high flow rate (1.5ml/min) would have a significant impact on the bacterial removal.

The reason might be that when the rice husk size is too small or too large, the pores inside the CPF are either too small or too big such that changing the pore size has a limited impact on bacterial removal. Thus, the determining factor of bacterial removal of CPFs is flow rate. When the rice husk size is medium, the determining factor of CPFs bacterial removal is rice husk size, thus, changing the flow rate will not notably affect bacterial removal of CPFs. This conclusion can be seen more clearly in Figure 4-10, which plots the bacterial LRV of all the rice husk sizes together as a box plot to show the relationship.

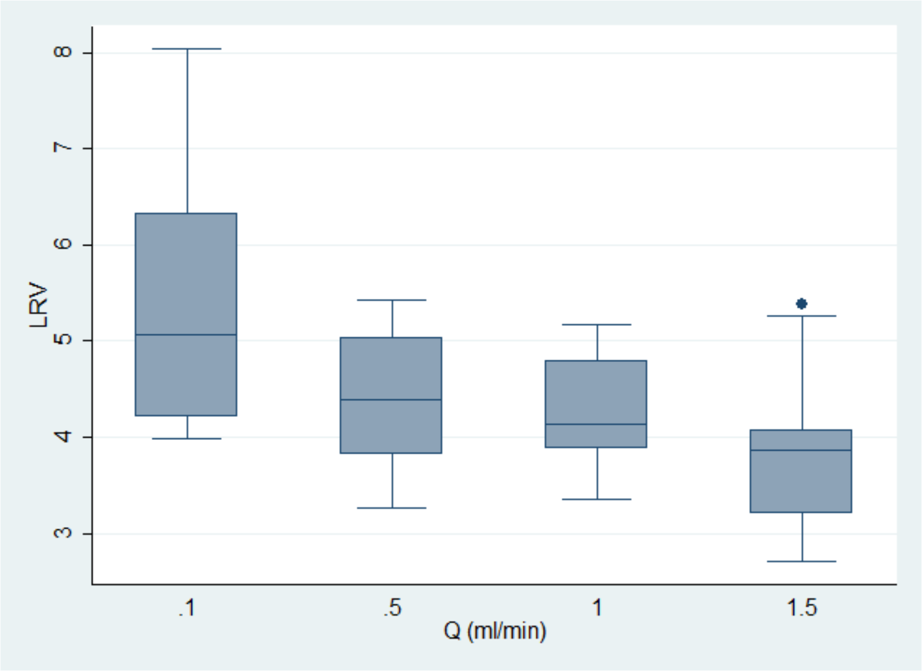

Figure 4-10 The box plot of the relationships between LRV and flow rate (Group M)

4.2.2 Rice Husk Size & Bacterial Removal Test

Next, the relationship between rice husk size and bacterial removal rate was investigated. The method applied to this experiment was already described in Section 3.4. Besides Disk Group M, Disk Group T_P and Disk Group T_F, this experiment was also conducted with the full-sized filters made in Tamale. The data sets presented below are the same as in Section 4.2.1, but showing the relationship between bacterial LRV and RHS at each flow rate.

1) Disk Group M

As shown from Figure 4-11 to Figure 4-14, the relationship between rice husk size and bacterial removal rate is plotted at four different flow rates (1.5mL/min, 1.0mL/min, 0.5mL/min and 0.1mL/min) from fastest (1.5ml/min) to slowest (0.1ml/min). The y-value in the figures is LRV, which represents bacterial removal rate, and the x-value is the average rice husk size of the tested disk. Each point in the figures corresponds to a specific disk.

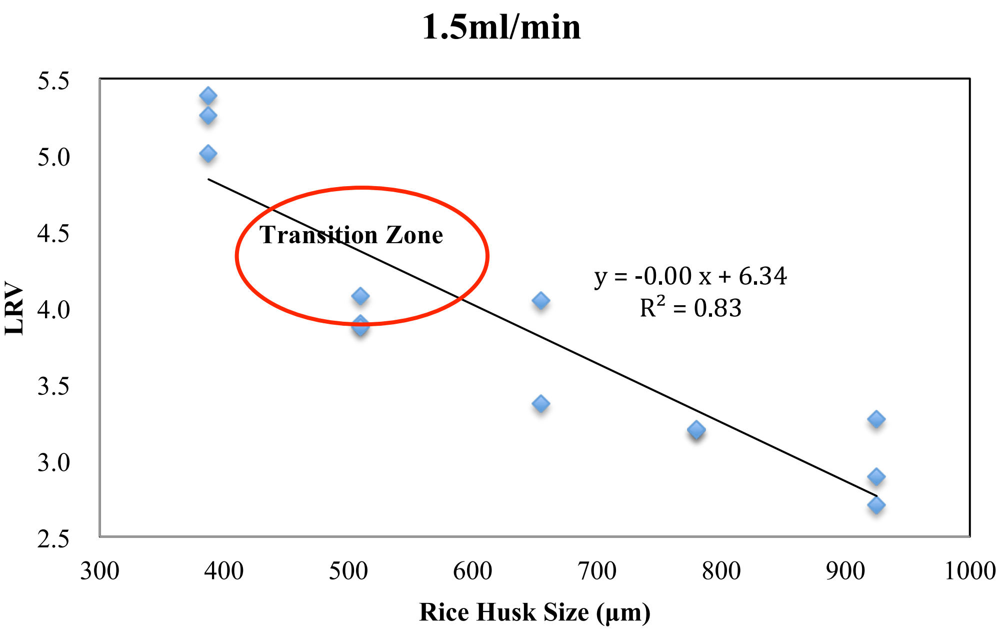

Figure 4-11 Relationship between LRV and RHS at 1.5 ml/min flow rate (Group M)

Figure 4-11 suggests that there may be two interpretations for the relationship at a flow rate of 1.5ml/min: the first explanation is that bacterial removal and rice husk size has a negative linear correlation; the other one is that they has a negative step function relationship with two regimes for LRV, one relatively high (approximately 5.0) and the other relatively low (approximately 3.2), and a transition (the horizontal circle) occurring at a rice husk size range between 420µm and 600µm. That is, the bacterial removal rate is independent of rice husk size in the range of 600µm to 1000µm at the flow rate of 1.5ml/min. These two interpretations are the same as that which Servi proposed in her Master's thesis (Servi, 2013).

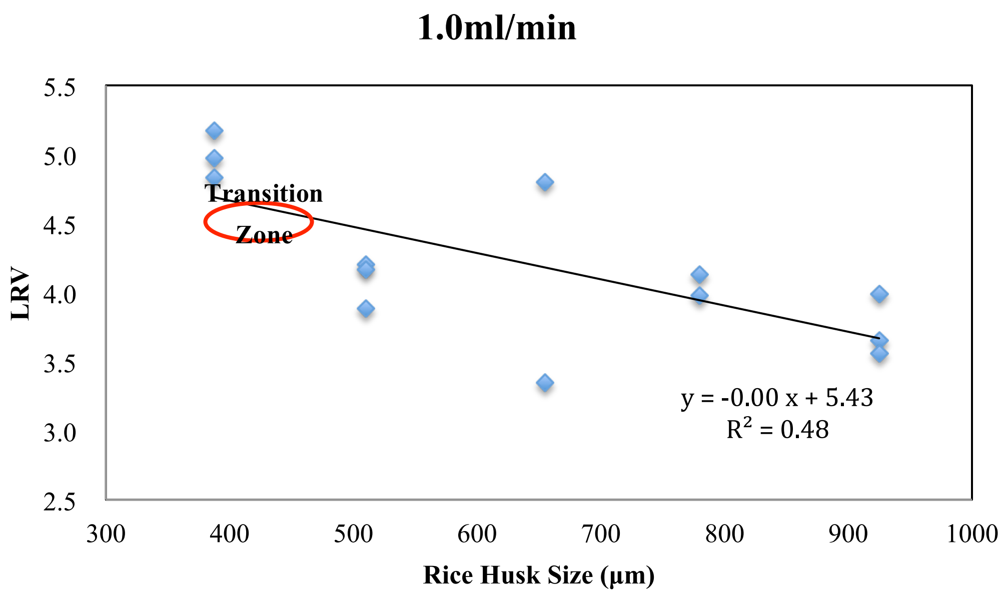

Figure 4-12 Relationship between LRV and RHS at 1.0 ml/min flow rate (Group M)

As is shown in Figure 4-12, R^2 is as low as 0.48, but it might be caused by the limited data quantity. Another probable explanation is that at a flow rate of 1.0ml/min, the bacterial LRV and rice husk size has a negative step function relationship with two regimes for LRV, one relatively high (approximately 4.6) and the other relatively low (approximately 3.8) with a transition (the red circle) occurring at a rice husk size range of 400-500µm. This verifies Servi's step function relationship explanation in her Master's thesis (Servi, 2013). This interpretation means that the bacterial removal rate is independent of rice husk size in the range of 510µm to 925µm at the flow rate of 1.0ml/min.

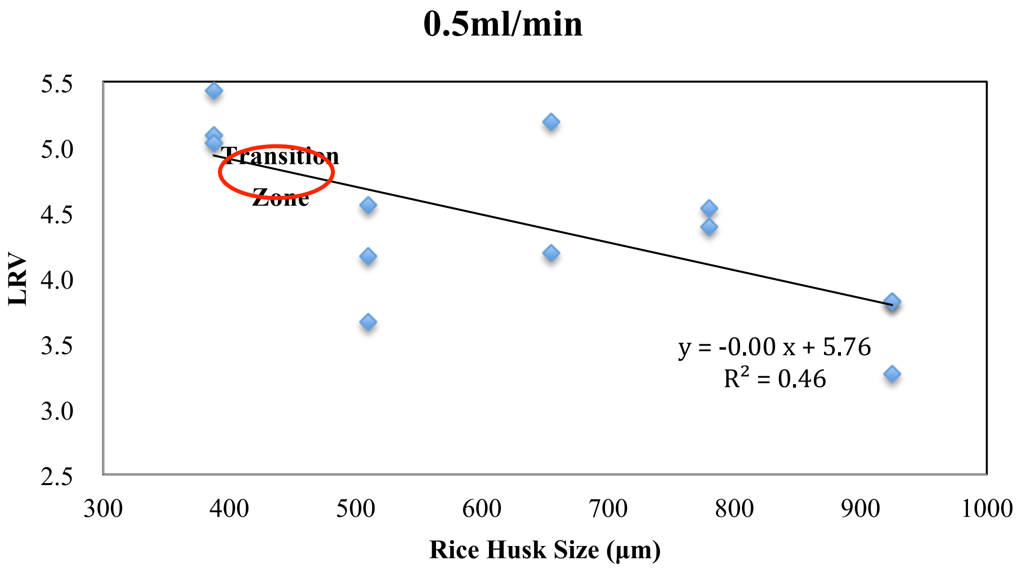

Figure 4-13 Relationship between LRV and RHS at 0.5 ml/min flow rate (Group M)

Figure 4-13 also suggests two possible relationships at a flow rate of 0.5ml/min: negative linear correlation and negative step function relationship. As for the negative step function relationship, there are two regimes for LRV. The higher one is approximately 4.9 and the lower one is approximately 3.8. The transition zone (the red circle) is the same as in Figure 4-12. That is, the bacterial removal rate is independent of rice husk size in the range of 510μm to 925μm at the flow rate of 0.5ml/min. This verifies Servi's step function relationship explanation in her Master's thesis (Servi, 2013).

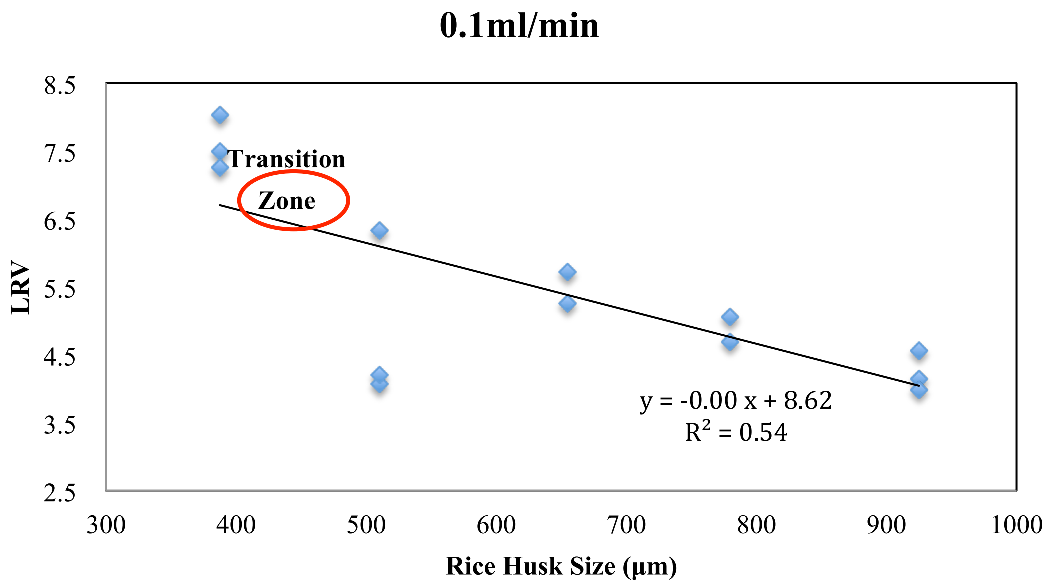

Figure 4-14 Relationship between LRV and RHS at 0.1 ml/min flow rate (Group M)

The relationship in Figure 4-14 also agrees with the negative step function relationship at the flow rate of 0.1ml/min: there are two regimes of LRV, the higher one is approximately 6.9 and the lower one is approximately 4.6, with a transition zone (the red circle) the same as in Figure 4-12 and Figure 4-13. That is, the bacterial removal rate is also independent of rice husk size in the range of 510µm to 925µm at the flow rate of 0.1ml/min. This again verifies Servi's step function relationship explanation in her Master's thesis (Servi, 2013). It might also be a negative linear correlation, but because of the limited data amount, the relationship is not clear.

A t-test of each of the two data sets of adjacent rice husk sizes under the same flow rate was conducted to verify the discussion above. The t-test method is the same as that used in Section 4.2.1. The results are shown in Table 4-2.

Table 4-2 The t-test under the flow rates of 1.5ml/min, 1ml/min, 0.5ml/min, 0.1ml/min

Flow Rate	1.5ml/min		1.0ml/min		0.5ml/min		0.1ml/min	
t-test Pair	P	S/NS	P	S/NS	P	S/NS	P	S/NS
387.5μm and 510μm	0.0002	S	0.0455	S	0.0499	S	0.0508	NS
510μm and 655μm	0.0458	S	0.5039	NS	0.6867	NS	0.8772	NS
655μm and 780μm	0.2441	NS	0.7495	NS	0.9602	NS	0.3121	NS
780μm and 925μm	0.8760	NS	0.7790	NS	0.0997	NS	0.2912	NS

*S represents “significant”, and NS represents “not significant”.

When P>0.05, the difference is “not significant”; when P<0.05, the difference is “significant”.

Table 4-2 suggests that at the flow rate of 1.5ml/min, the LRV of rice husk sizes from 655μm to 780μm are not significantly different, but they are significantly different from 387.5μm to 655μm. This is in accord with the conclusion from Figure 4-11. At the flow rate of 1.0ml/min, the mean LRV of rice husk sizes from 510μm to 925μm are not significantly different, but they are significantly different from 387.5μm to 510μm. This is also in accord with the conclusion from Figure 4-12. At the flow rate of 0.5ml/min, the mean LRV of rice husk sizes from 510μm to 925μm are not significantly different, but they are significantly different from the mean LRV of rice husk sizes from 387.5μm to 510μm. It is also consistent with the conclusion from Figure 4-13. At the flow rate of 0.1ml/min, the mean LRV of rice husk sizes from 387.5μm to 925μm are all not significantly different. It is not the same as the conclusion from Figure 4-13, but considering the P value of the first pair data is very close to 0.05, it is difficult to decide whether it is significant or nor significant. Thus, the conclusion from Figure 4-13 was chosen for the overall conclusion.

In order to show the overall tendency of the relationship, the box plot of the LRV of each rice husk size at all the flow rates is shown in Figure 4-15.

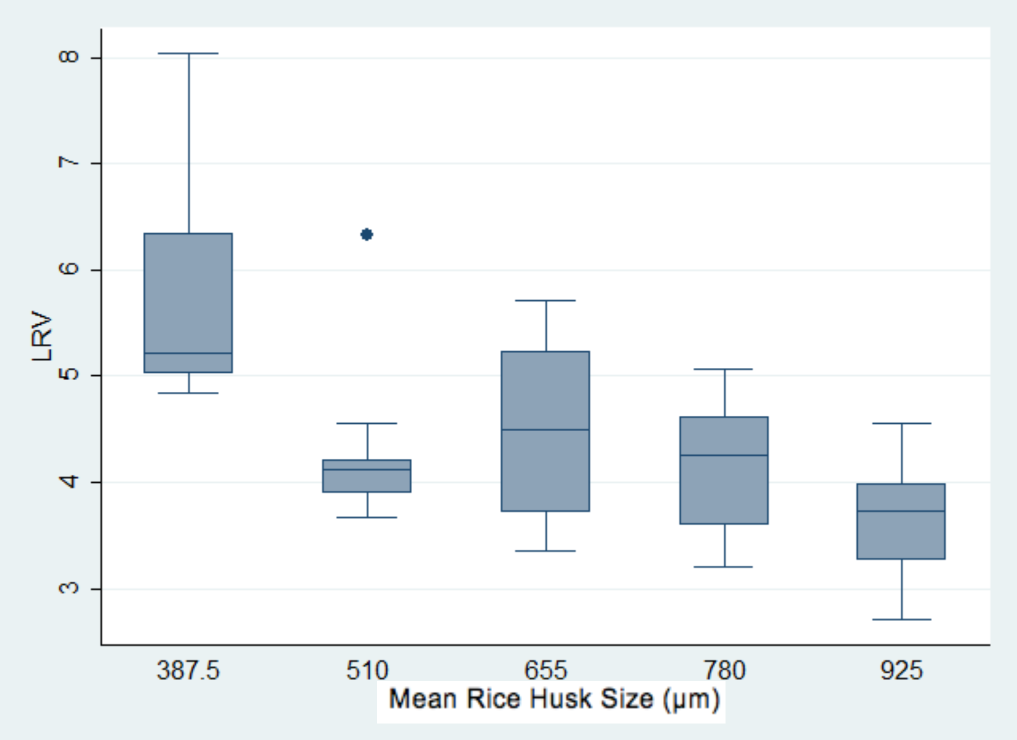

Figure 4-15 The box plot of the relationship between LRV and RHS

To summarize, the relationship between bacterial removal and rice husk size is most probably a negative step function relationship. The LRV of the rice husk sizes with a diameter of 387.5µm are higher than the LRV of other sizes, but the LRV of the rice husk sizes from 510µm to 925µm are not significantly different. Only when the flow rate is 1.5ml/min, the LRV of the 510µm rice husks are lower than that of 655µm rice husks. Thus, the overall tendency is that the LRV of the rice husk sizes from 510µm to 925µm are independent to rice husk sizes, so the rice husk size could be increased up to 925µm without hurting the bacterial removal effectiveness.

The reason might be that when the rice husk size is too small, the pore size inside the CPF is too small to let the bacteria pass through, thus, the determining factor is the rice husk size. But when the rice husk size is within the range of 510-925µm, the impact of rice husk size on bacterial removal becomes limited, and the determining factor turns to the flow rate. Thus, when the rice husk size is between 510 to 925µm, as long as the flow rate is the same, the

bacterial removal would not change with the rice husk size much.

2) Disk Group T_F and Disk Group T_P

Disk group T_F consists of disks cut from the full-sized filters of each size, and Disk Group T_P consists of disks cut from the hand-made plates of each size. The experimental method was already described in Section 3.5.2 and Section 3.5.3. Each disk was tested under the same water head. The relationship between rice husk size and LRV for Disk Group T_F and Disk Group T_P are plotted in Figure 4-16 and Figure 4-17 separately. The y-value in the figures is LRV, which represents bacterial removal rate, and the x-value stands for the average rice husk size of the tested disk. Each point in the figures corresponds to a specific disk.

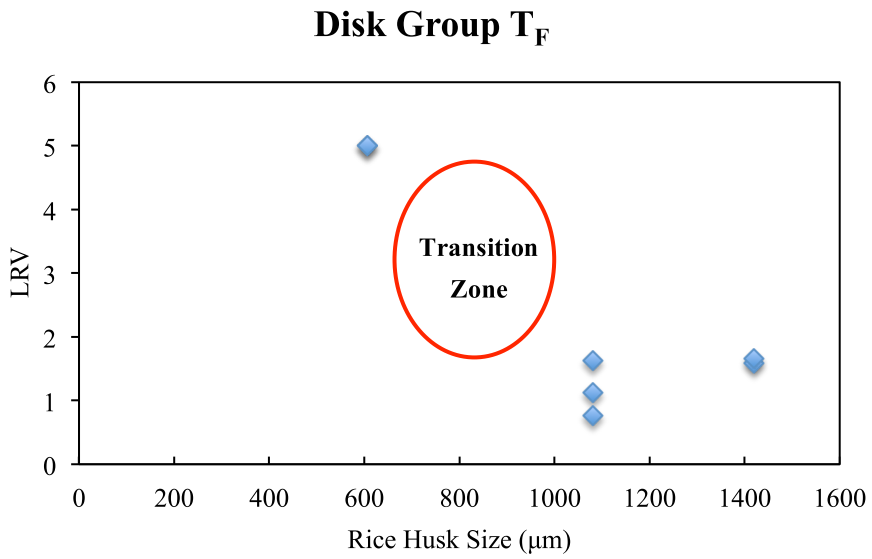

Figure 4-16 Relationship between LRV and RHS of the disks cut from full-sized filters

The LRV of the disks with a mean rice husk size of 600µm are higher than 5, but because 5 is the upper detection limit determined by the selected concentration of the influent, it is chosen to represent the LRV. Thus, Figure 4-16 suggests that the LRV of Disk Group T_F has two regimes: one is relatively high (>5) and the other is relatively low (approximately 1.2) with a transition (the red circle) occurring at a rice husk size range of 607 to 1080µm. **In conclusion, when rice husk size is larger than 1000µm, the bacterial removal rate dropped significantly to a lower**

level. This drop down could be related to the size of *E.coli*. The relationship between bacterial removal and rice husk size for Group T_F is the same negative step function relationship as Group M, but the regimes and transition zone happen in different rice husk size ranges. This is likely to be caused by the different recipes and where the disks were cut from.

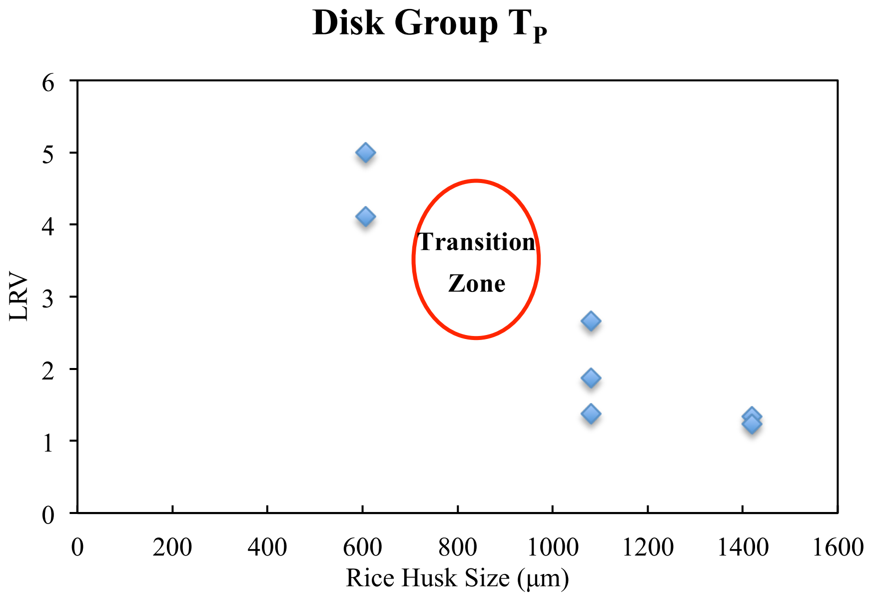

Figure 4-17 Relationship between LRV and RHS of the disks cut from hand-made plate

The LRV of the disks with a mean rice husk size of 600μm are higher than 5, thus 5 is also chosen to represent the LRV. Therefore, similar to Group T_F, Figure 4-17 suggests that the LRV of Disk Group T_P has two regimes: one is relatively high (approximately 5) and the other is relatively low (approximately 1.2) with a transition (the red circle) occurring at a rice husk size range of 607 to 1080μm. **This result also suggests that when the rice husk size is larger than 1000μm, the bacterial removal rate decreases significantly with the increase of rice husk size.** The relationship between bacterial removal and rice husk size for Group T_P is also the same negative step function relationship as Group M. The regimes and transition zone happen in different rice husk size ranges with Group M but in the same ranges with Group T_F. Thus, the difference is most likely caused by the different recipes.

The t-test of two data sets with adjacent rice husk sizes was also conducted to verify the conclusion above. The t-test method is the same as in Section 4.2.1. The results are shown in Table 4-3.

Table 4-3 The t-test of Disk Group T_F and Disk Group T_P

t-test Pair	P		S/NS
	Disk Group T_F	Disk Group T_P	
607μm and 1080μm	0.0218	0.0013	S
1080μm and 1420μm	0.8238	0.2570	NS

*S represents "significant", and NS represents "not significant".

When $P>0.05$, the difference is "not significant"; when $P<0.05$, the difference is "significant".

Table 4-3 suggests that for both Disk Group T_F and Disk Group T_P, the bacterial removal rates of the disks with a mean rice husk size of 607μm are significantly different from those of the disks with a mean rice husk size of 1080μm. And the bacterial removal rates of a mean rice husk size of 1080μm are not significantly different from those of the disks with a mean rice husk size of 1420μm. This conclusion is in accord with the results from Figure 4-16 and Figure 4-17.

In order to show the overall tendency of the relationship, the mean LRV of each rice husk size at each flow rate was calculated to represent the LRV of that size and flow rate. The tendency of the overall relationship of LRV and rice husk size (RHS) is shown in Figure 4-18.

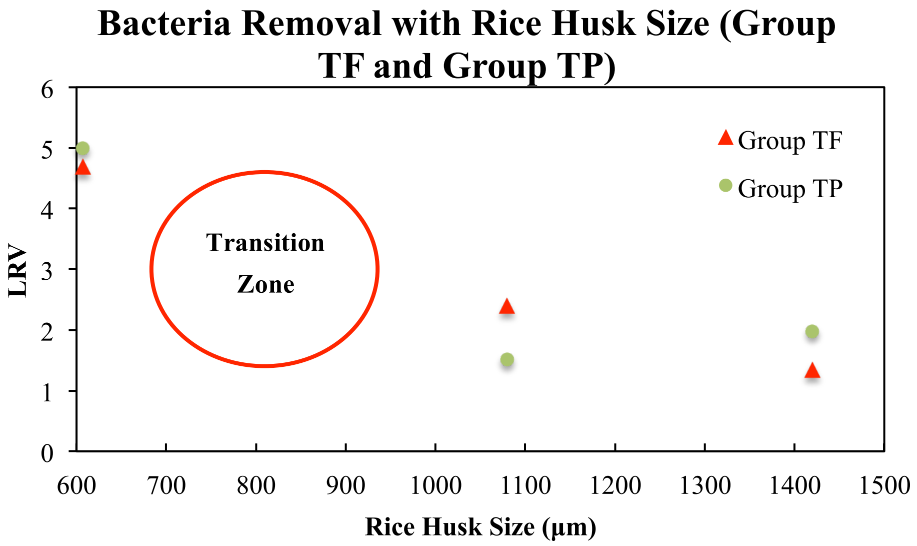

Figure 4-18 Relationships between LRV and RHS

Figure 4-18 suggests that the two groups had similar overall tendencies and close bacterial removal at the same rice husk size. The tendency is that the bacterial removal rates of the disks with rice husk sizes larger than 1000µm are much lower than those of the disks with rice husk sizes smaller than 1000µm.

3) Full-sized Filter Tested at the Same Water Head as Group T_F and T_P

Finally, the relationship of bacterial removal rate and rice husk size for full-sized filters was examined. The experimental method was described in Section 3.5.4. Each filter was tested under the same water head as Group T_F and T_P as described in Section 3.5.2. The results are plotted in Figure 4-19. The y-value in the figure is LRV, which represents bacterial removal rate, and the x-value is the average rice husk size of the tested filter.

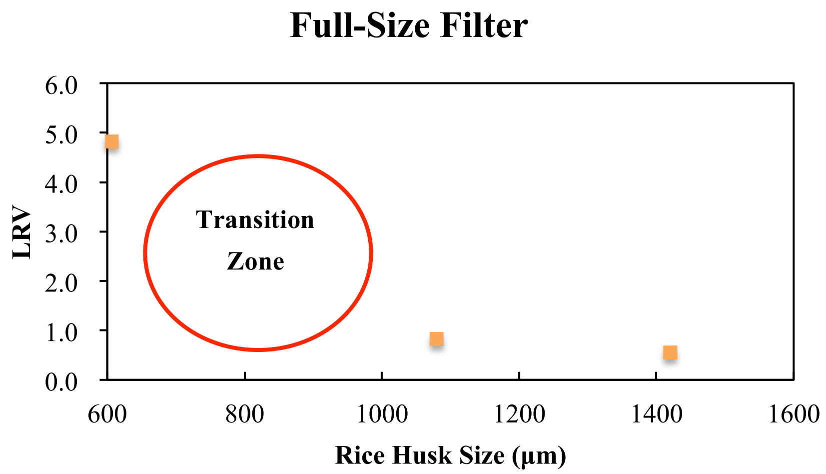

Figure 4-19 The relationship between LRV and RHS for full-sized filter

Figure 4-19 suggests that the bacterial removal rates of filters whose rice husk sizes are from 980µm to 1660µm are independent of rice husk size and are significantly lower than the filter whose mean rice husk size is 510µm. It also has a negative step function relationship between bacterial removal and rice husk size, and the transition zone happens in the same rice husk size range as Group T_F and T_P.

To summarize, the relationship between bacterial removal and rice husk size for all the disk

groups and full-sized filters are all a negative step function relationship, and the recipe (mass ratio and the rice husk origin) determines where the transition zone happens.

4.2.3 Hydraulic Conductivity & Bacterial Removal Test

The relationship between *E.coli* LRV and hydraulic conductivity K is investigated using all the data from Group M (Figure 4-20). Group T_P and Group T_F are not used because their data points are too few. Table 4-4 is the experimental data of Group M showing the relationship between hydraulic conductivity and bacterial removal under different flow rates. Figure 4-20 is the box plot showing the relationship between K and bacterial LRV combining all the data under different flow rates for each rice husk size.

Table 4-4 Experimental data of K vs. bacterial removal (Group M)

Sample #	Mean RHS (μm)	K (cm/hr)	LRV			
			1.5 ml/min	1.0 ml/min	0.5 ml/min	0.1 ml/min
121	387.5	0.16	5.01	5.17	5.09	7.49
122	387.5	0.15	5.26	4.97	5.43	7.26
123	387.5	0.19	5.39	4.83	5.03	8.03
131	510	0.25	3.90	4.20	4.17	6.33
132	510	0.26	3.87	4.17	4.56	4.07
133	510	0.39	4.08	3.88	3.66	4.20
141	655	0.77	4.04	4.80	5.19	5.26
142	655	0.55	3.37	3.35	4.19	5.72
151	780	1.07	3.20	3.97	4.53	4.70
153	780	1.35	3.20	4.13	4.39	5.06
161	925	1.95	2.89	3.65	3.82	4.15
162	925	2.27	2.71	3.56	3.27	3.99
163	925	2.65	3.27	3.99	3.82	4.56

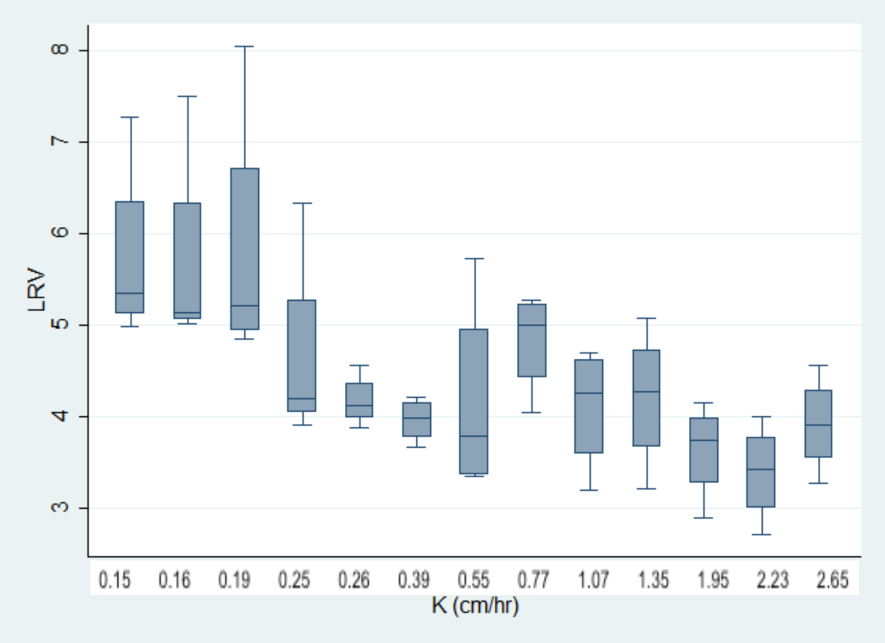

Figure 4-20 The box plot of the relationship between bacterial LRV and hydraulic conductivity (Group M)

It can be seen from Figure 4-20 that bacterial LRV and hydraulic conductivity have a negative correlation. Because of the limitation of data quantity, the specific relationship is not very clear.

Higher hydraulic conductivity means it is easier and faster for consumers to get access to clean water, but as shown by Figure 4-20, the bacterial removal will be sacrificed. Thus, it is important to find the right balance between hydraulic conductivity and bacterial removal for CPF factories. For a specific factory, the geometry of the filters normally will not be changed, so the way to control hydraulic conductivity is to change rice husk size and rice husk mass ratio.

4.2.4 Mixing Process & Bacterial Removal Test

1) Hand-mixed Filters

From a set of 50 filters, we chose 13 hand-mixed filters randomly and tested their total coliform removal using IDEXX Quanti-Tray method as mentioned in Section 3.5.5. The analytic result is shown in Figure 4-21.

2) Pugmill-mixed Filters

The same as with the hand-mixed filters that has mentioned above, 13 filters were chosen for testing. The analytic results are also shown in Figure 4-21.

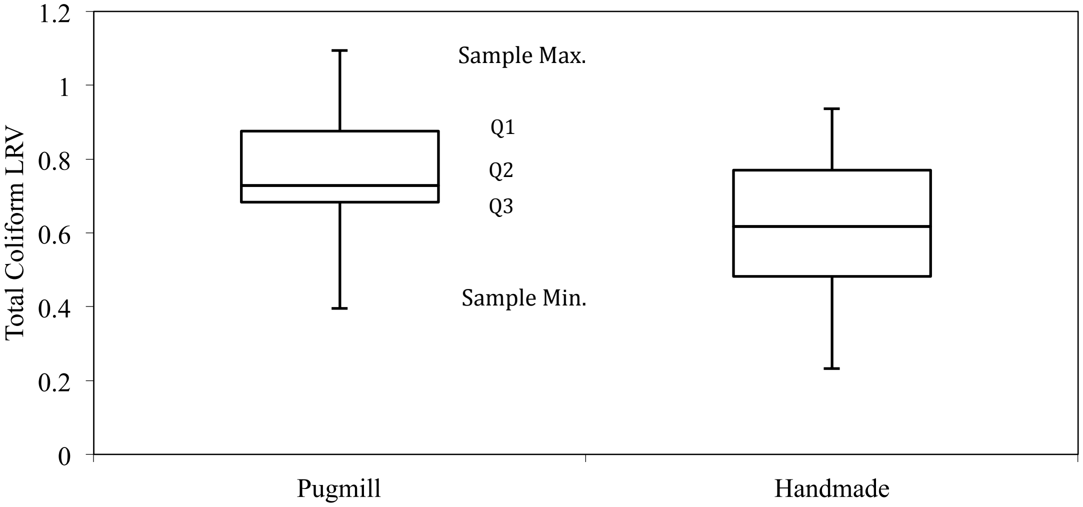

Figure 4-21 The Boxplot of pugmill-mixed and hand-mixed filters

The comparison of the analytic results between hand-mixed and pugmill-mixed filters is shown in Table 4-5.

Table 4-5 Basic Statistics of Total Coliform LRV of Pugmill-mixed Filters and Hand-mixed Filters

	Min.	**Q1**	**Median**	**Mean**	**Q3**	**Max.**	**Standard Deviation**
Hand-mixed	0.23	0.48	0.62	0.63	0.77	0.94	0.20
Pugmill-mixed	0.33	0.68	0.73	0.77	0.88	1.09	0.24

As shown in the graphs and the summaries regarding the two data sets, the LRV performance of each filter is different even if they are under the same mixing method. For example, the minimum LRV of hand-mixed filters is 0.23 while the maximum LRV is much higher, i.e., 0.94. **And pugmill-mixed filters show the same trend of variation with a low minimum LRV of 0.33 and a high maximum LRV of 1.09.** As regards hand-mixed filters vs. pugmill-mixed filters, the pugmill-mixed filters have better performance in terms of total coliform removal than hand-mixed ones, since the mean of the latter are higher than the former's by 22%.

According to the empirical experiences obtained when we made the full-sized filters, the author observed that the strength of the filter is related to the rice husk size and composition. The coarser the rice husk, the easier the filter cracks and fails. Also, during the production process, adding too much water will make it difficult for the filter to maintain its shape while drying.

5 Comparison Between Disks and Full-sized Filters

5.1 Performance Criteria 1: Bacterial Removal Rate

It had been the author's intention that Disk Group M and T_P would be compared in order to determine the differences between the disks made at MIT lab and those made at the Pure Home Water factory. This would have further indication of the relationship between the disks made at MIT lab and the real full-sized filters. However, because the recipes for making Disk Group M and Disk Group T_P were different (as indicated in Table 3-1), and because the opening sizes of the two sets of sieves were also different which the author didn't know until after she arrived in Ghana, the comparison between these two groups could not be done in this thesis. It could be investigated in further research by choosing the identical composition and screen opening sizes.

Figure 5-1 shows the combined results of Group M under each flow rate and Group T_P. It can be seen clearly that the data points of Group T_P are not in the same rice husk size range as Group M. The y-value represents the LRV of *E.coli.* All of the "bacterial LRV" in this section means the LRV of *E.coli*.

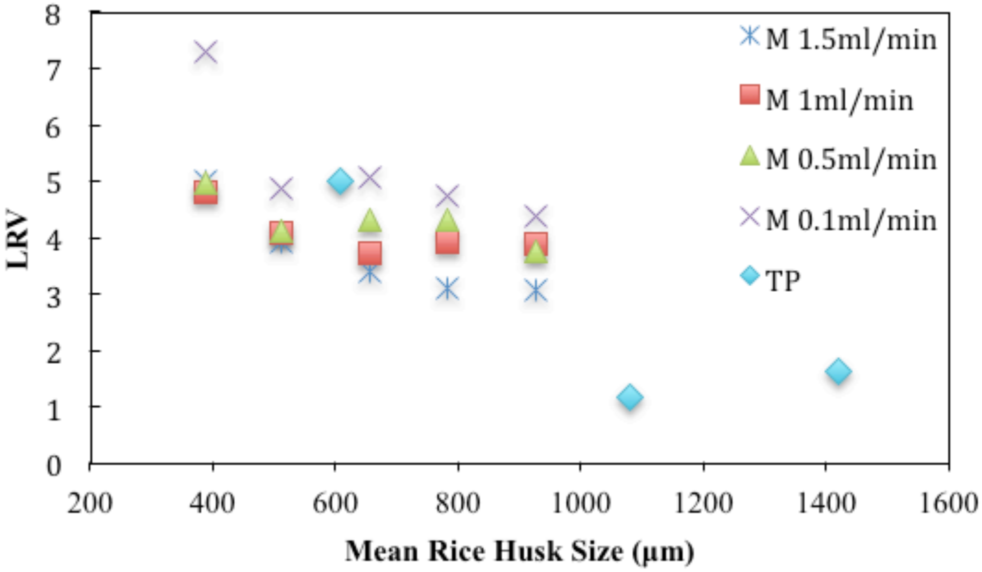

Figure 5-1 Comparison between Disk Group M & Disk Group T_P

5.1.1 Disk Group T_F & Disk Group T_P

Disk Group T_F and Disk Group T_P are compared to determine whether it is realistic to use hand-made plates to represent real filters. Bacterial LRV is compared in Figure 5-2, and the data from Group T_F and T_P are plotted together in this figure. Every point in the figure represents one disk. The x-axis presents the mean rice husk size of each disk.

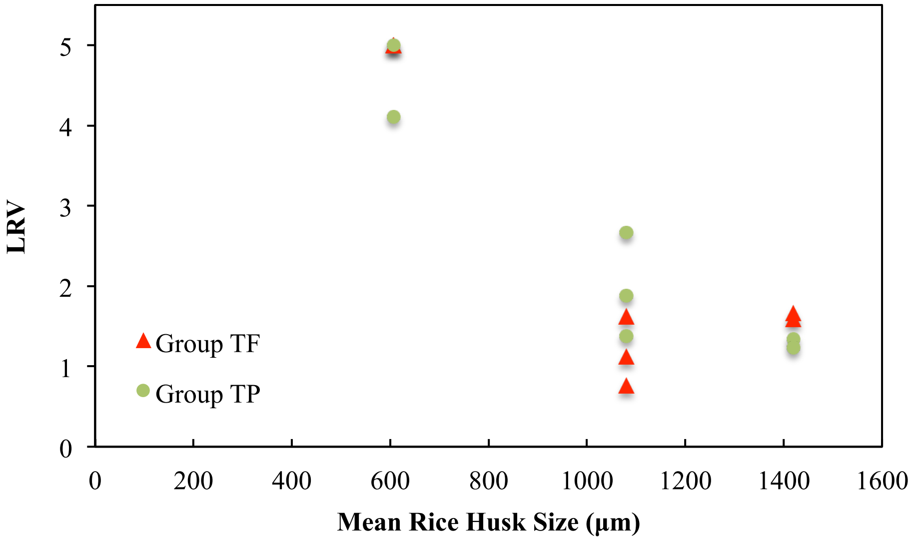

Figure 5-2 Comparison of LRV between T_F & T_P

Figure 5-2 suggests that:

1) When the Mean Rice Husk Size is at about 607µm, the bacterial removal rates of both Disk Group T_F and Disk Group T_P are very high (>4 LRV). And the bacterial removal rate of Disk Group T_F is higher than that of Disk Group T_P.

2) When the mean rice husk size is 1080µm, the bacterial removal rate of Disk Group T_F is lower than that of Disk Group T_P.

3) When the Mean Rice Husk Size is 1420µm, the bacterial removal rate of Disk Group T_F is higher than that of Disk Group T_P.

In general, the bacterial removal rates of Disk Group T_F and Disk Group T_P are very

similar. The nuance between Disk Group T_F and Disk Group T_P likely results from where they were cut from and the different pressing methods: the mixture of clay and rice husks was pressed in the press machine in the PHW factory for Disk Group T_F, while the mixture was pressed by hand for Disk Group T_P.

5.1.2 Disk Group T_F & Full-sized Filters

Disk Group T_F and full-sized filters are compared to investigate whether it is realistic to use disks to represent full-sized filters. Bacterial LRV is compared in Figure 5-3, and the data from T_F and full-sized filters are plotted together in the figure. Every point in the figure represents one disk or one filter. The x-axis presents the Mean Rice Husk Size of each disk and filter.

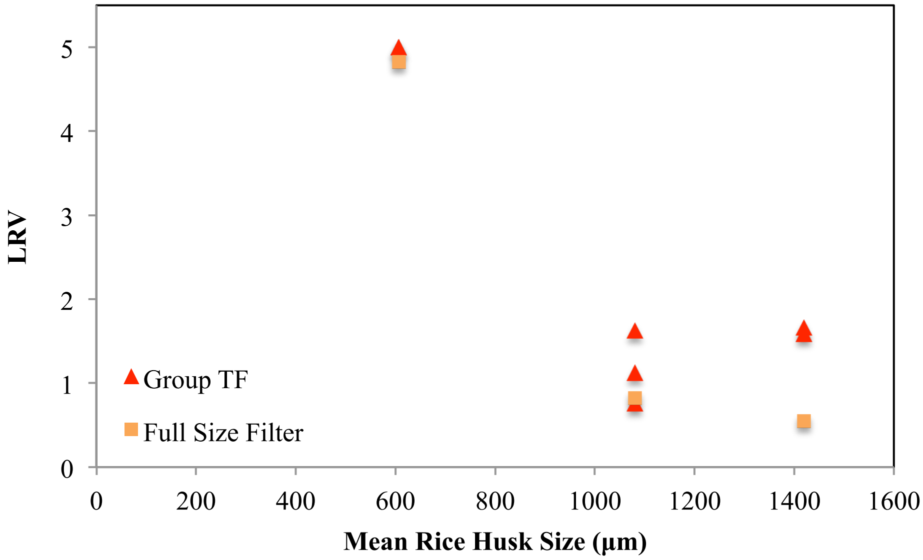

Figure 5-3 Comparison of LRV between T_F & full-sized filters

Figure 5-3 suggests that at the same rice husk size, the bacterial LRV of Disk Group T_F is higher than full-sized filters, and that the difference becomes more significant as the rice husk size becomes bigger: when the mean rice husk size is smaller than 1080µm, the bacterial removal rates of Disk Group T_F and full-sized filters are almost at the same magnitude; when the mean rice husk size is bigger than 1080µm, the difference between the bacterial removal rates is very significant. The reason for the difference is possibly because of the different pressing methods as mentioned in Section 5.1.1. Also, the path of water through the full-sized filters maybe more tortuous and longer than it is through the disks because full-sized filters have larger volume, and the paths inside may connect together making the flow more complicated inside the wall.

5.2 Performance Criteria 2：Flow Rate

5.2.1 Disk Group M & Disk Group T_P

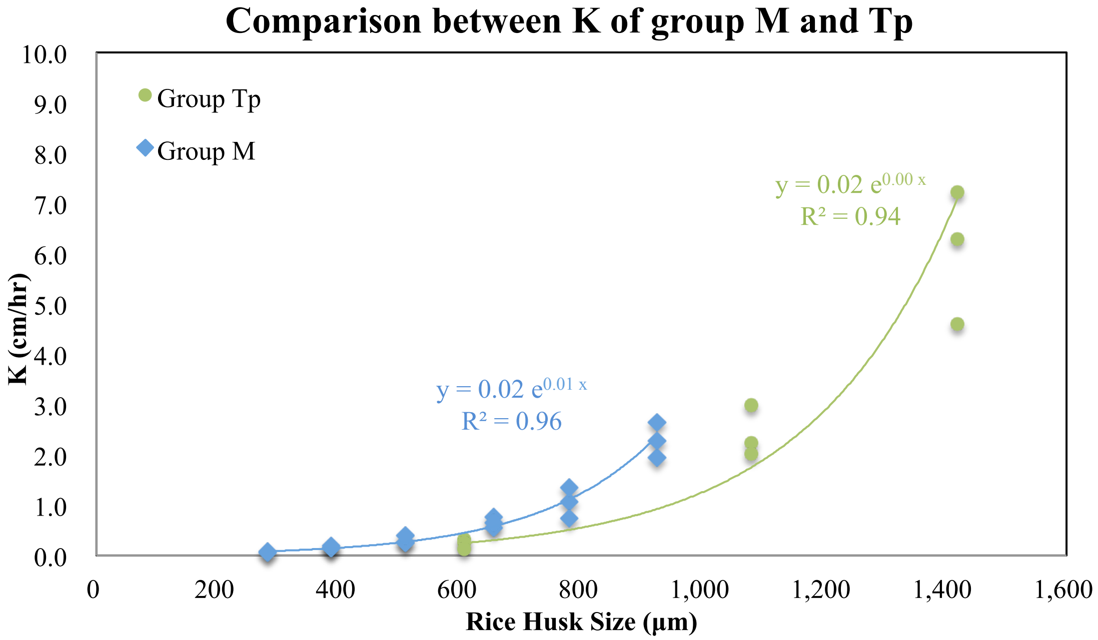

Figure 5-4 The hydraulic conductivities of Group M & Group T_P

Figure 5-4 shows that the hydraulic conductivities of Disk Group M are generally higher than Disk Group T_P, especially in the range from 0.6mm to 1.0mm. This phenomenon may result from the different mixing method and the different resources of rice husks. For making Disk Group M, the author mixed the mixture of clay, rice husks and water; while for making Disk Group T_P, the mixture was mixed by the women in PHW factory. And the rice husks used in Group M were from Cambodia, and those used in Group T_P were from Ghana. These differences make Disk Group T_P more compacted than Disk Group M, resulting in the higher K value of Disk Group T_P.

5.2.2 Disk Group T_P & Disk Group T_F

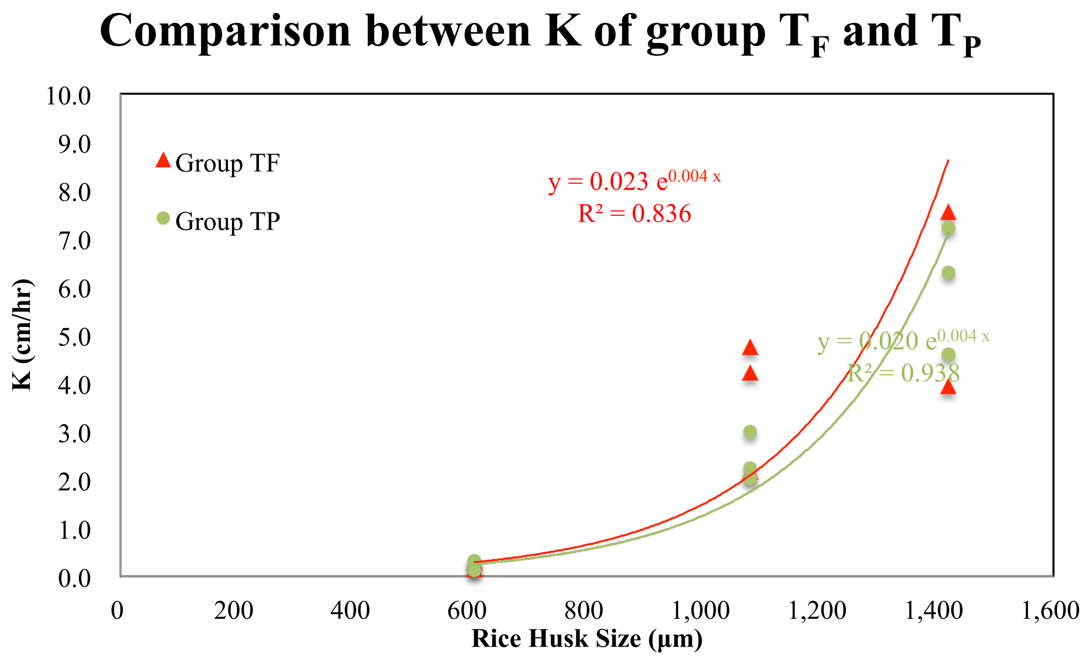

Figure 5-5 The hydralic conductivities of Group T_F and Group T_P

Figure 5-5 shows that the hydraulic conductivities of Disk Group T_F and Disk Group T_P are similar. In order to see their difference, the mean value and standard deviation are calculated in Table 5-1, and the t-test is shown in Table 5-2.

Table 5-1 The means and variances of K values for Group T_P with different RHS

RHS(μm)	607		1080		1460	
	Group T_P	Group T_F	Group T_P	Group T_F	Group T_P	Group T_F
μ (cm/hr)	6.04	5.75	2.42	3.72	0.24	0.22
σ^2	1.33	2.56	0.51	1.37	0.10	0.10

Applying the t-test method to test each pair of data sets, in order to determine whether they are significantly different from each other.

Table 5-2 The t-test of two sets of mean values for Group T_F and Group T_P

Tested Item	P	S/NS
μ	0.89	NS
σ^2	0.43	NS

*S represents "significant", and NS represents "not significant".

When $P>0.05$, the difference is "not significant"; when $P<0.05$, the difference is "significant".

In this case, the unpaired form of the t-test is used. The threshold chosen for statistical significance is $\alpha=0.05$. We found that, for both the mean value and variance, the K values of Group T_F and Group T_P are not significantly different from each other. It confirms that the pressing process (hand pressing and machine pressing) will not significantly influence the hydraulic conductivity of disks.

5.2.3 Disk Group T_F & full-sized filters

In this section, in order to compare the flow rate performance of sample disks and full-sized filters, the author utilizes the actual measured hydraulic conductivity data (K) from Group T_F to calculate the theoretical flow rate of a full-sized filter, and then compares it with the real flow rate of full-size filters the author tested.

1) Modeling the theoretical flow rate of a full-sized filter

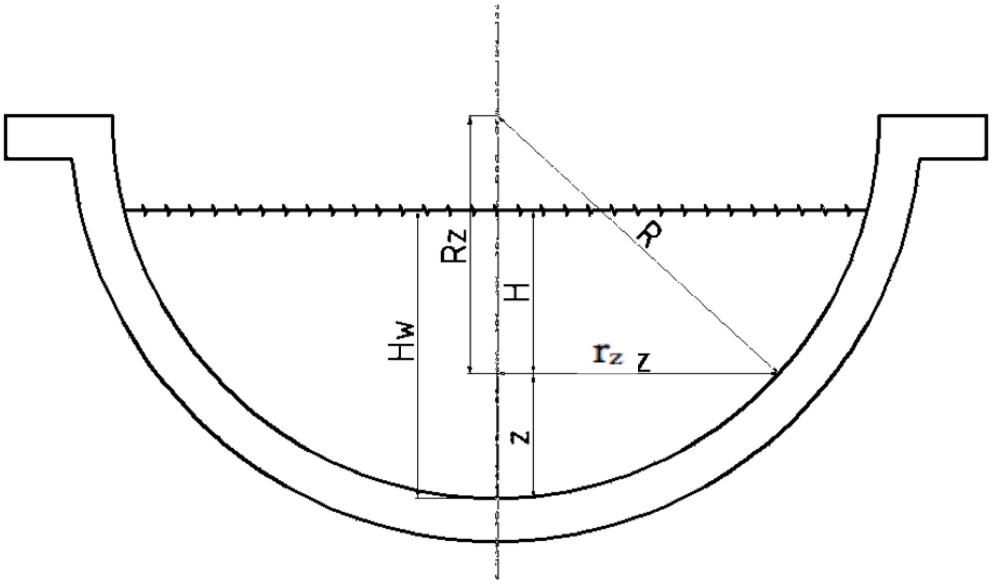

Figure 5-6 Geometry of a CPF

If dA is the filter surface area associated with an incremental unit of height dz:

$$\boldsymbol{dA = 2\pi r_z\sqrt{dz^2 + dr_z^2}} \qquad \textbf{Equation 6}$$

Where A is filter surface area measured on the internal surface of the filter, z is the height above the bottom of the filter, and r_z is the radius of the filter in the horizontal plane at height z.

In order to determine the value of r_z as a function of z, we take into account the radius of the full filter, R. Hence,

$$\boldsymbol{(R - z)^2 + r_z^2 = R^2} \qquad \textbf{Equation 7}$$

Solving for r_z,

$$\boldsymbol{r_z = \sqrt{2Rz - z^2}} \qquad \textbf{Equation 8}$$

Taking the derivative of r_z with respect to z:

$$\boldsymbol{\frac{dr_z}{dz} = \frac{R-z}{\sqrt{2Rz-z^2}}} \qquad \textbf{Equation 9}$$

Moving the d_z to the right hand side

$$dr_z = \frac{R-z}{\sqrt{2Rz-z^2}}dz$$ **Equation 10**

The values for r_z and dr_z expressed in Equations 10 and 8 can now be substituted back into Equation 6

$$dA = 2\pi\sqrt{2Rz-z^2}\sqrt{dz^2 + \frac{(R-z)^2}{2Rz-z^2}dz^2} = 2\pi dz\sqrt{(2Rz-z^2))(1+\frac{(R-z)^2}{2Rz-z^2})} = 2\pi Rdz$$

Equation 11

At height z, the hydraulic head h is

$$h = H_w - z$$ **Equation 12**

Where H_w is the deepest water depth. Thus, recalling Darcy's law for laminar flow through porous media $Q = KAh/L$ (Equation 5), the volumetric flow rate Q is:

$$Q = \frac{K}{L}\int_0^{A(H_w)} hdA = \frac{K}{L}\int_0^{H_w}(H_w - z)(2\pi R)dz$$ **Equation 13**

Where K is the hydraulic conductivity, and L is the wall thickness.

Solving the integral we get:

$$Q = \frac{\pi RK}{L}H_w^2$$ **Equation 14**

This derivation is based on Miller's model of flow through paraboloid filter in his Master's thesis (Miller, 2010) in his Section 8.3. Equation 14 indicates that for a hemisphere filter, when the filter's radius, wall thickness and hydraulic conductivity are known, the flow rate Q is only related to the deepest water depth H_w, and they have a positive correlation. More specifically, Q and H_w^2 has a positive linear correlation. Kelly conducted experimental tests to investigate the relationship between flow rate and water height for different filter shapes in her Master's thesis (Kelly, 2013). She gave an empirical relationship for the hemisphere filters she tested, which also showed a positive correlation between flow rate and water height.

$$Q = 0.03Kh^2 + 0.006Kh$$ **Equation 15**

If the filter is full of water $(H_w = R)$, $Q = \frac{\pi R^3 K}{L}$.

The filters made by Pure Home Water factory are with the geometry:

R=16cm, L=2.4cm

Using the mean K of Group T_F to calculate the theoretical flow rate, the results are listed in Table 5-3, and the calculation is shown below.

Table 5-3 Theoretical flow rate and % error results

Mean Rice Husk Size (μm)	K (cm/hr)	Theoretical Q (L/hr)	Actual Q (L/hr)	% Error
1420	5.7	30	29	3.3%
1080	3.7	20	15	25%
607	0.22	11	9	18%

Calculations:

For filters with rice husk size of 1420 micron, the theoretical flow rate should be:

$$Q_1 = \frac{\pi R^3 K_1}{L} = \frac{3.14 \times (16.0cm)^3 \times 5.7cm/hr}{2.4cm} = 3.0 \times 10^4 mL/hr \ \ (30\text{L/hr})$$

So the relative error between the theoretical flow rate and actual flow rate is:

$$\delta_1 = \frac{|30L/hr - 29L/hr|}{30L/hr} = 4.0\%$$

For filters with rice husk size of 1080 micron, the theoretical flow rate should be:

$$Q_2 = \frac{\pi R^3 K_2}{L} = \frac{3.14 \times (16.0cm)^3 \times 3.7cm/hr}{2.4cm} = 2.0 \times 10^4 mL/hr \quad (20\text{L/hr})$$

The relative error is:

$$\delta_2 = \frac{|20L/hr - 15L/hr|}{20L/hr} = 25\%$$

For filters with rice husk size of 607 micron, the theoretical flow rate should be:

$$Q_3 = \frac{\pi R^3 K_3}{L} = \frac{3.14\times(16.0cm)^3\times0.22cm/hr}{2.4cm} = 1.1\times10^3 mL/hr \quad (11\text{L/hr})$$

The relative error is:

$$\delta_3 = \frac{|11L/hr - 9L/hr|}{11L/hr} = 17\%$$

6 Conclusions and Recommendation

This projects aims to investigate the relationship between rice husk size, hydraulic conductivity, mixing process, flow rate and bacterial removal of CPFs by analyzing sample ceramic disks and full-sized filters in order to optimize filter performance. Specifically, the author of this thesis has sought to focus on those manufacturing parameters and performance metrics that have had little or no research about them until now. Those manufacturing parameters and performance metrics are identified by the ovals in Table 6-1. Sections 2 - 5 presented the experimental methods, results and analysis. In this chapter, the author synthesizes the analysis to generate overall conclusions, make recommendations to Pure Home Water, and propose further research.

Table 6-1 Parameter/performance matrix combining prior researches and new results.

	Flow Rate	**Bacterial Removal**
Rice Husk Size	Servi (2013): exponential or positive step	Servi (2013): negative linear or negative step
	Klarman (2009): no correlation	Rayner (2012): negative correlation
	Zhang (2014): positive exponential	Gensburger (2011): negative correlation
		Zhang (2014): negative step
Flow Rate	N/A	Rayner (2012): no corelation
		Bloem (2009): no correlation
		Klarman (2009): negative correlation
		Zhang (2014): negative linear or negative step
Hydraulic Conductivity	——	Zhang (2014): negative correlation
Mixing Process	——	Zhang (2014): pugmill performs better than hand in mixing

6.1 Conclusion

6.1.1 The Influence of Rice Husk Size on Hydraulic Conductivity

1) **There is a positive correlation between hydraulic conductivity and rice husk size, and exponential relationship works better for this study than $y=ax^2$ relationship.** As said in Section 1.1.3, rice husk incinerates when the CPF is fired, which leaves small pores so that the CPF can filter water through it. Thus, when the rice husk size is larger, the pores left in the CPF are larger, resulting in higher hydraulic conductivity. This exponential relationship is possibly because when the rice husks become larger, several rice husks would join together to make enormous pores. This effect is magnified when the rice husk becomes bigger, so the flow rate increases faster as the rice husk size becomes larger. In Servi's thesis (Servi, 2013), she suggested two possible relationships: positive exponential or positive step function. This conclusion verifies Servi's first explanation of a positive exponential relationship. For sample ceramic disks containing the same percentage rice husk, it is possible to calculate the flow rate by controlling the rice husk size range.

6.1.2 The Influence of Flow Rate on Bacterial Removal

There is a negative correlation between bacterial removal and flow rate, which is the same as the negative relationship found by Klarman (2009), but different from Rayner's (2012) and Bloem's (2010) finding of no correlation. Two explanations for the negative correlation exist in this study: negative linear correlation or negative step function correlation. It should be noted that the data collected in this aspect study is limited, thus, further research still needs to be done to determine which one or both combined together can best describe the influence of flow rate on bacterial removal. If the relationship between flow rate and bacterial removal could be found, then it is possible to determine an acceptable flow rate associate with a relatively high bacterial removal.

6.1.3 The Influence of Hydraulic Conductivity on Bacterial Removal

There is a negative correlation between hydraulic conductivity and bacterial removal, which means that getting clean water faster would sacrifice bacterial removal rate. Thus, it is important to find a balance. However, because of the limitation of data amount, the specific relationship still needs further research.

6.1.4 The Influence of Rice Husk Size on Bacterial Removal

There is a negative relationship between bacterial removal and rice husk size. Two explanations exist for the relationship: negative linear correlation and negative step function relationship.

For the negative step function relationship, the rice husk size range where the transition zone happens may change according to different recipes. For the recipe used for Group M, it is safe to increase the rice husk size up to 925μm without hurting the bacterial removal effectiveness.

Gensburger (2011), Rayner (2012) and Servi (2013) all found a negative correlation between rice husk size and bacterial removal, which agrees with the negative relationship found in this study. In addition, Servi (2013) suggested two possible explanations: negative linear and negative step function. This study verifies the negative step function relationship. By knowing the relationship and the transition zone, the manufacturers could determine the biggest rice husk size that can give a high flow rate without sacrificing the bacterial removal.

For Disk Group M, a transition occurs at a rice husk size of 510μm; for Disk Group T_P & T_F and full-sized filters, a transition occurs at a rice husk size of about 1080μm. However, the two sets of experiments used rice husk sizes of different ranges so that the results cannot be compared. We suppose that the general tendency within a range of 200μm to 1600μm will be like that shown in Figure 6-1. But this hypothesis needs further research to verify.

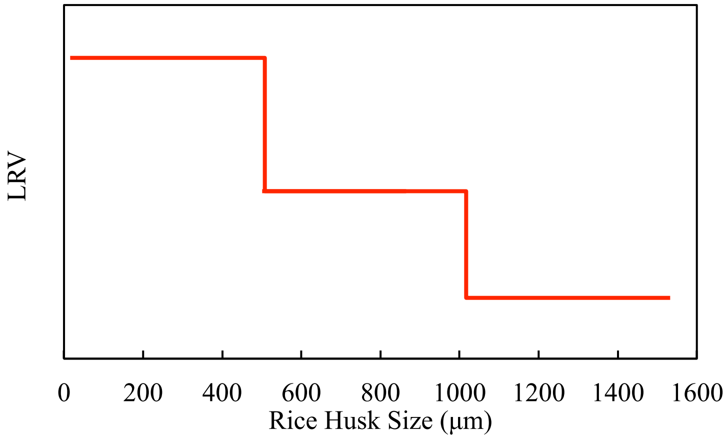

Figure 6-1 Proposed general LRV tendency when rice husk size increases in the range of 200µm to 1600µm

6.1.5 The Influence of Mixing Method on Bacterial Removal

In terms of total coliform removal, the mean LRV of hand-mixed filters is 0.63 while the mean LRV of pugmill-mixed filters is 0.77. **Thus, hand-mixed filters have a less effective bacterial removal performance than pugmill-mixed ones.**

6.1.6 The Feasibility of Conducting Tests Using Sample Disks Cut from Plates

In terms of both bacterial removal and flow rate, Group T_F and T_P have similar results for all rice husk sizes, which means conducting research using sample disks cut from plates gives the same results as using sample disks cut from filters. The bacterial removal of Group T_F and full-size filters are not significantly different when the mean rice husk size is smaller than 1080µm. Thus, it is feasible to use the bacterial removal results from disks to represent full-size filters. However, the flow rate difference between Group T_F and full-size filters varied a lot (from 4% to 25%) in these filters. Whether it is feasible or not to use flow rate results from disks to represent full-size filters needs further research.

6.2 Recommendations

6.2.1 Recommendations for CPF Manufacturers

1) Rice Husk Size

Based on the above stated conclusions, the bacteria removal of the filter whose mean rice husk size is larger than 1080μm are significantly lower than the filter whose mean rice husk size is 607μm. As the flow rate of the filter with a mean rice husk size of 607μm was too slow to be acceptable, we suggest that the PHW uses a mean rice husk size of between 607μm and 1080μm. As the 880μm mesh screen is the one the author found that gives a pore size between 607μm and 980μm (the factory already has the 980μm mesh, see Table 6.2 medium), the conclusion above suggested change in current PHW factory production from a rice husk size range of 0-1680μm to a proposed rice husk size in the range of 0-880μm to 0-1180μm will improve the performance of PHW filters. Future research needs to be done to narrow this range and find out an even more exact mean rice husk size to ensure both adequate flow rate and acceptable level of bacterial removal. (For further recommendations, see Appendix C.)

2) The Mixing Process

Based on the conclusion in Section 6.1.5, pugmill works better for mixing water, rice husk and clay powder. It is recommended to mix with the pugmill instead of by hand in the manufacturing process.

6.2.2 Recommendations for Further Research

1) Expand the range of rice husk size (200 to 1600μm) and find the two transitions. As said in Section 6.1.2, the author found a transition zone for each set of the experiments. But the two sets of experiments used rice husk sizes of different ranges so that the results cannot be compared. The author hypothesizes that if we expand the range of rice husk sizes from 200μm to 1600μm, two transition zones will be found as per Figure 6-1. This hypothesis still needs further research

to verify.

2) Use different method to sieve rice husks when making full-sized filters. As mentioned in Section 3.3.3, the author prepared three different sizes of rice husks using a set of four mesh screens listed in Table 6-2.

Table 6-2 Parameters of the old (2012-2014) sets of mesh screens used

Name	Opening size/µm	Mesh	Wire diameter/inch
"USA new"	1660	12	0.018
"Nigeria"	1180	16	0.016
"Medium"	980	18	0.017
"Small"	234	60	0.0075

Thus, the three different rice husk sizes were: 1180-1660µm, 980-1180µm, and 234-980µm. But in real manufacturing, PHW factory manufacturers only use one mesh screen that has an opening size of 1680µm. Thus, the size of rice husks used to manufacture real full-sized filters at the factory is 0-1680µm. Actually, it is very difficult for PHW manufacturers to use two screens to obtain a certain range of rice husk size because it will increase workload and require more rice husks. Therefore, we suggest using a set of different screens to get rice husk sizes shown in Table 6-3, and then choose the best screen opening size.

Table 6-3 Suggested new (2015) screen opening size and rice husk size obtained

	Opening size/µm	Name	Rice husk size range /µm	Mean rice husk size /µm
Using one sieve	1220	New	0-1220	610
	880	New	0-880	440
Using two sieves	1180 690	Nigeria New	690-1180	935
	1220 540	New New	540-1220	880

The detailed recommendations of what PHW should do with the new mesh sizes are described in Appendix C.

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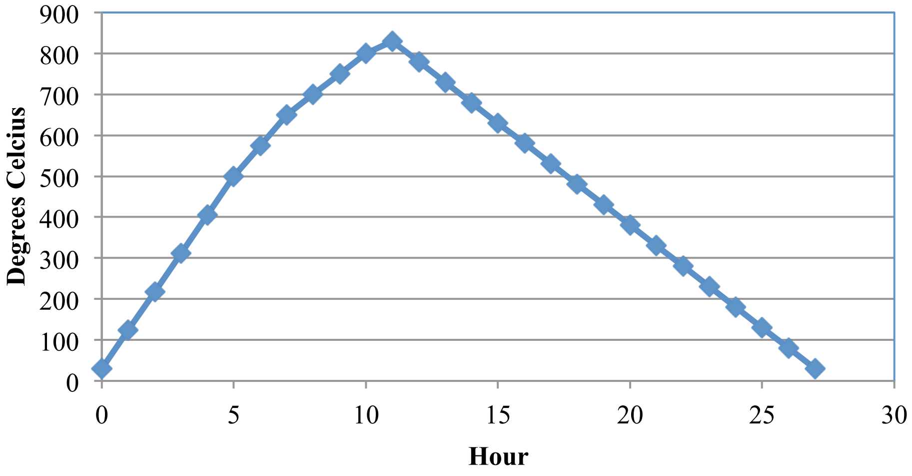
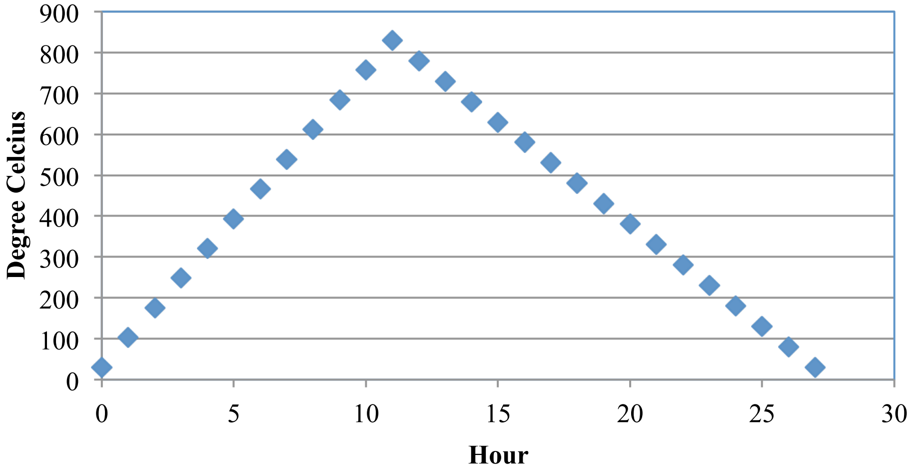
Appendix A The Firing Profile

Hour	**Ideal degree C**	**Actual degree C**
0	30	30
1	124	103
2	218	175
3	312	248
4	406	321
5	500	394
6	575	466
7	650	539
8	700	612
9	750	685
10	800	757
11	830	830
12	780	780
13	730	730
14	680	680
15	630	630
16	580	580
17	530	530
18	480	480
19	430	430
20	380	380
21	330	330
22	280	280
23	230	230
24	180	180
25	130	130
26	80	80
27	30	30



Ideal firing profile



Actual firing profile used

Appendix B Standard Operating Procedure for Culturing *E.coli*

Chemicals/Organisms:

- Tryptone (8.0g)
- NaCl (0.5g)
- LB media plates (10)
- LB broth (500 mL, supports 10^9/mL *E.coli*)
- Freeze-dried K12 *E.coli* (1 vial)
- Distilled water (1.0L)

Equipment:

- Refrigerator (4 degrees Celsius)
- Incubator (37 degrees Celsius)
- Autoclave (121 degrees Celsius)
- Hood

Metal/Glassware:

- Glassware (>1L)
- Test tube (>5mL)
- Vial (>10mL)
- Test tube holder
- Pipette (0.5mL, 5mL, 10mL)
- Sterile mix-sticks

Prepare the freeze-dried K12

- Mix Tryptone (8.0g), NaCl (0.5g) and distilled water (1.0L) in a 1.5L glassware.
- Autoclave the mix at 121C for 15 minutes

To be done in the hood:

- Pipette 0.5mL broth into the vial containing the K12
- Mix the liquid in the vial into a slurry

- Add this slurry to 4.5mL additional broth
- Incubate broth at 37 degrees C for 8 hours
- Store broth at 4 degrees C, the broth will keep for one month

Streak a plate

- Dip a sterile mix-stick into the broth and streak it onto the plate
- Incubate plate at 37 degrees C for 8 hours
- Store plate at 4 degrees C, the colonies will keep for one month

Prepare broth

- Pipette 10mL LB broth into vial
- Dip sterile mix-stick into a colony on the plate
- Dip mix-stick into the broth
- Incubate the broth at 37 degrees Celsius for 24 hours
- Store broth at 4 degrees C, the *E.coli* will keep for 1 month
- When nearing the end of the month, streak a plate with *E.coli* from the broth and repeat the above steps

Appendix C Recommendations for the New Mesh Sizes for Pure Home Water Factory

The new meshes are: 1220 µm mesh; 880 µm mesh, 690 µm mesh, and 540 µm mesh. These mesh screens have been purchased and shipped to Tamale Ghana in May 2014 for future research to determine the most proper rice husk size to use and for PHW factory. Please refer to Table 6-2.

1. Recommendation for the 1220 µm mesh:

a) Use it individually to sieve rice husk so that the factory can get rice husks in the size range of 0-1220 µm.

b) Use these rice husks to produce three to five filters as normal.

c) After the filters are produced, test their flow rate as well as the bacterial removal LRV using dugout water as influent.

d) Then compare the flow rate and bacterial removal LRV with the performance of the filters currently produced in the PHW factory. If the flow rate still satisfies the adequate flow requirement, and the bacterial removal LRV increases, then use this new mesh; if the flow rate decreases to an inadequate level and the bacterial removal LRV doesn't increase a lot, then do not use this new mesh.

2. Recommendation for the 880 µm mesh:

If the 1220 µm mesh can be used after the comparison in the step d) above, then test the 880 µm mesh in the same a), b), c) and d) steps as the 1220 µm mesh above to determine whether 880 µm mesh can be used for production.

3. Recommendation for 690 µm & 1180 µm mesh set

a) Use the 690 µm & 1180 µm mesh as a set to sieve the rice husks, so that the factory will get rice husks in the size range of 690-1180 µm.

b) Produce, test, and compare in the same as the b), c) and d) steps in the recommendation for the 1220 µm mesh to determine whether this mesh set performs better than the currently used mesh.

4. Recommendation for 540 µm & 1220 µm mesh set

a) If the 690 µm & 1180 µm mesh set performs well after the comparison in the previous b) step, then use the 540 µm & the 1220 µm mesh as a set to sieve the rice husks, so that the factory will get rice husks in the size range of 540-1220 µm.

b) The same as the b) step in the recommendation for 690 µm & 1180 µm mesh set to determine whether this 540 µm & 1220 µm mesh set can be used in the production.

Appendix D Experimental Data

Rice husk size/ Hydraulic conductivity

Group	Sample	Rice Husk Size (μm)	Thickness (mm)	Diameter (mm)	Cross Area (mm^2)	Head (cm)	Flow Rate (mm3/min)	K (cm/hr)
Group M	111	210-355	18.22	27.28	584.62	29.50	77.00	0.05
	112	210-355	17.85	27.28	584.62	29.50	128.00	0.08
	121	355-420	17.69	26.83	565.49	29.50	246.00	0.16
	122	355-420	18.83	26.82	565.07	29.50	215.67	0.15
	123	355-420	18.49	26.99	572.26	29.50	289.00	0.19
	131	420-600	16.84	27.00	572.40	29.50	417.33	0.25
	132	420-600	17.63	27.06	574.94	29.50	413.00	0.26
	133	420-600	17.87	27.09	576.22	29.50	618.67	0.39
	141	600-710	18.89	27.53	595.38	29.50	1186.00	0.77
	142	600-710	17.96	27.20	581.05	29.50	870.67	0.55
	143	600-710	17.83	27.46	592.36	29.50	1067.78	0.65
	151	710-850	17.74	27.36	587.91	29.50	1746.00	1.07
	152	710-850	18.17	27.34	587.05	29.50	1171.00	0.74
	153	710-850	17.74	27.00	572.68	29.50	2135.00	1.35
	161	850-1000	18.40	25.75	520.62	29.50	2710.00	1.95
	162	850-1000	17.17	26.63	556.81	29.50	3626.00	2.27
	163	850-1000	17.28	26.75	561.98	29.50	4233.00	2.65
Group T_P	221	1180-1660	19.50	26.00	530.93	14.00	3.03	4.76
	222	1180-1660	19.83	25.93	528.21	14.00	4.70	7.56
	223	1180-1660	20.33	26.83	565.51	14.00	4.70	7.24
	231	980-1180	21.23	26.80	564.10	14.00	1.66	2.67
	232	980-1180	21.67	26.83	565.51	14.00	1.51	2.48
	233	980-1180	21.23	27.10	576.80	14.00	2.32	3.67
	241	234-980	18.40	27.17	579.65	14.00	0.25	0.35
	242	234-980	19.40	27.20	581.07	14.00	0.21	0.29
	243	234-980	18.93	27.40	589.65	14.00	0.10	0.14

Group T_F	321	1180-1660	22.67	25.80	522.79	14.00	4.82	8.96
	322	1180-1660	23.67	25.83	524.14	14.00	2.53	4.90
	331	980-1180	25.33	25.57	513.38	14.00	1.33	2.82
	332	980-1180	23.23	25.83	524.14	14.00	2.71	5.15
	333	980-1180	23.80	27.23	582.49	14.00	3.77	6.60
	341	234-980	21.50	27.13	578.22	14.00	0.23	0.37
	342	234-980	25.33	27.73	604.08	14.00	0.13	0.22
Full-sized Filter	2	1180-1660				14.00	480.00	
	3	980-1180				14.00	251.50	
	4	234-980				14.00	15.15	

Rice Husk Size / Bacterial Removal & Flow Rate / Bacterial Removal

			Flow Rate							
			1.5 ml/min		1.0 ml/min		0.5 ml/min		0.1 ml/min	
Group	Sample	Rice Husk Size (μm)	LRV	Ave.	LRV	Ave.	LRV	Ave.	LRV	Ave.
Group M	**121**	**355-420**	5.01	5.22	5.17	4.99	5.09	5.19	7.49	7.59
	122	**355-420**	5.26		4.97		5.43		7.26	
	123	**355-420**	5.39		4.83		5.03		8.03	
	131	420-600	3.90	3.95	4.20	4.08	4.17	4.13	6.33	4.87
	132	420-600	3.87		4.17		4.56		4.07	
	133	420-600	4.08		3.88		3.66		4.20	
	141	600-710	4.04	3.71	4.80	4.08	5.19	4.69	5.26	5.49
	142	600-710	3.37		3.35		4.19		5.72	
	151	710-850	3.20	3.20	3.97	4.05	4.53	4.46	4.70	4.88
	153	710-850	3.20		4.13		4.39		5.06	
	161	850-1000	2.89	2.96	3.65	3.74	3.82	3.64	4.15	4.23
	162	850-1000	2.71		3.56		3.27		3.99	
	163	850-1000	3.27		3.99		3.82		4.56	
			Water Head: 14cm							
			LRV	Ave.						
Group	221	1180-166	3.67	2.48						

T_P		0		
	222	1180-1660	1.29	
	231	980-1180	2.25	2.55
	232	980-1180	3.72	
	233	980-1180	1.69	
	241	234-980	4.11	4.55
	243	234-980	>5	
Group T_F	321	1180-1660	1.88	3.03
	322	1180-1660	4.17	
	331	980-1180	2.12	1.52
	332	980-1180	1.37	
	333	980-1180	1.06	
	341	234-980	>5	5
	342	234-980	>5	
Full-sized Filter	2	1180-1660	0.55	
	3	980-1180	0.82	
	4	234-980	4.82	

Mixing Process / Bacterial Removal

	Sample #	Total Coliform (MPN/100ml)	Ave. Total Coliform	E.coli (MPN/100ml)
Influent	1	122	64.67	10
	2	52		0
	3	20		10
Manufacturing Process	Sample #	Total Coliform (MPN/100ml)	Total Coliform LRV	E.coli (MPN/100ml)
Pugmill	3	5.2	1.09	0
	7	23.3	0.44	2
	12	8.6	0.88	1
	16	13.4	0.68	0

	19	30.5	0.33	1
	9	5.2	1.09	0
	27	13.4	0.68	2
	29	5.2	1.09	1
	38	9.8	0.82	0
	40	13.4	0.68	0
	41	9.8	0.82	0
	46	14.8	0.64	0
	47	12.1	0.73	0
Handmade	5	11	0.77	0
	9	17.5	0.57	0
	10	16.1	0.60	2
	11	8.5	0.88	0
	16	13.4	0.68	0
	18	7.5	0.94	0
	26	11	0.77	0
	32	21.3	0.48	0
	38	23.3	0.44	0
	43	11	0.77	0
	47	37.9	0.23	1
	49	24.3	0.43	0
	50	15.6	0.62	2